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Proceedings

A Scale-Up Approach for Gas Dispersion in Non-Newtonian Fluids with a Coaxial Mixer: Analysis of Mass Transfer †

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† Presented at the 1st International Electronic Conference on Processes: Processes System Innovation, 17–31 May 2022; Available online: https://ecp2022.sciforum.net.

Abstract: Coaxial mixers have shown a uniform energy dissipation rate throughout the mixing tank and a high mass transfer rate. However, to the best of our knowledge no investigation has been conducted on the scale-up of the aerated coaxial mixers. In this study, the gas hold-up profile, energy dissipation rate profile, power consumption, and mixing hydrodynamics were explored to keep the mass transfer of the large-scale mixer the same as its small-scale counterpart. The effects of the impeller type, impeller speed, pumping direction, and aeration rate on the reliability of the proposed scale-up technique were explored through electrical resistance tomography, simplified dynamic pressure method, and computational fluid dynamics.

Keywords: scale-up; gas-liquid mixing; tomography; mass transfer; non-newtonian fluid

Citation: Rahimzadeh, A.; Ein-Mozaffari, F.; Lohi, A. A scale-up approach for gas dispersion in non-Newtonian fluids with a coaxial mixer: Analysis of mass transfer. *Proceedings* **2022**, *69*, x. https://doi.org/10.3390/xxxxx

Academic Editor: Firstname Lastname

Published: date

1. Introduction

The scale-up of the gas-liquid mixing process is a challenging task. Some of these challenges are associated with the fluid's non-Newtonian behavior resulting in oxygen depletion zones upon scale-up. Coaxial mixers comprising of a central impeller and an anchor have shown promising performance in mixing non-Newtonian fluids [1]. The mass transfer coefficient, gas hold-up, power consumption, and flow hydrodynamics obtained by an aerated coaxial mixer filled with non-Newtonian fluid have been studied by a few number of researchers [2–7].

Mass transfer coefficient (k_La) is a process limiting parameter in many mixing operations used in biochemical industries [8]. Because of that there have been many efforts to maintain the mass transfer constant upon scale-up of a mixing tank [9–12]. It was shown that the k_La is largely depends on the specific power consumption and the aeration rate. Thus, controlling the specific power consumption and proper aeration rate are crucial to maintain the mass transfer rate of the large-scale mixer the same as the small-scale counterpart [13,14].

According to the literature review, there has never been a scale-up investigation of the coaxial mixer. Therefore, the main objective of this study is to determine the coaxial mixer's scalability by maintaining the mass transfer coefficient constant. In this study, a scale-up analysis was carried out using two coaxial mixer scales containing a non-Newtonian fluid. The gas hold-up profile, energy dissipation rate profile, mixing hydrodynamics, and power consumption were investigated to propose a successful scale-up approach by exploring the effect of the impellers' speed, aeration rate and central impeller pumping direction.

2. Experimental Setup and Methods

Experimental Method

A cylindrical tank with a diameter of 40 cm was used in this study as a small-scale mixing tank. A large-scale mixing vessel was built based on the geometrical similarities and with a scale-up factor of 1.5. Two impellers namely as a central impeller and an anchor were mounted on to the upper and lower shafts, respectively. Each shaft was able to rotate independently. The pitched blade impeller was used as a central impeller. The geometrical parameters of both small-scale and large-scale coaxial mixer are listed in Table 1. The air was introduced inside the mixing tank through a ring sparger. The operational conditions used in this study can be found in Table 2. Carboxymethyl cellulose (CMC) solution with a concentration of 0.5 wt% was used as a working fluid. The rheological data of the working fluid was obtained by a Rheometer. It was found that the rheological behavior of the CMC solutions at room temperature (22 ±1 °C) obeys the power-law model as follow:

$$\tau = 0.3875\, \dot{\gamma}^{0.8591} \tag{1}$$

where, τ and $\dot{\gamma}$ are the shear stress and shear rate, respectively.

The gas hold-up was measured using the electrical resistance tomography (ERT) method. In this method the conductivity profile constructed for each plane of the ERT system was used to determine the gas hold-up by applying the simplified Maxwell equation. The ERT systems employed for both large-scale and small-scale mixers were consisted of four planes.

The mass transfer coefficient was obtained by dynamic pressure gassing-out method. In this study, three dissolved oxygen meters were employed at different heights of the mixing vessel to record the oxygen concentration inside the CMC solution.

The power consumption of each impeller was acquired from the relevant torque meter. The residual torque due to the friction was subtracted from the measured torque to obtain the net power consumption.

Table 1. Geometrical parameters of the coaxial mixers.

Mixer	vessel	Central impeller	Anchor impeller
Small-scale	Diameter = 40.0 cm, height = 40.0 cm	Diameter = 18.0, width = 3.4 cm, clearance = 17.5 cm	Diameter = 36.0 cm, width = 3.1 cm, height = 36.0 cm
Large-scale	Diameter = 60.0 cm, height = 60.0 cm	Diameter = 27 cm, width = 5.1 cm, clearance = 26 cm	Diameter = 54.0 cm, width = 4.7 cm, height = 54.0 cm

Table 2. Operating conditions.

Mixer	Central impeller speed range	Anchor impeller speed range	Aeration rate (*vvm*)
Small-scale	142-288 rpm	10–30 rpm	0.12
Large-scale	95-210 rpm	10–30 rpm	0.08 and 0.12

3. Numerical Method

The numerical model to solve the gas-liquid multiphase flow was generated by ANSYS FLUENT (2020 R1) software. In this model the Eulerian-Eulerian approach was adopted to solve the mass and momentum transport equations. The dispersed $k-\varepsilon$ turbulence model was implemented. The modified Brucato [15] drag model was utilized and Sato [16] model was used to consider the bubble induced turbulence effect.

The moving zones inside the mixing tank were modeled by using the sliding mesh technique. The top surface of the mixing vessel was set to the degassing boundary condition and the mass flow rate boundary condition was defined at the top surface of the sparger.

The time step used in this numerical model was 0.001 s. The mathematical model was solved for almost 24 revolutions of the central impeller. The grid independency test was performed. The 1,653,952 cells and 4,673,962 cells were found to be optimum grid sizes for the small-scale and large-scale models, respectively. Both mixer scales were validate using the gas hold-up profile, power consumption, and mass transfer coefficient.

4. Results and Discussion

Previously, it was found that the mass transfer efficiency obtained for the coaxial mixer comprised of a pitched blade impeller in the upward pumping direction and an anchor (PBU-anchor) in the co-rotating mode was higher than those for the other coaxial mixer configurations [2]. Thus, in this study the PBU-anchor mixer in the co-rotating mode was investigated.

As analysis of the cavity size and local gas hold-up is one of the methods to determine the flow regime inside the mixing vessel [17]. Therefore, in this study the local gas hold-up profile was investigated both experimentally and numerically. The local gas hold-up profile obtained from the ERT plane located near the central impeller showed a good agreement with the results attained from the CFD model. As can be seen in Figure 1, it was found that at the higher power consumptions the cavity size at vicinity of the central impeller was almost negligible and the mixing flow regime was under complete dispersion condition.

The results accomplished from ERT depicted in Figure 1a shows that the flow hydrodynamics was almost uniform throughout the mixing vessel. Furthermore, according to the results illustrated in Figure 1b, it was found that the gas hold-up distributions in both radial and axial direction were uniform and the cavity size generated by the coaxial mixer at the vicinity of the central impeller was insignificant.

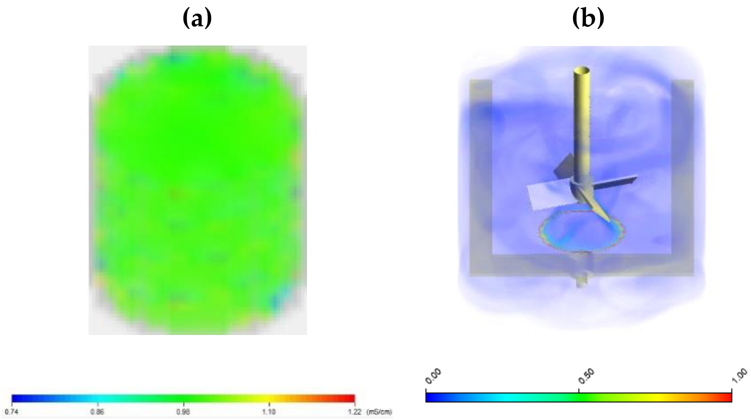

Figure 1. Gas dispersion upon scale-up: (a) 3D tomogram obtained from ERT, and (b) gas volume fraction obtained from CFD (central impeller speed =192 rpm, anchor impeller speed =10 rpm, and aeration rate of 0.12 *vvm*, 0.5 wt% CMC)

The flow-regime attained by the coaxial mixer was further investigated by analyzing the relative power demand (*RPD*). In order to measure *RPD*, the aerated power consumption was divided by the unaerated power consumption. It was found that *RPD* has an inverse relation with the cavity size. In another words, by increasing the cavity size the *RPD* value obtained by the PBU-anchor mixer decreased. This was due to the fact that under large cavity size conditions, only a small amount of drag force was produced against the central impeller rotation and as a result the amount of the power consumption obtained by the central impeller was decreased.

It was revealed that for the large-scale PBU-anchor mixer in the co-rotating mode under the same specific power consumption and central impeller tip speed, the *RPD* results followed the same pattern as its small-scale counterpart upon scale-up. This finding was important since it showed that the large-scale flow-regime could be predicted based on the flow-regime observed by its small-scale counterpart.

k_La and the aeration rate (volumetric flow rate of air per volume of working fluid) were kept constant at both small and large scales to investigate the performance of the PBU-anchor mixer upon scale-up. The specific power consumption of the large-scale mixing tank was found to be lower than that of the small-scale mixing tank when this method was used as a scale-up approach to maintain the mass transfer coefficient constant. As can be seen in Figure 2, it was observed that reasonable gas hold-up and the energy dissipation rate distributions achieved for the large-scale mixer. As shown in Figure 2c, the fluid velocity vector profile demonstrated that the flow regime acquired by the large-scale PBU-anchor mixer in the co-rotating mode was under complete dispersion condition upon scale-up.

(a) **(b)** **(c)**

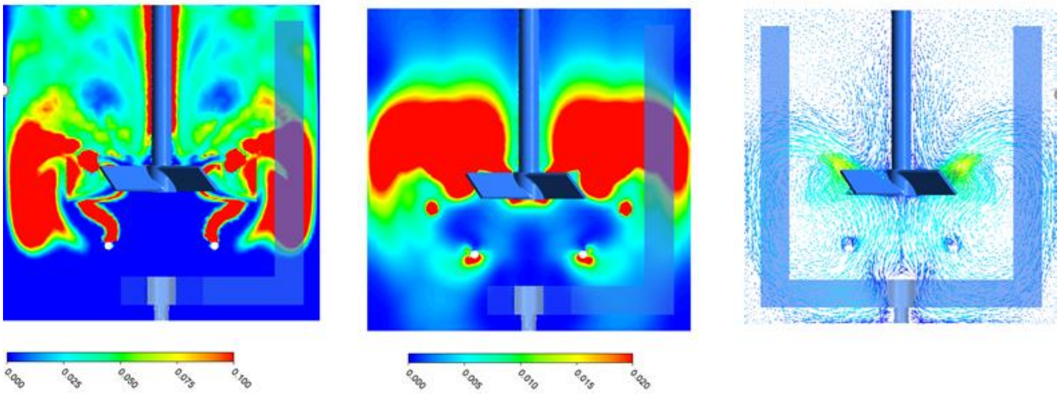

Figure 2. The performance of the PBU-anchor mixer upon scale-up: (a) gas hold-up profile (b) energy dissipation rate profile, and (c) fluid velocity vector (central impeller speed =173 rpm, anchor impeller speed =10 rpm, and aeration rate of 0.12 *vvm*, 0.5 wt% CMC).

5. Conclusions

The scale-up study was performed for an aerated coaxial mixer comprising of a pitched blade impeller in an upward pumping direction as a central impeller and an anchor as a close-clearance impeller. The effectiveness of the scale-up study was assessed by investigating the power consumption, energy dissipation rate, gas hold-up, mass transfer, and fluid hydrodynamics.

It was observed that at the same central impeller tip speed and anchor impeller rotational speed, the flow regime attained by the large-scale mixer was almost the same as its small-scale counterpart. Furthermore, for the first time the scale-up study of the PBU-anchor mixer in the co-rotating mode was conducted successfully. The established scale-up was based on maintaining the mass transfer coefficient constant between the two scales.

Acknowledgments: The financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC) is gratefully acknowledged.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. P. Lins Barros, F. Ein-mozaffari, A. Lohi, Gas Dispersion in Non-Newtonian Fluids with Mechanically Agitated Systems : A Review, Process. 10 (2022) 275. https://doi.org/https://doi.org/10.3390/pr10020275.
2. A. Rahimzadeh, F. Ein-moza, A. Lohi, New Insights into the Gas Dispersion and Mass Transfer in Shear- Thinning Fluids Inside an Aerated Coaxial Mixer via Analysis of Flow Hydrodynamics and Shear Environment, (2022). https://doi.org/10.1021/acs.iecr.1c04586.

3. M. Jamshidzadeh, F. Ein-Mozaffari, A. Lohi, Experimental Analysis of the Mass Transfer Coefficient and Interfacial Area in an Aerated Coaxial Mixing System Comprising a Non-Newtonian Solution, Ind. Eng. Chem. Res. 6 (2020). https://doi.org/10.1021/acs.iecr.0c03641.
4. M. Jamshidzadeh, F. Ein-Mozaffari, A. Lohi, Local and Overall Gas Holdup in an Aerated Coaxial Mixing System Containing a Non-Newtonian Fluid, AIChE J. 66 (2020). https://doi.org/10.1002/aic.17016.
5. M. Jamshidzadeh, F. Ein-Mozaffari, A. Lohi, Local Distribution of Oxygen Mass Transfer Coefficient in CMC Solutions in Bioreactors Furnished with Different Types of Coaxial Mixers, Chem. Eng. Res. Des. 174 (2021) 213–224. https://doi.org/https://doi.org/10.1016/j.cherd.2021.08.006.
6. S. Jegatheeswaran, A. Kazemzadeh, F. Ein-Mozaffari, Enhanced aeration efficiency in non-Newtonian fluids using coaxial mixers: High-solidity ratio central impeller with an anchor, Chem. Eng. J. 378 (2019) 122081. https://doi.org/https://doi.org/10.1016/j.cej.2019.122081.
7. S. Jegatheeswaran, F. Ein-Mozaffari, Investigation of the detrimental effect of the rotational speed on gas holdup in non-Newtonian fluids with Scaba-anchor coaxial mixer: A paradigm shift in gas-liquid mixing, Chem. Eng. J. 383 (2020) 123118. https://doi.org/https://doi.org/10.1016/j.cej.2019.123118.
8. F. Sher, Z. Sajid, B. Tokay, M. Khzouz, H. Sadiq, G. Editorial, Study of gas–liquid mixing in stirred vessel using electrical resistance tomography, Asia-Pacific J. Chem. Eng. 11 (2016) 855–865. https://doi.org/10.1002/apj.2019.
9. J. Gimbun, C.D. Rielly, Z.K. Nagy, Modelling of mass transfer in gas-liquid stirred tanks agitated by Rushton turbine and CD-6 impeller: A scale-up study, Chem. Eng. Res. Des. 87 (2009) 437–451. https://doi.org/10.1016/j.cherd.2008.12.017.
10. R.J. Wilkens, C. Henry, L.E. Gates, How to scale-up mixing processes in non-newtonian fluids, Chem. Eng. Prog. 99 (2003) 44–52.
11. N. Alam, F. Razali, SCALE-UP OF STIRRED AND AERATED BIOENGINEERING BIOREACTOR BASED ON CONSTANT MASS TRANSFER COEFFICIENT, J. Teknol. 43 (2005) 95–110.
12. E. Mahdinia, D. Cekmecelioglu, D. A, Bioreactor Scale-Up, in: Essentials Ferment. Technol., Springer, Cham, 2019: p. 313. https://doi.org/10.1007/978-3-030-16230-6.
13. H. Noorman, An industrial perspective on bioreactor scale-down: What we can learn from combined large-scale bioprocess and model fluid studies, Biotechnol. J. 6 (2011) 934–943. https://doi.org/10.1002/biot.201000406.
14. R. Takors, Scale-up of microbial processes: Impacts, tools and open questions, J. Biotechnol. 160 (2012) 3–9. https://doi.org/10.1016/j.jbiotec.2011.12.010.
15. A. Brucato, F. Grisafi, G. Montante, Particle drag coefficients in turbulent fluids, Chem. Eng. Sci. 53 (1998) 3295–3314. https://doi.org/https://doi.org/10.1016/S0009-2509(98)00114-6.
16. Y. Sato, K. Sekoguchi, Liquid velocity distribution in two-phase bubble flow, Int. J. Multiph. Flow. 2 (1975) 79–95. https://doi.org/https://doi.org/10.1016/0301-9322(75)90030-0.
17. P. Doran, 8.1 Functions of Mixing, Bioprocess Eng. Princ. (2013) 255–332. https://doi.org/10.1016/B978-0-12-220851-5.00008-3.