CHEMICAL ENGINEERING TRANSACTIONS

VOL. 32, 2013

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet

Chief Editors: Sauro Pierucci, Jiří J. Klemeš

ISBN 978-88-95608-23-5; **ISSN** 1974-9791

DOI: 10.3303/CET1332243

CFD Model Based Comparison of Mixing Efficiency of Different Impeller Geometries

Bálint Molnár*, Attila Egedy, Tamás Varga

University of Pannonia, Department of Process Engineering, Egyetem Str. 10, H-8200 Veszprém, Hungary, mbecikepes@gmail.com

The efficient blending and mixing of liquids are very important in most industrial technologies. Mixing is often carried out in tanks, reactors, or mixing apparatuses. Impellers are widely used in many industrial processes ranging from mining through hydrometallurgy to complex processes based on chemical reactions (e.g. fermentation, wastewater treatment, polymerization, crystallization). Mixing can be created in mechanical way by rotary elements on a shaft, or in pneumatically way by high-speed fluid flow. The quality of mixing has huge affect on the rate of transport processes (energy and/or mass) and on the reaction rate too in a chemical reactor. The mixing also contributes to the evaluation of the effects of the optimal operating parameters.
The required power and the flow pattern in a vessel depend on the impeller geometry. In the literature, there are only recommendation and no indices to help choosing an impeller for a defined mixing task. And that is not possible to optimize the revolution per minutes at mixing element that have the same design.
The primary goal of our research is to create a measure for quantitative characterization of the level of homogeneity in a stirred system resulted by different impeller geometries and rotating speed, and to compare the power consumptions.

1. Introduction

In chemical industry stirred vessels are among the most commonly used pieces of equipment. Stirred vessels can be classified in different ways. They can be sorted by the way of operation (batch, semi-batch, continuous), or by thermal operation (isotherm, adiabatic), or by the applied impeller type (turbine, jet, blade, etc.).
Since these devices are often part of an existing technology, it can be difficult to obtain experimental information or collect additional data during production. Hence, to build an accurate model of the mixed system can require so much time which cannot be afford. The experiments in pilot plant or laboratory scale can support the modeling process. However, in these cases the scale-up of the units to industrial scale can be the problem because this step can have significant influence on the developed flow pattern. The operation of the equipments can be studied in details without disrupting the production by using Computational Fluid Dynamics (CFD) tools. CFD simulators can be applied not only in modeling the hydrodynamic behavior of the investigated system but after the integration of the mathematical descriptions of considered phenomena it can describe mass and energy related transport processes (Sommerfeld et al., 2003).
Electric energy consumption is an important factor in the design of reactors, stirred vessels. It is defined as the amount of electric energy necessary in a period of time, in order to generate the movement of the fluid within a vessel by means of mechanical and pneumatic agitation. The costs associated with power drawn contribute significantly to the overall operation costs of industrial plants. Therefore it is desired that the mixing process is performed efficiently with a minimum expense of energy (Bader, 1987). The first techniques used for power draw measurements are performed by wattmeters and ammeters (Brown, 1997). It is a simple method, where little instrumentation is required, but in laboratory-scale tanks, the losses occurring in the agitation system can be very significant, accounting for as much as high as 70 % of the total power supply. Therefore, it is necessary to determine efficiency and power factor of the applied

Please cite this article as: Molnar B., Egedy A., Varga T., 2013, Cfd model based comparison of mixing efficiency of different impeller geometries, Chemical Engineering Transactions, 32, 1453-1458 DOI: 10.3303/CET1332243

mixing elements. To correct the losses, calorimetric measurements are applied based on energy balance. According to Oosterhuis et al. (1981), the heat energy loss (through the wall) calculated by energy balance is only 1 % of the invested energy. It is a very precise technique, but it requires high sensitivity instrumentation and the position of thermistors within the tank is needed to choose carefully.
An alternative way of measuring the power draw in mixed tanks is by the use of dynamometers, which is based on Newton's third law (Holland et al., 1966). This method can cover wide torque range, but has a high installation cost. However, power distribution for each impeller cannot be determined in multiple agitation systems (Machon et al., 1985)
The torquemeter is widely used at industrial level as well as in research laboratories. Torquemeters can be adapted for measurements of torque, velocity, force, pressure and flow (Himmelstein, 1994). Advantages of this device are that wide range of torque can be measured, and little instrumentation is needed. Although, in systems with multiple agitator, the measurement of independent power draw is not unbound too. Only strain gauges can measure independent power measurement (Chatwin et al., 1987).
The degree of mixing can be evaluated qualitative or quantitative, which for several methods have been developed in recent decades. Based on the aim of the homogenization there can be different techniques which can be applied to measure the homogeneity of the mixed phase. Hence, the mixed time measurements are applied more often, but gathering information on the homogenization of the stirred phase gain more and more ground.
Mixing time is the time taken from that moment when a specific volume of fluid is added to the fluid in the mixed vessel and blended in it with a pre-chosen degree of uniformity (Paul et al., 2004). Various methods were developed to study the mixing time. One of these methods is the flow visualization technique (Paul et al., 2004). The simplest (cost effective) way for examining flow patterns in a mixed system is light sheet visualization. A narrow light sheet is shone through the mixing vessel, illuminating reflective tracer particles in the fluid. This can also be videotaped (Nurtono et al., 2009). Further refinements of this technique include the use of laser with a rod prism. Quantitative measurement of the mixing time based on addition of chemicals with different property to the bulk. Depending on the sampling techniques off-line, Schlieren-effect based (Vusse, 1995), thermocouple-based (Spero, 2011), and conductivity probe mixing time measurement (Kramers et al., 1953) can be differentiate.
Stirred equipments can be qualified by the mixing coefficient. One of these methods based on the fact when two reactive fluids are brought together, reaction cannot proceed until the reactive molecules are stirred intimately on a molecular level. The product distribution from the reactions will therefore reflect the mixing history; and with the use of suitable mixing models, these distributions can be used to back-calculate mixing rates (Hayes et al., 1998).
In this research the 3D mathematical models of the investigated batch reactors have been implemented in a commercial CFD software package, COMSOL Multiphysics. The impeller geometry and the number of the blades are analyzed based on physical and simulation experiments. Examined Rushton turbine impellers with different blade numbers were implemented into our model. The proposed measure of the vessel homogeneity is based on the logarithmic histogram of velocity field in the stirred system. The simulation extends to the analyses of physical properties of the stirred phase (density, viscosity) and the rotation speed of the impeller. The electric power consumption of all the investigated impellers was defined.

2. Experimental and modeling methods

2.1 Experimental mixed system

To validate the results of the simulations a laboratory measurement system was developed, which contains a 1 liter laboratory glass reactor, one computer-controlled IKA Eurostar Power-Control Visc mixing motor, and plastic impellers made by 3D printer based on CAD drawings. Figure 1 (a) shows the experimental apparatus. A torque sensor was integrated to the impeller motor, so with these data and angular velocity the power requirement can be calculated. Torque measurements of Rushton turbines with different number of blades were investigated at different rotational speeds, and the power absorbed by the electric mixing motor was measured too.

2.2 CFD model of the stirred vessel

For calculating the flow pattern in the vessel the Rotating Machinery model of COMSOL Multiphysics was used, which is described the motion of rotating parts as well as Navier-Stokes equations augmented with k-ε turbulence model. A detailed description about the correlations built into the applied model is discussed in article of Kumaresan et al. (2005). The model can be used to study the dynamic behavior of the vessel. The experimental vessel was modeled in 3D, because the mixing elements did not allow reducing the number of space coordinates. Three, four, five and six-blades Rushton turbines (show in Figure 1 (b)) were investigated based on experimental and simulation results. The geometry is split into a large number of finite elements (it is 63036 in case of 6-blades turbine) to reach the required computational precision without a huge computational demand. Ethylene-glycol was used in experiments because its viscosity notably depends on temperature. In order to gather sufficient information about the calculated velocity field all the geometry axes were divided into 10 equidistant parts. The calculated velocity magnitudes were collected in the resulted intersection points.

(b)

(a)

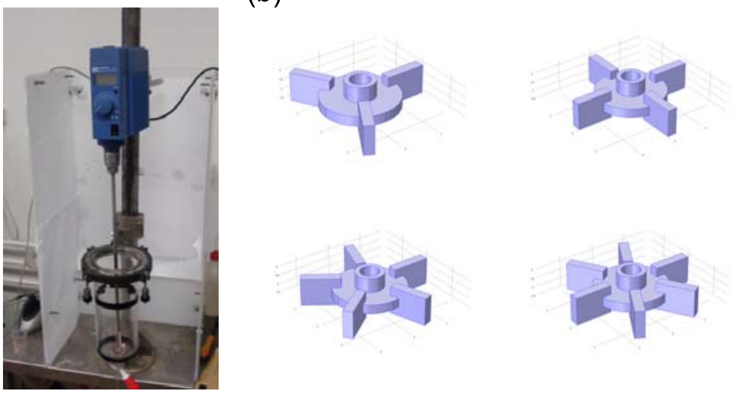

Figure 1: (a) Experimental apparatus (b) The investigated impeller types

3. Calculate the homogeneity and electric energy consumption

Both simulations and experiments were carried out at 50-500 1/min with the resolution of 50 1/min. The effect of the material properties on the electric power consumption was investigated in the temperature range of 20 °C to 90 °C with 10 °C steps.
The extracted velocity averages from the simulation with each impeller, at each rotational speed were plotted in histograms. In these histograms logarithmic abscissa represents the velocity values, and the ordinate represents the frequency of these velocity values.
Equation (1) was used to calculate the electric power requirement from the simulated results.

$$P = r \cdot \omega \cdot c_f \cdot \left(\iint \frac{\rho}{2} \cdot u^2 dxdy \right) \tag{1}$$

The surface integral in the parenthesis represents the force awakened on the surface of the blades. This force multiplied by the length of the lever arm, in this case the length of the mixing blades (r), result in torque. The torque multiplied by the angular velocity (ω) results in power requirement of the impeller at a defined rotational speed. Dimensionless resistance factor, c_f in Equation (2) must be determined in an experimental way (Lazauskas, 1979). The resistance factor is related to the properties of the stirred material. We identified the following equation to describe the resistance factor as the function of Reynolds number:

$$c_f = \mathrm{x} \cdot \mathrm{Re}^2 + \mathrm{y} \cdot \mathrm{Re} + \mathrm{z} \tag{2}$$

Table 1: Parameters for Equation (2) at three temperatures

Parameter\Temperature (°C)	20	50	90
x	$5 \cdot 10^{-4}$	$1 \cdot 10^{-4}$	0
y	$-1.08 \cdot 10^{-1}$	$-4.88 \cdot 10^{-2}$	$-1.54 \cdot 10^{-2}$
z	3.69	3.80	3.82

The constants (shown in Table 1) in Equation (2) were determined with a parameter identification applying a global search algorithm (Particle Swarm Optimization) based on experimental data (Birge, 2003). In Equation (2) Re is the dimensionless Reynolds-number, that gives a measure of the ratio of inertial forces to viscous forces and consequently quantifies the relative importance of these two types of forces for given flow conditions. Re is determined based on the simulation results as the surface average of the calculated Reynolds-number on one blade at each rotational speed.

4. Results

To characterize the developed histograms of reactor homogeneity, mean values and standard deviation was calculated for the easier comparability. The standard deviation is an absolute and not a relative value, so to get the normalized standard deviation; it was divided with the mean value and multiplied by one hundred. For demonstration the results were shown at 20 °C (a), 50 °C (b), and 90 °C (c) with the rotational speeds 50 1/min, 250 1/min and 500 1/min. Figure 2 shows the histograms of the reactor at these temperatures and rotational speeds. It can be seen that the mean value (MV) rise, so the obtainable velocity magnitudes increase too if the rotational speed is gone up. Comparing of the normalized standard deviation (NSTD) shows that the increase in the rotational speed from 50 1/min to 500 1/min the percent variance decreases from 80 % to 23 %. So if the rotational speed is increased from 50 1/min to 500 1/min the homogeneity of the system will be four times better. This improving falls off at 50 °C (two times) and at 90 °C (cc. equal). At a given rotational speed as the temperature is increased the NSTD shows the homogeneity is 80 % at 20 °C and 25 % at 90 °C. This correspondence at 500 1/min is 23 % to 22 %. So we can see that the homogeneity is independent from the viscosity at high rotational speed.

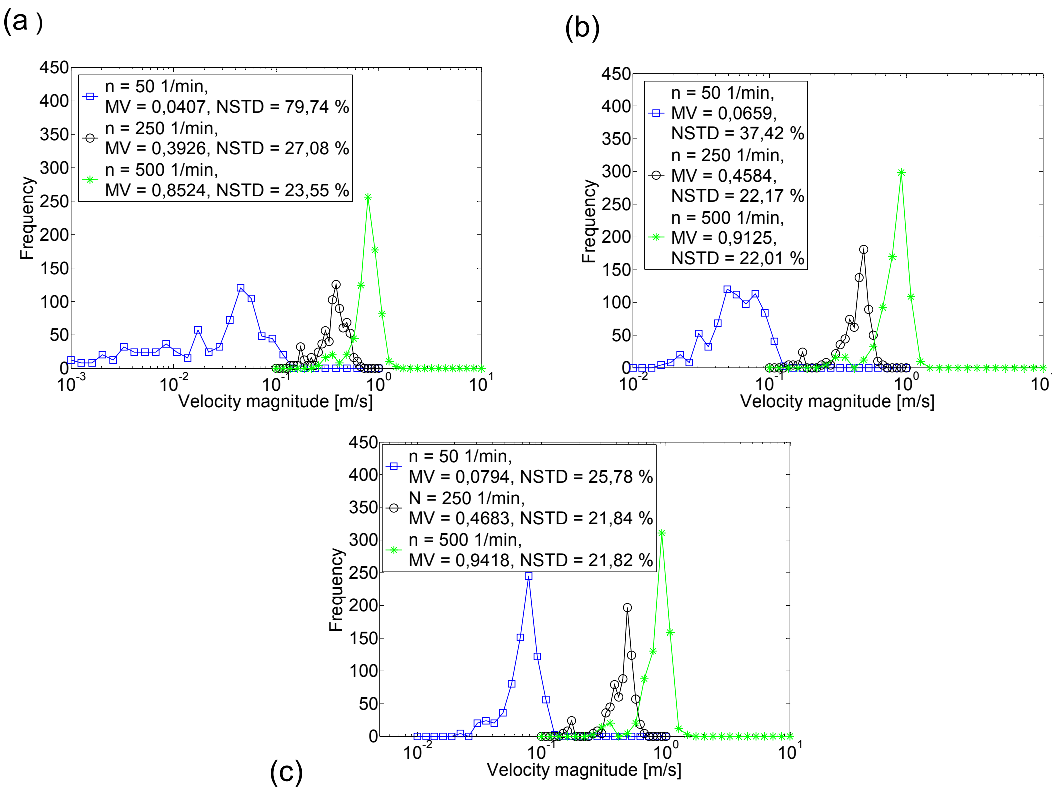

Figure 2 (a) Logarithmic histograms of rotational speed's effect of reactor homogeneity at 20 °C (b) Logarithmic histograms of reactor homogeneity at 50 °C (c), Logarithmic histograms of reactor homogeneity at 90 °C

The effect of the blade number was examined too at 20 °C. For demonstration the three, five, and six-blade Rushton turbine were used. The results are shown in Figure 3. It can be seen that the three- (a) and five-blade (b) Rushton turbines have always worse performance than the six-blade (c) one. To be exact the percent variance is 116 % for the three-blade form, 113 % for the five-blade form and 80 % for the six-blade form at 50 1/min. A huge gap is experienced between Rushton turbines with five- and six-blade at each rotational speed. The width of this gap is decreased by the increasing of the rotational speed, but at 250 1/min and 500 1/min the gap is stayed unchanged.

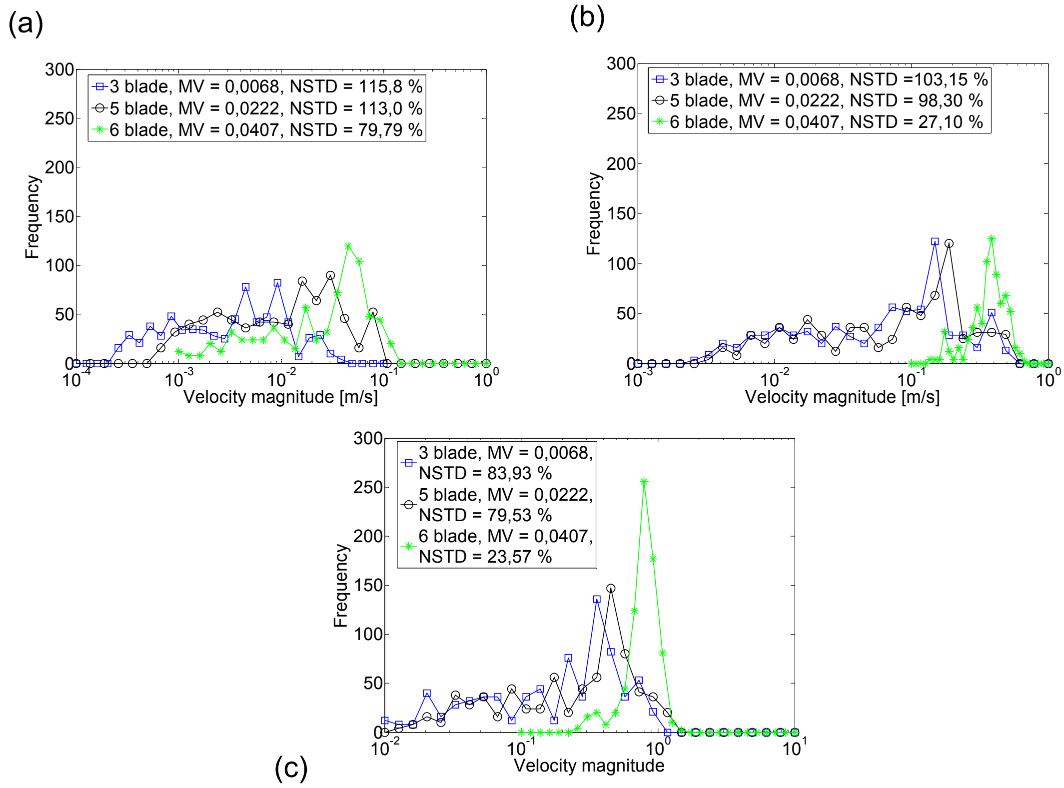

Figure 3: Effect of the changes in the blade number on the reactor homogeneity at (a) 50 1/min, (b) 250 1/min and (c) 500 1/min

Table 1 shows the result of the parameter identification. The identified parameters were used in Equation (2). In Figure 4 the comparison of experimental and calculated power consumption can be seen. Based on the fitting it can be stated that the developed CFD model can be applied to calculate the electric consumption of the mixer. As it was seen if the rotational speed is increased from 50 1/min to 500 1/min the homogeneity will be four times better. To achieve this improvement in the homogeneity cc. 10 % increase in electrical power consumption of the motor is required.

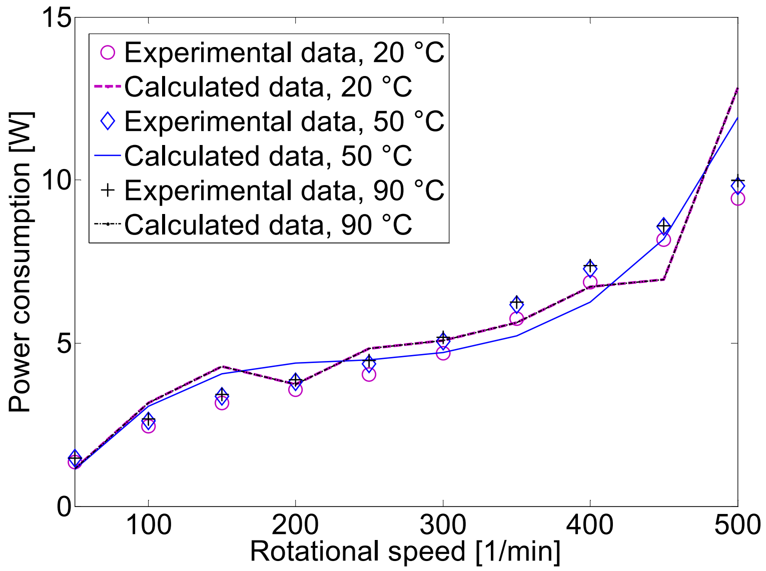

Figure 4: Comparison of experimental and calculated electric power consumption with the six-blade Rusthon turbine

5. Conclusion

Homogeneity of the velocity field and power consumption were studied in a stirred equipment. Four different impeller geometries were investigated at many rotating speeds. Homogeneity of the velocity field in the vessel was plotted on logarithmic histograms. As it was shown the homogeneity was depended on the temperature and the rotational speed. The blade number of the Rushton turbine shows great difference in the achieved homogeneity of the mixed phase.
The c_f dimensionless resistance factor was determined with parameter identification to calculate the power consumption. The simulated electric power consumption was compared to the experimental ones and a proper fitting was experienced. Further research is needed to define optimal rotational speed for each impeller type.

Acknowledgements

This work was supported by the European Union and financed by the European Social Fund in the frame the TAMOP-4.2.2/B-10/1-2010-0025 and TÁMOP-4.2.2/A-11/1/KONV-2012-0071 projects.

References

Bader F. G., 1987, Modelling mass transfer and agitator performance in multiturbine fermentor, Biotechnol Bioeng, 30, 37-51

Birge B., 2003, PSOt – a particle swarm optimalization toolbox for use with Matlab, Swarm Intelligence Symposium, 182 - 186

Brown D. E., 1997, The measurement of fermentor power input, Chem Ind, 16, 684-688

Carreau P. J., Paris J., Guérin P., 1992, Mixing of Newtonian and no-Newtonian liquids: screw agitator and draft coil system, Can J Chem Eng, 70, 1071-1082

Chatwin S., Nienow A. W., 1985, Successful power measurement in agitated vessels, Lab Sci. and Tech., September, 19

Hayes R. E., Facan A., Boulanger B., Tanguy P. A., 1998, Experimental Study of Reactive Mixing in a Laminar Flow Batch Reactor, Chemical Engineering Research and Design, 76, 73-81

Himmelstein S., 1994, Precision Torquemeter Readouts, Bulletin 360D, (Himmelstein & Co., USA)

Holland I. A., Chapman F. S., 1966, Liquid Mixing and Processing in Stirred Tanks (Reinhold, New York, USA)

Kramers H., Baars G. M., Knoll W. H., 1953, A comparative study on the rate of mixing in stirred tanks, Chem Eng Sci, 2, 35-42

Kumaresan T., Joshi B. J., 2005, Effect of impeller design on the flow pattern and mixing in stirred tanks, Chem Eng J, 115, 173-193

Lazauskas L. V., 2005, Hydrodynamics of Advanced High-Speed Sealift Vessels, Master Thesis, University of Adelaide, Australia

Machon V., Vlcek J., Shrivanek J., 1985, Dual impeller systems for aeration of liquids: an experimental study, Proceedings of 5th European conference on Mixing (BHRA Fluid Engineering, Cranfield Institute, Bedford, UK), 155-169

Nurtono T., Setyawayan H., Altway A., Winardi S., 2009, Macro-instability characteristic in agitated tank based on flow visualization experiment and large eddy simulation, Chemical Engineering Research and Design, 87, 923-942

Oosterhuis N. M. G., Kossen N. W. F., 1981, Power input measurements in a production scale bioreactor, Biotechnol Lett, 3, 645-650

Paul E. L., Atiemo-Obeng V. A., Kresta S. M., 2004, Handbook of industrial mixing: science and practice, Wiley & Sons, New Jersey. USA

Sommerfeld M., Decker S., 2003, State of the art trends in CFD simulation of stirred vessels, Proceedings of the 11th European Conference on Mixing, Bamberg, p. 1.

Spero P. M., 2011, Thermocouple Temperature Measurements for Twin Jet Thermal Mixing, Master's Dissertation, University of Tennessee, USA.

Tamburini A., Cipollina A., Micale G., 2011, CFD Simulation of Solid Liquid Suspensions in Baffled Stirred Veesels below Complete Suspension Speed, Chemical Engineering Transactions, 24, 1435

Van de Vusse J. G., 1995, Mixing by agitation of miscible liquids, Chemical Engineering Science, 4, 178-200