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Optimal location of axial impellers in a stirred tank applying evolutionary programing and CFD

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ABSTRACT

The optimal location of one and two impellers on the central shaft of a tall stirred tank was obtained using a combination of Evolutionary Programing (EP) and Computational Fluid Dynamics (CFD) techniques; this location was evaluated through the determination of the normalized mixing time (T_N) and power consumption (P_C). The systems were simulated using 45° pitched, down-pumping, 4-blade turbine impellers (PBT). The EP method considered a small population of 6 individuals (systems) where the impeller(s) were located on the shaft in order to cover most of the search space through the fitness function. Populations were generated by applying the selection and mutation of genetic operators to the best individuals for the next generation. Four generations of population were needed to find the optimal location of the impeller(s) in the shaft. The results show the best individual performance for the systems with one and two impellers.

1. Introduction

Stirred tanks are widely used in most industries, such as: chemical, petrochemical, biotechnological, pharmaceutical, metallurgical and so on (Yapici et al., 2008). They are used in unit operations, such as: polymerization, emulsification and solvent extraction, among others (Cheng et al., 2013). The stirred tanks are also widely used for blending two miscible fluids in the food, pharmaceutical and chemical industries (Zadghaffari et al., 2009).

An appropriate combination of the number and the location of impellers in a stirred tank allows the reduction of the power consumption and the mixing time. Supplying mechanical rotary motion with minimal power consumption is important in a large variety of processes in the chemical and process industry, because the cost associated with the power input contributes significantly to the overall operation cost of the plant. Various works have been reported on the effect of the impellers location on mixing time and power consumption. Hiraoka et al. (Hiraoka et al., 2001) studied the best set-up positions of impellers and determined the power consumption and the mixing time for double impellers in stirred tanks, defining the relationship of mixing time to power consumption for all system studied. Montante et al. (Montante et al., 2005) applied CFD simulation strategy for the calculation of mixing time in stirred tanks for fluids characterized by either Newtonian or non-Newtonian rheological behavior. They stated that the turbulent Schmidt number was critically

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Nomenclature

B	baffle width (m)
C_L	clearance (dimensionless)
D	impeller diameter (m)
D_s	shaft diameter (m)
D_A	diffusivity of species A in the mixture ($m^2\,s^{-1}$)
H	liquid level (m)
p	total pressure (Pa)
P_C	power consumption (dimensionless)
Re	Reynolds number
S_1	distance between the lower and upper impeller (dimensionless)
Sc_t	turbulent Schmidt number
T	tank diameter (m)
T_N	Normalized mixing time (dimensionless)
u_i, u_j	velocity component ($m\,s^{-1}$)
W	blade width (m)
w_A	mass fraction of species A

Greek letters

Γ	production rate of kinetic energy ($m^2\,s^{-3}$)
ε	turbulent kinetic energy dissipation rate ($m^2\,s^{-3}$)
κ	turbulent kinetic energy ($m^2\,s^{-2}$)
μ	dynamic viscosity (Pa s)
μ_t	turbulent dynamic viscosity (Pa s)
ν	kinematic viscosity ($m^2\,s^{-1}$)
ν_t	turbulent kinematic viscosity ($m^2\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
σ_κ	Prandtl number for κ (1.0)
σ_ε	Prandtl number for ε (1.2)
ω	angular velocity (rpm)

important for obtaining a good forecast of both homogenization curves and mixing time. Taghavi et al. (Taghavi et al., 2011) studied experimentally the power consumption and flow regimes in dual Rushton impeller stirred tank in both single and two phase conditions, proposing some correlations to predict the flow regime transitions as well as local and total power consumption. Woziwodzki and Jedrzejczak (Woziwodzki and Jedrzejczak, 2011) examined the size, positions and structure of the isolated mixing regions (IMR) as a function of the Reynolds number and the eccentricity ratio in vessel equipped with double turbine impellers. They found that the eccentricity causes a strong compartmentalization effect, which affects the mixing pattern and the occurrence of ribbon-like IMR (RIMR), where for a small eccentricity; the structure was similar to structures in concentric systems. Somnath and Sumanta (Somnath and Sumanta, 2012) studied the mixing time in a stirred tank to identify the effects of low frequency macroinstability oscillations in the impeller speed. The mixing time is significantly reduced when the flow is perturbed using a steep-change in the impeller speed with a specific macroinstability frequency, also leading to an energy improvement strategy for faster mixing. However, the sudden changes in rotational speed during a perturbation cycle can result in higher wear of rotating components in mechanical seal assemblies, and hence can reduce the seal life. Machado et al. (Machado et al., 2013) analyzed the transitional flow in stirred tanks considering impeller Reynolds number, the scaling of mean velocity profiles and energy dissipation to keep the flow in the fully turbulent regime, concluding that the transitional regime for the flow in a stirred tank is at $Re = 20{,}000$ in a substantial part of the bench scale tank, and a Reynolds number higher than 20,000 is enough to sustain fully turbulent flow; however, it is clear that this general rule is only valid for regions close to the impeller; therefore, having regions with transitional flow inside the stirred tank can produce uncertainties in the design. Machado and Kresta (Machado and Kresta, 2013) presented a new design of the confined impeller stirred tank (CIST), where active circulation and fully turbulent flow are sustained in the entire tank. This design considers the use of multi-impellers to obtain a more uniform turbulence field than the conventional stirred tank; however, there are still several gaps related to the use of the impeller locations and number of impellers in a stirred tank.

Surrogate modeling consists of building an approximate model for the objective function to be used in the solution process of the given optimization problem. When used in conjunction with evolutionary algorithms, surrogate models can help to reduce complexity, to smooth the fitness landscape and to deal effectively with noisy environments (Fonseca et al., 2012). Jin et al. (Jin, 2011) highlights the importance of surrogate modeling for CFD problems. The approximation of CFD processes is performed by stopping simulations before convergence and only computing exact simulation for a small number of candidate solutions (Giannakoglou et al., 2006). Asouti et al. (Asouti et al., 2009) combined the use of evolutionary algorithms and surrogate models for the design of aerodynamic shapes. The surrogate metamodels used in this work are Multi Layer Perceptrons and Radial basis Function Networks. Both of them are Artificial Neural Network Models.

The optimization of a mixing process is quite complex and just few papers can be found in the literature about this topic; e.g. Mohammadpour et al. (Mohammadpour et al., 2015) developed experimentally an statistical design which included the response surface methodology (RSM) in a surface aeration tank. On the other hand, evolutionary algorithms (EA) have been used as an alternative tool to classical optimization algorithms in Computational Fluid Dynamics (CFD) related problems, e.g. the optimization of micro heat exchangers, proposed by Foli et al. (Foli et al., 2006). Their approach uses Multi-Objective Evolutionary Algorithms (MOEA) and they compared their performance top the analytical approach. The main advantage of the evolutionary approach has been found to be its capability to simultaneously compute the parameters of the optimal shape and the optimal dimensions of the heat exchanger. Hilbert et al. (Hilbert et al., 2006) have also addressed a heat exchanger design problem using parallel genetic algorithms, where the goal is to optimize the shapes of the blades of the heat exchanger. On the other hand, Li et al. (Li et al., 2013) carried out the optimization of the operation of the ventilation system of offices. The authors found an increased resolution in the positioning of the thermal comfort zones, an optimization of the energy cost and an improvement of the indoor air quality after using a genetic algorithm (GA).

Applications of evolutionary and CFD techniques to reach optimal design have been reported mainly to airfoils. Kumar et al. (Kumar et al., 2011) used an ant colony optimization (ACO) method to develop a CFD solver to optimize the shape of airfoils. Jahangirian and Shahrokhi (Jahangirian and Shahrokhi, 2011) also propose the use of genetic algorithms for aerodynamic shape optimization problems. Andrés et al. (Andrés et al., 2012) proposed to integrate EP and support vector regression algorithms for optimal airfoil design. In the case