

## LETTER TO EDITOR

### COMMENTS ON *FLOW CHARACTERISTICS OF AXIAL HIGH SPEED IMPELLERS* (CHEM. PROCESS ENG., 2010, 31, 661)

Jyeshtharaj B. Joshi<sup>1, 2\*</sup>

<sup>1</sup> Institute of Chemical Technology, Matunga, Mumbai 400 019, India

<sup>2</sup> Homi Bhabha National Institute, Anushaktinagar, Mumbai 400 094, India

Fořt et al. (2010) have written another useful article on flow characteristics generated by axial high speed impellers. I agree with the authors that the knowledge of flow patterns is crucial for developing reliable design procedures for instance, for mixing and blending (Baldyga and Bourne, 1997; Nienow, 1997; Ranade et al., 1991), for solid suspension (Raghva Rao et al., 1988; Zwietering, 1958), for gas induction (Joshi and Sharma, 1977) and bioreactions where controlled shear is important (Joshi et al., 1996). With this context, the work of Fořt et al. (2010) needs some clarification and further extension.

1. The commented paper recommends pitched blade downflow turbine ( $\alpha = 45^\circ$ ,  $n_b = 6$ ,  $W/D = 0.2$ ) for mixing and blending. For their experiments, they have employed  $D/T = C/T = 1/3$ . For such a geometrical arrangement, Nienow (1997) has comprehensively analysed published literature, supported the analysis by sound theory and proposed the following correlation

$$N_p N \theta_{mix} (D/T)^{1/3} = \text{constant} \quad (1)$$

Patwardhan and Joshi (1999) estimated the mixing time for 35 designs of axial downflow impellers and observed that

$$\theta_{mix} = \frac{12.66 N_p^{1/3} T^{2/3}}{N_{QS} (P/M)^{1/3}} \quad (2)$$

The 35 designs included wide variations in the number of blades, blade angles, blade width, variations in blade angle (twist) and blade width from hub to tip. The observations indicated that the six bladed downflow pitched turbine ( $\alpha = 45^\circ$ ) is not the most efficient. As compared to this impeller, ten other designs have shown higher potential for mixing efficiency.

2. Authors have further recommended that the most convenient impeller for suspension of solid particles in liquid seems to be the axial impeller with profiled blades TX 335. The reason behind this recommendation is that the impeller TX 335 exhibits the highest efficiency ( $N_{QP}/N_P$ ) of the transformation capacity of power to flow. It may be pointed out that, in the published literature, there are at least ten impeller designs having superior values of efficiency than TX 335. Further, authors will agree that the direct correlation of hydraulic efficiency ( $N_{QP}/N_P$ ) with efficient solid suspension is difficult with the present status of knowledge. The available published literature may not be sufficient to develop clear recommendations over a wide range of fluid and solid properties and geometrical details of stirred tanks (Bourne and Sharma, 1974; Chapman et al., 1983; Dohi et al., 2004; Lali et al., 1989; Musil et al., 1978; Nienow, 1968; Raghav Rao et al.

\*Corresponding author, e-mail: jbjoshi@gmail.com

1988; Rewatkar et al., 1991a; 1991b; Zhu and Wu, 2002; Zweitering, 1958). Substantial additional work is needed for the development of relationship between the efficiency of solid suspension and the hydraulic efficiencies ( $N_{QP}/N_P$  or  $N_{QS}/N_P$ ).

3. Authors have nicely compiled the values of  $N_P$ ,  $N_{QP}$ ,  $N_{QS}$  and the other parameters for four impeller designs. The published literature (Armenante and Chou, 1996; Armenante et al., 1997; Bakker and Oshinowo, 2004; Bakker and van den Akker, 1994; Bakker et al., 1996; Bakker et al., 1997; Brucato et al., 1998; Bugay et al., 2002; Derksen, 2001; Fentiman et al., 1998; Firoz et al., 2004; Fokema et al., 1994; Harvey et al., 1995; Harvey et al., 1996; Jahoda et al., 2007; Jaworski et al., 1996; Kumaresan et al., 2005; Li et al., 2005; Mavros et al., 1998; Murthy et al., 2007; Murthy et al., 2008; Nere et al., 2001; Nurtono et al., 2009; Ranade et al., 1989; Ranade et al., 1992; Ranade et al., 2002; Roussinove et al., 2003; Roy et al., 2010; Rutherford et al., 1996; Sahu and Joshi, 1995; Sahu et al., 1998; Sahu et al., 1999; Schafer et al., 1998; Tomas et al., 2003; Tyagi et al., 2007; Xu and McGrath, 1996; Zhou and Kresta, 1996) gives some information about fifty different impeller designs. There are some cases where one research group has investigated 25 impeller designs. These studies may be useful. On the basis of outstanding track record of the author's group, it will be a good idea to present a comprehensive comparison and make recommendations for optimum design for blending, heat transfer, suspension, dispersion, etc.

## SYMBOLS

|          |  |
|----------|--|
| $C$      | impeller clearance from tank bottom, m                                 |
| $D$      | impeller diameter, m   |
| $M$      | mass of fluid in the tank, kg  |
| $N$      | impeller speed, rps  |
| $N_P$    | power number, $P/\rho N^3 D^5$ (-)                                     |
| $N_{QP}$ | primary flow number, $Q_P/ND^3$ (-)                                    |
| $N_{QS}$ | secondary flow number, $Q_t/ND^3$ (-)                                  |
| $n_b$    | number of blades, (-)  |
| $P$      | power consumption, W   |
| $Q_P$    | flow directly generated by impeller, $m^3 s^{-1}$                      |
| $Q_t$    | total flow which equals primary flow plus entrained flow, $m^3 s^{-1}$ |
| $T$      | tank diameter, m   |
| $W$      | blade width, m   |

### Greek symbols

|                |                             |
|----------------|-----------------------------|
| $\alpha$       | blade angle, degrees        |
| $\rho$         | liquid density, $kg m^{-3}$ |
| $\theta_{mix}$ | mixing time, s              |

## REFERENCES

- Armenante P.M., Chou C., 1996. Velocity profiles in a baffled vessel with single or double pitched-blade turbines. *AIChE J.*, 42, 42-54. DOI: 10.1002/aic.690420106.
- Armenante P.M., Luo C., Chou C., Fort I., Medek J., 1997. Velocity profiles in a closed, unbaffled vessel: comparison between experimental LDV data and numerical CFD predictions. *Chem. Eng. Sci.*, 52, 3483-3492. DOI: 10.1016/S0009-2509(97)00150-4.
- Bakker A., van den Akker H.E.A., 1994. A computational model for the gas-liquid flow in stirred reactors. *Chem. Eng. Res. Des.*, 72, 594-606.

- Bakker A., Myers K.J., Ward R.W., Lee C.K., 1996. The laminar and turbulent flow pattern of a pitched blade turbine. *Chem. Eng. Res. Des.*, 74, 485.
- Bakker A., Laroche R.D., Wang M.H., Calabris R.V., 1997. Sliding mesh simulation of laminar flow in stirred reactors. *Chem. Eng. Res. Des.*, 75, 42-44. DOI: 10.1205/026387697523372.
- Bakker A., Oshinowo L.M., 2004. Modelling of turbulence in stirred vessels using large eddy simulation. *Chem. Eng. Res. Des.*, 82, 1169-1178. DOI: 10.1205/cerd.82.9.1169.44153.
- Baldyga J., Bourne J.R., 1999. *Turbulent mixing and chemical reactions*. John Wiley & Sons, New York.
- Bourne J.R., Sharma R.N., 1974. Homogeneous particle suspension in propeller-agitated flat bottomed tanks. *Chem. Eng. J.*, 8, 243-250. DOI: 10.1016/0300-9467(74)85030-6.
- Brucato A., Ciofalo M., Grisafi F., Micale, G., 1998. Numerical prediction of flow fields in baffled stirred vessels: A comparison of alternative modelling approaches. *Chem. Eng. Sci.*, 53, 3653-3684. DOI: 10.1016/S0009-2509(98)00149-3.
- Bugay S., Renaud E., Alain L., 2002. Experimental analysis of hydrodynamics in axially agitated tank. *AIChE J.*, 48, 463-475. DOI: 10.1002/aic.690480306.
- Bujalski W., Nienow A.W., Chatwin S., Cooke M., 1986. The dependency on scale of power numbers of Rushton disc turbines. *Proc. Inter. Conf. Mech. Agitation*, Toulouse, 1.37-1.46.
- Chapman C.M., Nienow A.W., Cooke M., Middleton J.C., 1983. Particle-gas-liquid mixing in stirred vessels. *Chem. Eng. Res. Des.*, 61, 167-181.
- Derksen J., 2001. Assessment of large eddy simulations for agitated flows. *Chem. Eng. Res. Des.*, 79, 824-830. DOI: 10.1205/02638760152721334.
- Dohi N., Takahashi T., Minekawa K., Kawase Y., 2004. Power consumption and solid suspension performance of large-scale impellers in gas-liquid-solid three-phase stirred tank reactors. *Chem. Eng. J.*, 97, 103-114. DOI: 10.1016/S1385-8947(03)00148-7.
- Fentiman N.J., Hill N.S. T., Lee K.C., Paul G.R., Yianneskis M., 1998. A novel profiled blade impeller for homogenization of miscible liquids in stirred vessels. *Chem. Eng. Res. Des.*, Part A 76. 835-842. DOI: 10.1205/026387698525586.
- Firoz R.K., Chris D.R., Grahan K.H, 2004. A multi-block approach to obtain angle resolved PIV measurements of the mean flow and turbulence fields in a stirred vessel. *Chem. Eng. Technol.*, 27, 264-369. DOI: 10.1002/ceat.200401998.
- Fokema M.D., Kresta S.M., Wood P.E., 1994. Importance of using the correct impeller boundary conditions for CFD simulations of stirred tanks. *Can. J. Chem. Eng.*, 72, 177-183. DOI: 10.1002/cjce.5450720201.
- Fořt I., Kysela B., Jirout T., 2010. Flow characteristics of axial high-speed impellers. *Chem. Proc. Eng.* 31, 661-679.
- Harvey III A.D., Lee C.K., Rogers E.S., 1995. Steady-state modeling and experimental measurement of a baffled impeller stirred tank. *AIChE J.*, 41, 2177-2186. DOI: 10.1002/aic.690411002.
- Harvey III A.D., Rogers E.S., 1996. Steady and unsteady computation of impeller-stirred reactors. *AIChEJ*, 42, 2701-2712. DOI: 10.1002/aic.690421002.
- Jahoda M., Mořtěk M., Kukuková A., Machoň V., 2007. CFD modelling of liquid homogenization in stirred tanks with one and two impellers using large eddy simulation. *Chem. Eng. Res. Des.*, 85, 616-625. DOI: 10.1205/cherd06183.
- Jaworski Z., Nienow A.W., Dyster K.N., 1996. A study of an up- and a down-pumping wide-blade hydrofoil impeller: Part II. CFD analysis. *Can. J. Chem. Eng.*, 74, 3. DOI: 10.1002/cjce.5450760503.
- Joshi J.B., Sharma M.M., 1977. Mass transfer and hydrodynamic characteristics of gas inducing type of agitated contactors. *Can. J. Chem. Eng.*, 55, 683-695. DOI: 10.1002/cjce.5450550609.
- Joshi J.B., Elias C.B., Patole M.S., 1996. Role of hydrodynamics shear in cultivation of animal, plant and microbial cells. *Chem. Eng. J. & Biochem. Eng. J.*, 62, 121-141. DOI: 10.1016/0923-0467(95)03062-X.
- Kumaresan T., Nere N.K., Joshi J.B., 2005. Effect of internals on flow pattern and mixing in stirred tanks. *Ind. Eng. Chem. Res.*, 44, 9951-9961. DOI: 10.1021/ie0503848.
- Kumaresan T., Joshi J.B., 2006. Effect of impeller design on the flow pattern and mixing in stirred tanks. *Chem. Eng. J.*, 115, 173-193. DOI: 10.1016/j.cej.2005.10.002.
- Lali A.M., Khare A.S. Joshi J.B., Nigam K.D.P., 1989. Behaviour of solid particles in viscous non-newtonian solutions: Settling velocity, wall effects and bed expansion in solid-liquid fluidized beds. *Powder Technol.*, 57, 39-50. DOI: 10.1016/0032-5910(89)80102-0.

- Li M., White G., Wilkinson D., Roberts K., 2005. Scale up study of retreat curve impeller stirred tanks using LDA measurements and CFD simulation. *Chem. Eng. J.*, 108, 81-90. DOI: 10.1016/j.cej.2005.01.005.
- Mavros P., Xuereb C., Bertrand J., 1998. Determination of 3-D flow fields in agitated vessels by laser-doppler velocimetry: use and interpretation of RMS velocities. *Chem. Eng. Res. Des.*, 1998, 76, 223-233. DOI: 10.1205/026387698524640.
- Medek J., Fort I., 1985. Mixing in vessel with eccentric mixing. *Proc. 5<sup>th</sup> Euro. Conf. Mix.*, Wurzburg, 10-12 June, Germany, 1985, 263.
- Murthy B.N., Deshmukh N.A., Patwardhan A.W., Joshi J.B., 2007. Hollow self-inducing impellers: Flow visualization and CFD simulation. *Chem. Eng. Sci.*, 62, 3839-3848. DOI: 10.1016/j.ces.2007.03.043.
- Murthy B.N., Joshi J.B., 2008. Assessment of standard image, RSM and LES turbulence models in a baffled stirred vessel agitated by various impeller designs. *Chem. Eng. Sci.*, 63, 5468-5495. DOI: 10.1016/j.ces.2008.06.019.
- Musil L., Vik J., 1978. Suspending solid particles in an agitated conical-bottom tank. *Chem. Eng. Sci.*, 33, 1123-1131. DOI: 10.1016/0009-2509(78)85018-0.
- Nere N.K., Patwardhan A.W., Joshi J.B., 2001. Prediction of flow pattern in stirred tanks: new constitutive equation for eddy viscosity. *Ind. Eng. Chem. Res.*, 40, 1755-1772. DOI: 10.1021/ie0004951.
- Nienow A.W., 1968. Suspension of solid particles in turbine agitated baffled vessels. *Chem. Eng. Sci.*, 1968, 23, 1453-1459. DOI: 10.1016/0009-2509(68)89055-4.
- Nienow A.W., 1997. On impeller circulation and mixing effectiveness in the turbulent flow regime. *Chem. Eng. Sci.*, 52, 2557-2565. DOI: 10.1016/S0009-2509(97)00072-9.
- Nurtono T., Setyawan H., Altway A., Winardi S., 2009. Macro-instability characteristic in agitated tank based on flow visualization experiment and large eddy simulation. *Chem. Eng. Res. Des.*, 87, 923-942. DOI: 10.1016/j.cherd.2009.01.011.
- Patwardhan A.W., Joshi J. B., 1999. Relation between flow pattern and blending in stirred tanks. *Ind. Eng. Chem. Res.*, 38, 3131-3143. DOI: 10.1021/ie980772s.
- Raghava Rao K.S.M.S., Rewatkar V.B., Joshi J.B., 1988. Critical impeller speed for solid suspension in mechanically agitated contactors. *AIChE J*, 34, 1332-1340. DOI: 10.1002/aic.690340811.
- Ranade V.V., Joshi J.B., Marathe A.G., 1989. Flow generated by pitched bladed turbine part ii: mathematical modeling and comparison with experimental Data. *Chem. Eng. Commun.* 81, 225. DOI: 10.1080/00986448908940540.
- Ranade V.V., Joshi J.B., 1989. Flow generated by pitched blade turbines. I: measurements using laser doppler anemometer. *Chem. Eng. Commun.*, 81, 197-224. DOI:10.1080/00986448908940539.
- Ranade V.V., Bourne J.R., Joshi J.B., 1991. Fluid mechanics and blending in agitated tanks. *Chem. Eng. Sci.*, 46, 1883-1893. DOI: 10.1016/0009-2509(91)80150-W.
- Ranade V.V., Mishra V.P., Saraph V.S., Deshpande G.B., Joshi J.B., 1992. Comparison of axial flow impellers using LDA. *Ind. Eng. Chem. Res.*, 31, 2370-2379. DOI: 10.1021/ie00010a016.
- Ranade V.V., Tayalia Y., Krishnan H., 2002. CFD predictions of flow near impeller blades in baffled stirred vessels: Assessment of computational snapshot approach. *Chem. Eng. Comm.*, 189, 895-922. DOI:10.1080/00986440213134.
- Rewatkar V.B., Raghava Rao K.S.M.S., Joshi J.B., 1991a. Critical impeller speed for solid suspension in mechanically agitated three phase reactors I: Experimental Part. *Ind. Eng. Chem. Res.*, 30, 1770-1784. DOI: 10.1021/ie00056a013.
- Rewatkar V.B., Raghava Rao K.S.M.S., Joshi J.B., 1991b. Critical impeller speed for solid suspension in mechanically agitated three phase reactors ii: mathematical model. *Ind. Eng. Chem. Res.*, 30, 1784-1971. DOI: 10.1021/ie00056a014.
- Roussinova V., Kresta S.M., Weetman R., 2003. Low frequency macroinstabilities in a stirred tank: scale-up and prediction based on large eddy simulations. *Chem. Eng. Sci.*, 58, 2297-2311. DOI: 10.1016/S0009-2509(03)00097-6.
- Roy S., Acharya S., Cloeter M., 2010. Flow structure and the effect of macro-instabilities in a pitched-blade stirred tank. *Chem. Eng. Sci.*, 65, 3009-3024. DOI: 10.1016/j.ces.2010.01.025.
- Rutherford K., Mahmoudi M.S., Lee K.C., Yianneskis M., 1996. The influence of Rushton impeller blade and disk thickness on the mixing characteristics of stirred vessel. *Chem. Eng. Res. Des.* 74, 369-378.
- Sahu A.K., Joshi J.B., 1995. Simulation of flow in stirred vessels with axial flow impellers: effects of various numerical schemes and turbulent model parameters. *Ind. Eng. Chem. Res.*, 34, 626-639. DOI: 10.1021/ie00041a025.

- Sahu A.K., Kumar P., Joshi J.B., 1998. Simulation of flow in stirred vessel with axial flow impeller: zonal modeling and optimization of parameters. *Ind. Eng. Chem. Res.*, 37, 2116-2130. DOI: 10.1021/ie970321s.
- Sahu A.K., Kumar P., Patwardhan A.W., Joshi J.B., 1999. CFD modelling and mixing in stirred tanks. *Chem. Eng. Sci.*, 54, 2285-2293. DOI: 10.1016/S0009-2509(98)00334-0.
- Schafer M., Yianneskis M., Wachter P., Durst F., 1998. Trailing vortices around a 45° pitched-blade impeller. *AIChE J.*, 44, 1233-1246. DOI: 10.1002/aic.690440602.
- Tomas M., Linek V., Eva P., 2003. Gas hold-up, mixing time and gas-liquid volumetric mass transfer coefficient of various multiple-impeller configurations: Rushton turbine, pitched blade and techmix impeller and their combinations. *Chem. Eng. Sci.*, 58, 1839-1846. DOI: 10.1016/S0009-2509(02)00682-6.
- Tyagi M., Roy S., Harvey III A.D., Acharya S., 2007. Simulation of laminar and turbulent impeller stirred tanks using immersed boundary method and large eddy simulation technique in multi-block curvilinear geometries. *Chem. Eng. Sci.*, 62, 1351-1363. DOI: 10.1016/j.ces.2006.11.017.
- Xu Y., McGrath G., 1996. CFD Predictions of Stirred Tank Flows. *Chem. Eng. Res. Des.*, 74, 471-475.
- Zhou G. Kresta S.M., 1996. Distribution of energy between convective and turbulent flow for three frequently used impellers. *Chem. Eng. Res. Des.*, 74, 379-389.
- Zhu Y., and Wu J., 2002. Critical impeller speed for suspending solids in aerated agitation tanks. *Can. J. Chem. Eng.*, 80, 1-6. DOI: 10.1002/cjce.5450800417.
- Zwitering T.N., 1958. Suspending of solid particles in liquid by agitators. *Chem. Eng. Sci.*, 8, 244-253. DOI: 10.1016/0009-2509(58)85031-9.

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