Available online at www.sciencedirect.com
ScienceDirect
Journal of Hydrodynamics
2017,29(6):1023-1034
DOI: 10.1016/S1001-6058(16)60816-8
www.sciencedirect.com/science/journal/10016058

Optimization design of multiphase pump impeller based on combined genetic algorithm and boundary vortex flux diagnosis*

Jin-ya Zhang (张金亚), Shu-jie Cai (蔡淑杰), Yong-jiang Li (李泳江), Xin Zhou (周鑫), Yong-xue Zhang (张永学)
College of Mechanical and Transportation Engineering, Beijing Key Laboratory of Process Fluid Filtration and Separation, China University of Petroleum, Beijing 102249, China, E-mail: zhjinya@163.com

(Received August 21, 2015, Revised December 7, 2015)

Abstract: A novel optimization design method for the multiphase pump impeller is proposed through combining the quasi-3D hydraulic design (Q3DHD), the boundary vortex flux (BVF) diagnosis, and the genetic algorithm (GA). The BVF diagnosis based on the Q3DHD is used to evaluate the objection function. Numerical simulations and hydraulic performance tests are carried out to compare the impeller designed only by the Q3DHD method and that optimized by the presented method. The comparisons of both the flow fields simulated under the same condition show that (1) the pressure distribution in the optimized impeller is more reasonable and the gas-liquid separation is more efficiently inhibited, (2) the scales of the gas pocket and the vortex decrease remarkably for the optimized impeller, (3) the unevenness of the BVF distributions near the shroud of the original impeller is effectively eliminated in the optimized impeller. The experimental results show that the differential pressure and the maximum efficiency of the optimized impeller are increased by 4% and 2.5%, respectively. Overall, the study indicates that the optimization design method proposed in this paper is feasible.

Key words: Optimization design, multiphase pump, genetic algorithm, boundary vortex flux, quasi-3D hydraulic design (Q3DHD)

Introduction

The oil well fluid is a mixture of the oil, the water and the natural gas. The traditional technology for the well head transport is to separate the gas from the oil and the water using a gas-liquid separator, and then to transport the liquid by oil pumps and the gas by compressors, respectively. The multiphase transporting system developed in recent decades can be directly used to transport the gas-liquid mixture without separation equipment at the wellhead. Compared with the traditional technology, the multiphase transporting technology shows remarkable economic benefits in recent years[1,2]. Thus, as a core of the multiphase transporting technology, the multiphase pump becomes a current research focus in oil fields.

The rotodynamic multiphase pump (RMMP) with features of large wrap angle and long flow passage is suitable for the mixture transport. The complex state of the gas-liquid two-phase flow in the multiphase pump impeller makes the separation of the gas and the liquid inevitable due to the centrifugal force. In severe cases, the gas-liquid separation often leads to the formation of air pocket, to affect the normal transportation of the two-phase flow to some extent. A reasonable geometry structure of the impeller is important for avoiding the gas-liquid separation and improving the hydraulic performance of a multiphase pump. Zhu et al.[3] comprehensively considered the hydraulic design method of the axial impeller and inducer with the properties of transporting the mixture and then put forward a basic geometry structure, a hydraulic design method, as well as a value range of key geometrical parameters of the RMMP impeller. Cao et al.[4] presented a hydraulic design method of the RMMP impeller through combining the inverse design and the computational fluid dynamics (CFD) analysis. Zhang et al.[5] derived the velocity gradient equation in the meridian plane of the impeller, and put forward a design method of the multiphase pump impeller based on the 2-D hydraulic design theory. Kim et al.[6] improved the hydrodynamic performance of a multiphase pump by optimizing the impeller and the diffuser using the design

* Project supported by the National Natural Science Foundation of China (Grant No. 51209217).
Biography: Jin-ya Zhang (1980-), Male, Ph. D., Associate Professor

of experiment techniques and the response surface method. In the optimization procedure, the lengths of the inlet and outlet regions of the meridional plane and the blade angles are selected as the design variables.

The hydraulic performance of an impeller is directly influenced by its shape, which is determined by many geometrical parameters. Due to the interactions among these parameters, the impellers designed with the existing methods need to be further optimized. With the help of the CFD technology and various optimization algorithms, various integrated impeller design methods were developed. It was amply shown that the application of the GA is effective in the optimization design of turbomachinery impellers[7]. Liu and Zhang[8] constructed an automatic optimal design platform and optimized a centrifugal pump impeller by combining the impeller parametric method, the multi-objective GA, and the numerical calculation software NUMECA. Zhang et al.[9] put forward a multi-objective and multi-operating mode optimization method for designing the multiphase pump impeller using the combination of the CFD, the BP Neural Network, and the NSGA-II. During the optimization, the CFD results were used to train the neural networks and find the objective functions. Lee et al.[10] conducted a systematic optimization study on the GA-based design optimization procedure to search the complex design landscape in an efficient and parallel manner. In their study, the fitness evaluations in the optimization procedure were performed with the RANS-based CFD simulations and the mesh regeneration was automatically carried out through a scripting process within the grid generator. Djavareshkian and Latifi[11] optimized a wind turbine airfoil using the GA-based optimization method, the CFD, and the artificial neural network (ANN), which was used as a surrogate model to reduce the computational cost and time. Goto et al.[12] developed a computer-aided system for the hydraulic design of the flow passage components of a centrifugal pump. The system has integrated the 3-D CAD model reconstruction, the grid automatic generation, the CFD calculation analysis, and the 3-D inverse problem design. The results can be directly applied to a rapid prototype to greatly shorten the design cycle of the centrifugal pump. Arturo et al.[13] optimized the location of impellers on the central shaft of a tall stirred tank using a combination of the evolutionary programing and the CFD. Derakhshan et al.[14] used a global optimization method based on the ANN and the Artificial Bee Colony algorithm along with a validated 3-D Navier-Stokes flow solver to redesign the impeller geometry and improve the performance of a Berkeh 32-160 pump. Židonis et al.[15] developed a generic optimisation method for Pelton turbine runners using CFD. Two different initial runners are optimized to achieve more generic results based on this method.

The BVF diagnosis, based on the vortex dynamic theory, can amplify the defect of the local flow by analyzing the flow on the wall of the impeller using the BVF analysis method, which can be used for identifying the parts with defects and providing a direct evidence for improving the design. Based on viscous flow equations, Wu and Wu[16] developed a complete theory of the boundary vortex dynamics and showed that the vortex flux on the object plane was not only the source of the lift force and the resistance, but also the cause of the unsteady separated flow. In this theory, the force and the momentum on the object plane can be calculated by the integration of the vortex flux; the balance between the lift force and the resistance can be achieved by controlling the vortex flux distribution on the object plane. Thus, the theory is applicable to the cases of any Mach number and Reynolds number, as well as both steady and unsteady flows. Zhang et al.[17] optimized the hydraulic performance of a high-specific speed centrifugal pump impeller by using the BVF diagnostic method. Li et al.[18] diagnosed the flow field distribution in the starting process of a centrifugal pump by using the vorticity dynamics method.

Many hydraulic design and optimization methods were proposed to improve the hydraulic performance of the RMMP. Among various optimization methods, the bench tests of pumps with impellers of different geometry parameters are time- and cost-consuming. For the use of the optimization method for the design of experiment combining the CFD, a great number of numerical simulations of flow fields of pumps with different geometry parameters are required. Moreover, the level numbers of optimization variables have a great effect on the result of optimization. The optimization method based on the GA is used widely due to its global optimization, high robustness, self-evolution and optimization searching. However, the fitness value evaluation, as one of the key steps for the optimization design, is the most time-consuming step in the optimization based on the GA. In our previous studies, the fitness values were evaluated by the CFD or the ANN. For the optimization by a combination of the GA and the CFD, sufficient 3-D viscous CFD studies should be carried out to establish the objective function in the optimization process. It will take a great amount of calculation source and time, and for the random changes of parameters in the optimization process, the shape modification and the grid reconstruction are required. For the optimization by a combination of the GA and the ANN, the evaluation function is obtained by training the ANN based on the results of the CFD. So, a large number of CFD simulations should be carried out. Moreover, the accuracy of the ANN can hardly be assured. Therefore, it is necessary to find a method to accelerate the