Impact of stirrer rotational speed on liquid circulation in a rectangular vessel – a study applying DPIV

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Abstract. This paper contains the results of experimental study concerned with liquid mixing process using a stirrer located in a rectangular vessel. The current study applied Digital Particle Image Velocimetry technique (DPIV). On the basis of non-invasive measurements, velocity vector profiles were determined with regard to the velocity of the mixing process, and they were subsequently applied for identification and assessment of liquid circulation in a vessel. The correlation between the rotational speed of the stirrer and fluctuations and directions of the liquid flow velocity were determined. This paper focuses on the assessment of the mixing intensity resulting from the rectangular geometry of the vessel. The study proposes and develops a dependence between the shape of the velocity profile of the circulating liquid and the intensity of the mixing process. The study demonstrates the existence of suitable conditions for performing mixing processes in rectangular vessels.

1 Introduction

Liquid mixing forms one of the most common processes in industry. The principal technology can rely on mixing, however, it usually forms just a part of a processing line in industry. For this reason, we often have to do with the conditions when the parameters of the final product are relative to quality of mixing [1, 7, 15]. Knowledge of the underlying phenomena during liquid mixing is indispensable in virtually any field of engineering. This pertains both to the processes associated with the generation of homogenous mixtures as well as in the processes of intensifying heat and mass exchange. The most common procedures associated with mixing in the liquid environment involve the use of mechanical stirrers. This type of mixing requires an input of external energy. Hence, the literature contains a variety of works concerned with the purpose of determining the impact of stirrer geometry and flow parameters on mixing quality [3, 8–11]. Studies have also been carried out (i) to optimize the energy used in mixers [9, 13, 17], (ii) into the effect of physico-

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chemical properties of the components on the mixing process [2, 8] and (iii) the development of new methods for identifying liquid circulation in a vessel [5–7]. However, the orientation of stirrers in vessels and the selection of the geometry of the vessels themselves in which mixing process is undertaken has not been fully studied**.** This paper leverages experimental and non-invasive identification of the hydrodynamic singularities throughout the process of liquid circulation in a rectangular vessel coupled with the statement of applicatory propositions to assess the intensity of the mixing process.

2 Outline of the measurement method

The present study applied Digital Particle Image Velocimetry (DPIV) techniques. A plane a light was generated by a laser and applied to illuminate a rectangular glass vessel with the dimensions of 0.23 x 0.23 x 0.23 m, in the vertical or horizontal plane. The vessel was filled with water and contained particles (20 μm diameter polyamide seeding particles with a density of 1.03 g/cm^3) that occupied the vessel to a height of 0.15 m. Inside the vessel, there was a cylindrical magnetic stirring bar with a length of 0.037 m and a diameter of 0.009 m. The ends of the cylindrical bar were rounded. The vessel was located on a tray containing a magnetic stirrer. The study was performed for four rotational speeds; 250, 500, 750 and 1000 rpm. The selection of the magnetic stirrer instead of the mechanical one was governed by the need to avoid the occurrence of a surface that was not illuminated resulting from the shade of the shaft joining the mechanical stirrer with the drive. In cases where the magnetic stirrer was used and the experiment did not contain a shaft, there were no physical barriers to obstruct the imaging process in the measurement section. The measurement section involved two configurations with different spatial orientations. This section comprised either the vertical section of the vessel (occupying a half of the side of the vessel) or the horizontal section of the vessel (half of the height of the liquid in the vessel). The DPIV system consisted of a Nd:YAG laser synchronized with a CCD camera. Regardless of the spatial orientation of the measurement section, the CCD camera was located perpendicular to it and the distance that was maintained provided for the accurate use of the available image resolution. The technical parameters of the DPIV system are summarized in Table 1 and a diagram of the measurement setup is presented in Fig. 1.

Table 1. Technical parameters of DPIV system.

Parameter	Description
Types of devices	Camera: Dantec Dynamics FlowSense EO 4M, Laser: Dantec Dynamics DualPower TR, Pulse generator: BNC 575-8
Time between pulses, μs	2000 (250 rpm), 1500 (500 rpm), 1000 (750 rpm), 500 (1000 rpm)
Interrogation area size (horizontal x vertical), pix	32 x 32 (with overlap 50% in both direction)
Interrogation area offset	Central difference
DPIV algorithm	Adaptive Correlation with Local Neighbourhood Validation
Universal Outlier Detection method	Normalized median validation

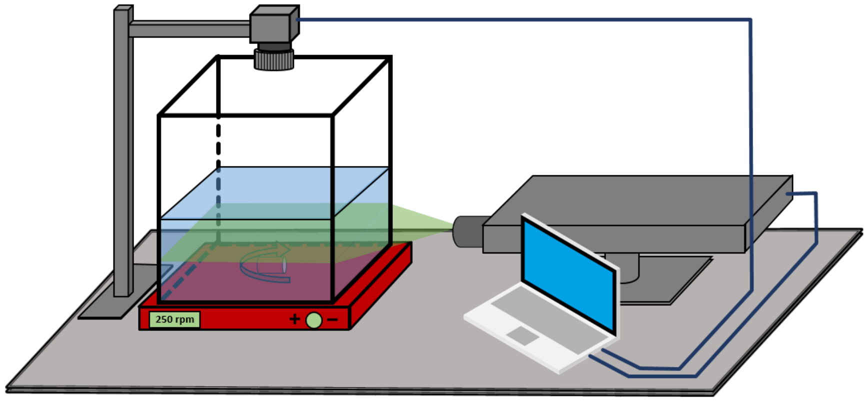

Fig. 1. Diagram of measurement setup in the horizontal plane.

3 Results and discussion

The input data for the conducted measurements comprised a series of 250 images. The measurements series were performed for each of the rotational speed in both configurations. After the completion of a series of analytical procedures and calculations (Fig. 2), the assessment of the hydrodynamics of the liquid circulation was performed throughout the duration of the mixing process. This assessment was based on the analysis of the velocity vector fields taken during the measurement, along with scalar velocity fields and streamlines of the liquid flow generated on their basis. The investigation of the local velocity profiles of the liquid applied an analysis of the velocity profiles. These profiles were determined along the lines that are perpendicular to the X axis and crossing it at the points corresponding to the 0.5 and 0.25 ratios of the length of the vessel side (A).

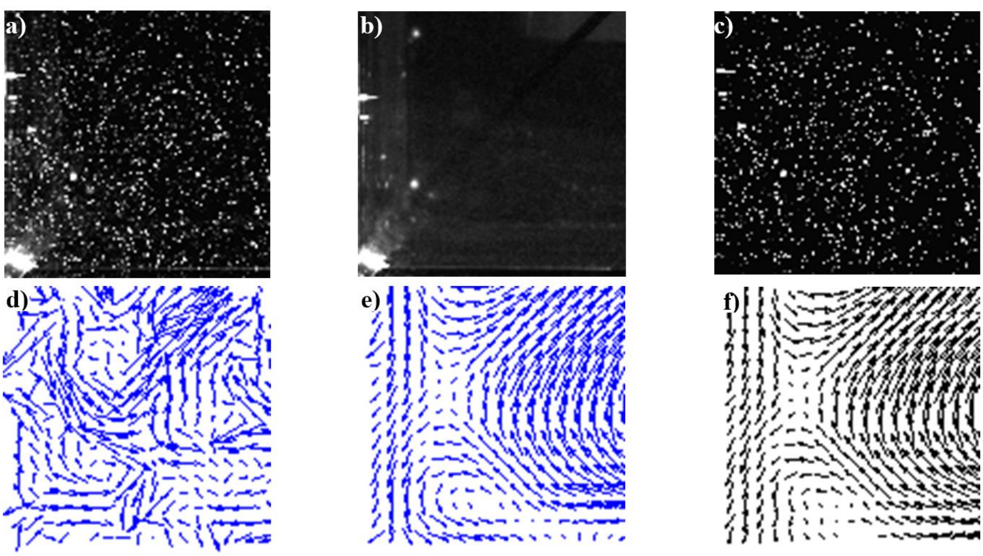

Fig. 2. Exemplary results of main successive stages of the measurement methodologies in the bottom left corner of the image: a) raw image, b) mean image, c) result of subtracting the mean image from the raw image, d) single velocity vector field, e) statistics velocity vector field, f) detection and removal of erroneous vectors by applying Universal Outlier Detection tool.

Throughout the process of determining the vector and scalar velocity profiles in the vertical measurement configurations of the rectangular vessel, standard axial circulations were identified in the mixing process (Fig. 3). The velocity vector fields in these cases demonstrated that the liquid stream exits at the centre of stirrer rotation and moves in the direction of its walls. This motion occurs virtually parallel to the bottom. Its hydrodynamic description occurs in accordance with the definition of the radial flow stated for the mixing processes [16]. After passing the vortex core, the liquid switches the flow direction to radial and is transferred along the vessel walls in the vertical direction. In this place we have to do with the axial flow. Just as for the case of the first reversal of the direction, this change occurs after the vortex core. Due to the lack of geometrical barriers in this region, this change has a smoother character. This is a consequence of the ability of the free surface of the liquid to undergo dynamic deformations under the influence of acting forces [14]. The overall axial flow direction is obtained after a contact is established with the free surface of the liquid. However, at this instant, the stream reverses and flows in the opposite direction, i.e. towards the center of the vessel. After it passes the vortex core, the stream descends thus closing the so-called large circulation loop. This circulation gains momentum along with the increase of the rotational speed of the stirrer. This increase leads not only to the increase of the relative velocity of the flow but also results in the decrease of the vortex core. It was also noted that the liquid that is found directly above the stirrer moves in the vertical direction downwards and feeds the large circulation loop. The intensity of this motion is also relative to the rotational speed of the stirrer as it rises following its increase.

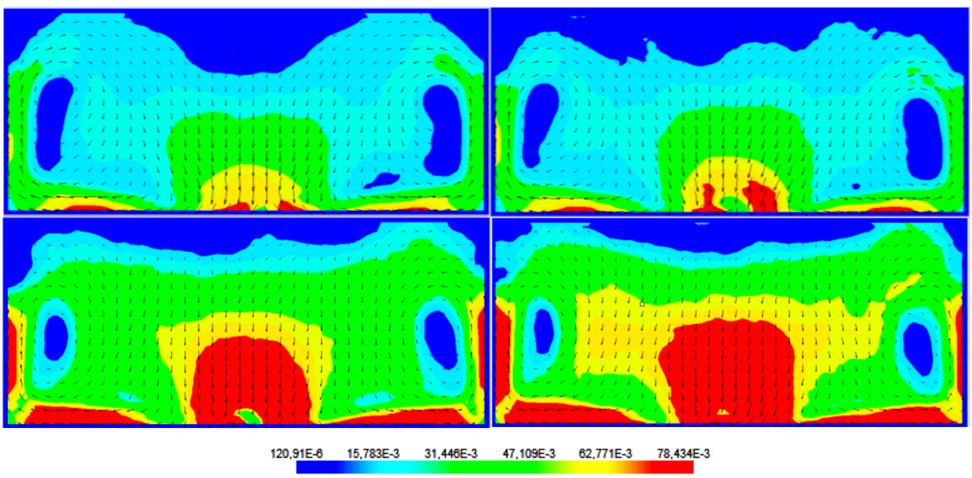

Fig. 3. Vector and scalar velocity fields (m/s) in the vertical plane: a) 250 rpm, b) 500 rpm, c) 750 rpm, d) 1000 rpm.

The vector and scalar velocity fields demonstrated different characteristics along the horizontal measurement regions (Fig. 4). Complex liquid circulation characteristics in the rectangular vessel were observed when compared to circulation characteristics recorded in vessels with a circular section. The images of circulation gained in this case assume a similar form to the liquid circulation throughout its mixing in a circular vessel comprising baffles [9, 10, 16]. The role of flow disruption that is normally taken on by the baffles in circular vessels is in this case taken on by the regions around the corner in the vessel. They are able to generate the forces capable of disrupting and minimizing the liquid flow velocity in close vicinity of the corners. As a consequence, in these regions, we have to do with a considerable deceleration of the rotational motion of the liquid flow and generation of a variety of vortex patterns. This phenomenon is demonstrated by the streamlines presented in Fig. 5. Along with the increase of the rotational speed of stirrers, the vortices located in the vicinity of each of the corners in the vessel are separated into derivative vortices located closer to the central part of the vessel. For the reason of the reverse directions of the liquid flow around them, the occurrence of both types of vortices along each other forms a factor leading to the greater intensity of the mixing process.

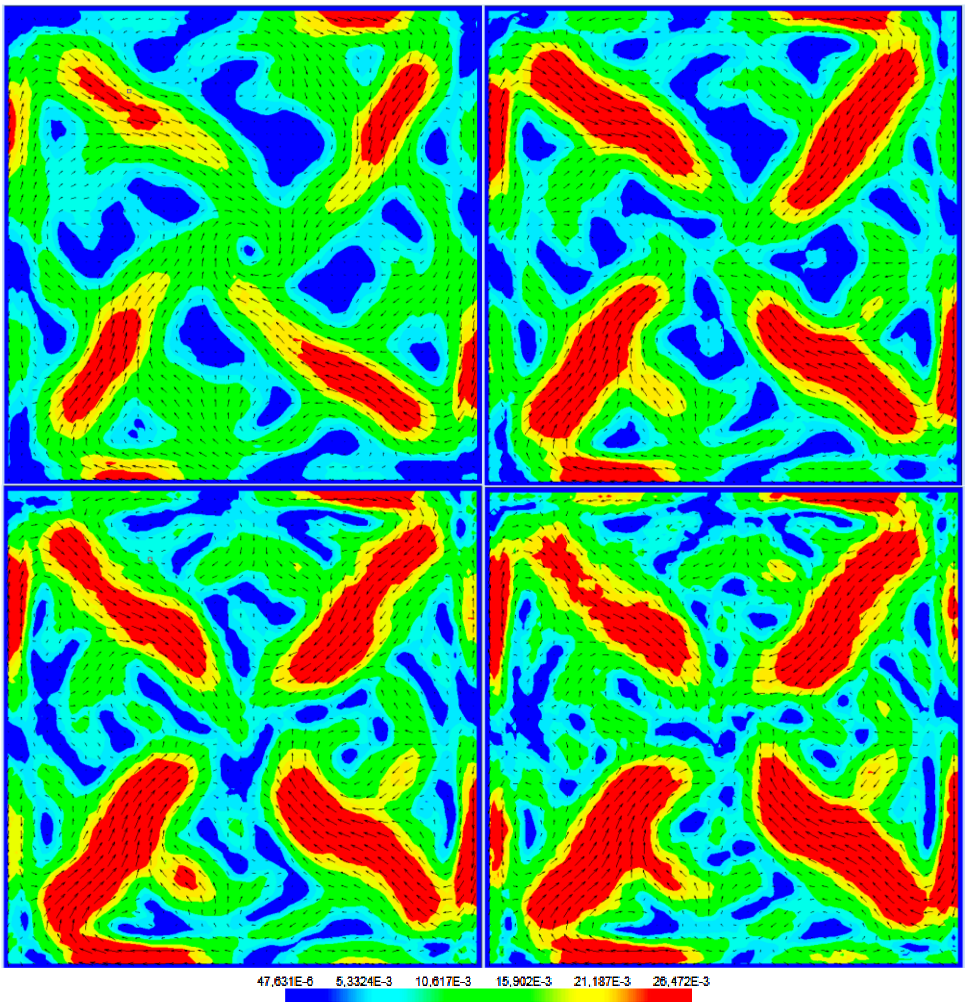

Fig. 4. Vector and scalar velocity fields (m/s) in the horizontal plane: a) 250 rpm, b) 500 rpm, c) 750 rpm, d) 1000 rpm.

Velocity profiles were developed with the purpose of determining the intensity of liquid circulation (Fig. 6). The fluctuations of velocity discernible in the velocity profiles are associated with the occurrence of vortex phenomena that disrupt liquid circulation. For the case of the velocity profiles determined for the 0.25 A line, the increase of the stirrer rotational speed primarily results in the qualitative changes in the velocity profiles (i.e. an increase of the liquid velocity). Nevertheless, in these cases there are still two characteristic maximums. With regard to the qualitative changes, there is no considerable differentiation of the velocity profiles. The profiles determined along the lines crossing the center of the vessel (0.5 A) are distinct. The course of these profiles demonstrates a clear qualitative change in the liquid circulation patterns. Along with the increase of the rotational speed, the number of derivative vortex structures tends to multiply. They are represented in the velocity profile in the form of an increase of the fluctuations of the velocity in the minimum-maximum range. In this context, the mean velocities determined in the profile are at a relatively constant level regardless of the rotational speed of the stirrer. In the consideration of the above, we can consider that the increase of the differentiation of the velocity profiles determined in the horizontal cross-sections of the vessel has a positive effect on the intensity of liquid circulation and, consequently, on the mixing quality. Consequently, this parameter can be considered as a measure of the intensity of the mixing process, in particular in regard to the rectangular vessels.

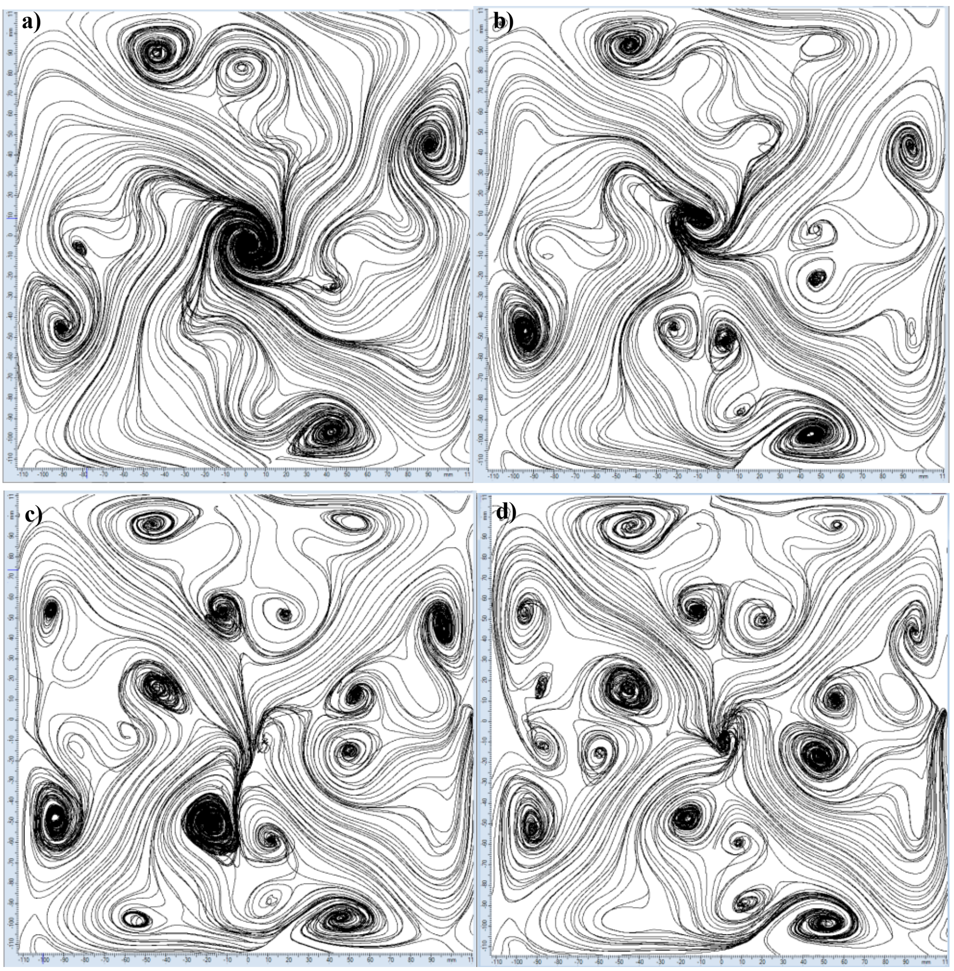

Fig. 5. Streamlines of liquid circulation in the horizontal plane: a) 250 rpm, b) 500 rpm, c) 750 rpm, d) 1000 rpm.

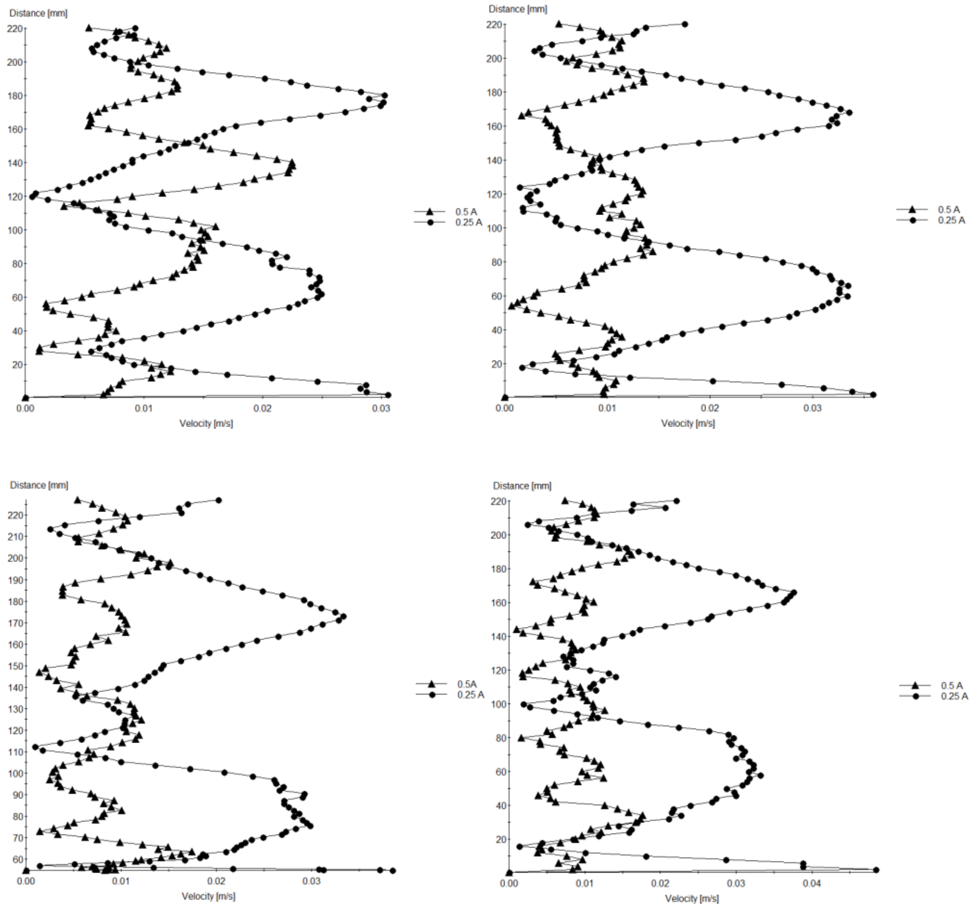

Fig. 6. Velocity profiles of liquid circulation in the horizontal plane: a) 250 rpm, b) 500 rpm, c) 750 rpm, d) 1000 rpm.

4 Conclusions

The following conclusions can be stated on the basis of the conducted measurements and analysis:

- DPIV method offers an effective tool with a potential application in hydrodynamics of mixing processes,
- vertical liquid circulation in a rectangular and circular channels form similar processes,
- horizontal liquid circulation in a rectangular channel demonstrates a considerable degree of disruption as a result of the occurrence of corners in the vessel. From the hydrodynamic perspective, corners play a similar role to baffles installed in vessels with a circular cross-section. The considerable diversity of horizontal circulation in terms of flow directions has a positive effect on the quality of the mixing process,
- an increase of the rotational speed of the stirrer in the rectangular vessel design does not lead to a proportional increase of the liquid circulation velocity in the entire horizontal cross-section of the vessel,
- the dynamic qualitative and quantitative changes in the velocity profiles determined along the side of the rectangular vessel can offer grounds for the assessment of the intensity of the mixing process.

References

1. E.P. Edward, V.A. Atiemo-Obeng, S.M Kresta, *Handbook Of Industrial Mixing* (John Wiley and Sons, Hoboken, 2004)
2. L. Genghong, G. Zhengming, L. Zhipeng, W. Jiawei, J.J. Derksen, AIChE Journal (to be published)
3. J. Fan, Q. Rao, Y. Wang, W. Fei, CES **59** (2004)
4. F. Long, X. Nong, Powder Technology, **320** (2017)
5. S. Wang, R. Stewart, G. Metcalfe, CES (2016)
6. S. Anweiler, M, Masiukiewicz, Energy Conversion and Management, **104** (2015)
7. H. Bockhorn, D. Mewes, W. Peukert, H-J Warnecke, *Micro and Macro Mixing* (Springer Verlag, Berlin-Heidelberg, 2010)
8. D. Hadjiev, N.E. Sabiri, A. Zanati, Biochemical Engineering Journal, **27** (2006)
9. N. Hashemi, F. Ein-Mozaffari, S.R. Upreti, D.K. Hwang, Chemical Engineering Journal, **289** (2016)
10. N. Hashemi, F. Ein-Mozaffari, S.R. Upreti, D.K. Hwang, ChERD, **109** (2016)
11. D. Malik, L. Pakzad, ChERD, **129** (2018)
12. N. Hai-Thong, K. Abdelhak, K. El-Hadj, N. Tien-Tung, T. Alain, S. Lecrux, Energy Procedia, **139** (2017)
13. Z. Pan, L. Zhao, M.C. Boufadel, T. King, B. Robinson, R. Conmy, K. Lee, Chemosphere, **166** (2017)
14. R.J. McSherry, K.V. Chua, T. Stoesser, Journal of Hydrodynamics, Ser. B **29**, 1 (2017)
15. N.P. Cheremisinoff, *Handbook of Chemical Processing and Equipment* (Butterworth-Heinemann, Wobrun, 2000)
16. J.J. Ulbrecht, G.K. Patterson *Mixing of Liquid by Mechanical Agitation* (Gordon and Breach Science Publishers, New York, 1996)
17. R. Shamsoddini, N. Aminizadeh, Chemical Engineering Communications **204**, 5 (2017)