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Multi-objective hydraulic optimization and analysis in a minipump

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Abstract Minipump is widely used in microfluidics system, active cooling system, etc. But building a high efficiency minipump is still a challenging problem. In this paper, a systematic method was developed to design, characterize and optimize a particular mechanical minipump. The optimization work was conducted to cope with the conflict between pressure head and hydraulic efficiency by an improved back-propagation neural network (BPNN) with the non-dominated sorting genetic algorithm-II (NSGA-II). The improved BPNN was utilized to predicate hydraulic performance and, moreover, was modified to improve the prediction accuracy. The NSGA-II was processed for minipump multi-objective optimization which is dominated by four impeller dimensions. During hydraulic optimization, the processing feasibility was also taken into consideration. Experiments were conducted to validate the above optimization methods. It was proved that the optimized minipump was improved by about 24 % in pressure head and 4.75 % in hydraulic efficiency compared to the original designed prototype. Meanwhile, the sensitivity test was used to analyze the influence of the four impeller dimensions. It was found that the blade outlet angle β_2 and the impeller inlet diameter D_0 significantly influence the pressure head H and the hydraulic efficiency η, respectively. Detailed internal flow fields showed that the optimum model can relieve the impeller wake and improve both the pressure distribution and flow orientation.

Keywords Minipump · Optimization · Back-propagation neural network · Non-dominated sorting genetic algorithm-II

1 Introduction

Over the last decade, the microfluidic systems have been developing at an exponential rate and widely applied in chemical analysis [1], polymer chain reaction [2], microelectronics cooling [3] and other fields. The micropump is the essential actuation component in microfluidic systems. It can pump, control or otherwise manipulate small fluid volumes against backpressure through the system [4].

A variety of micro- or minipumps have been developed based on various principles [5–10]. Mostly, the motivation of the pump development focuses on the pumping realization to adapt with the microfluidic components, operation ambient, and moreover the micro processing method. The performance effectiveness analysis and optimization, by contrast, play second fiddle. Several numerical modeling and optimization designs were presented according to the pumping mechanism. Da Silva et al. [11] proposed a viscous pump with a cylindrical rotor set in the channel housing. By comparing sets of channel dimensions and the rotor eccentricity, the optimum model was obtained to maximize the mass flow rate per unit of shaft power consumption. Choi et al. [12] developed a dual rotating cylinders pump. By taking the advantage of the sequential metamodel-based optimization algorithm, the optimum design variables were automatically determined within the specific constraint; meanwhile, the relation between the objectives was revealed.

We proposed a mechanical centrifugal minipump with a 2 L/min flow rate, 90 kPa pressure head at 22,000 r/min

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[13]. Figure 1 illustrates the components of the minipump. It generally consists of an impeller, a volute and a permanent magnet motor. Though this centrifugal minipump gets the similar form with the conventional pump, the hydraulic performance in conventional machine can be rarely referred to in minisize. In our previous work [13], it was demonstrated that the minipump equipped with open impeller could generate higher pressure head than that with the closed impeller while presenting a slightly efficiency drop. At the case of minisize, the leakage and disk friction of the closed impeller accounted for a large proportion in the overall power loss. Hence, to investigate the characteristics of geometry and flow in minisize is necessary.

In this paper, our study focuses on improving the hydraulic performance upon the open impeller model. This paper applied back-propagation neural network (BPNN) as a surrogate model to make prediction for the hydraulic performance, and non-dominated sorting genetic algorithm-II (NSGA-II) to optimize the objectives of pressure head and efficiency. Different from the existed works [14–17], to obtain a satisfied prediction accuracy overcoming inadequate training sample, this paper modified the standard BP network by combing with an enhanced simulated annealing (ESA) algorithm. The global sensitivity test was conducted to assess the influence of every decision variable upon the objective functions. Detailed operating curves and internal flow fields between the reference and optimum minipumps are analyzed.

2 Optimization statement

The overall optimization procedure can be generally described as follow: firstly, an original minipump is designed according to the partial emission pump theory. Secondly, the optimization space for four impeller variables is determined. After that, a training sample is established to construct the BPNN. Thirdly, the BPNN model is adopted instead of numerical calculation for objective prediction. Finally, with the obtained prediction model, the optimum minipump is selected by the NSGA-II.

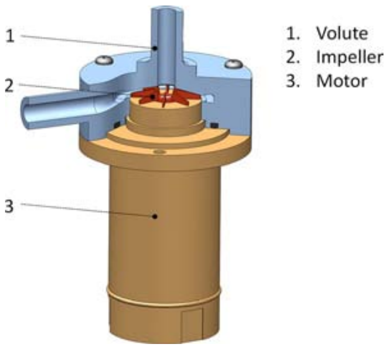

Fig. 1 (Color online) Components of the centrifugal minipump

2.1 Original design of minipump

The original reference minipump was designed to nominally generate a pressure head higher than 90 kPa under 2 L/min, 20,000 r/min. Through numerical simulation, the initial minipump model generates a pressure head of 99.56 kPa, and 46.98 % hydraulic efficiency at nominal operation conditions, which meet the given design objective. The detailed dimensions of the reference minipump will be given in the following.

2.2 Objective functions

Two objective functions are involved in this study including the pressure head H and the hydraulic efficiency of the impeller η, which are defined as

$$H = H_2 - H_1, \tag{1}$$

$$\eta = \frac{\rho g H Q}{P}, \tag{2}$$

where H, H_1, H_2, ρ, g, Q, and P represent the total head rise, inlet total pressure, outlet total pressure, density, gravity acceleration, volume flow rate and power, respectively.

2.3 Decision variables

Figure 2 illustrates the profile and design variables of the hydrodynamic components. The impeller design obeys the partial emission pump model; meanwhile, structure dimensions also shows high respect to processing consideration. Figure 2a shows the axial projection. The blade top and bottom edges are fixed by the tip clearances (x_1, x_2) which refer to the motor shaft axial displacement. The angle between the blade inlet edge and the hub γ (as shown in Fig. 2c) is defined as an 82° draft angle, which means the blade inlet diameter D_1 is subject to the inlet diameter D_0. As a result, the blade axonometric profile is dominated by the impeller inlet diameter D_0 and impeller outer diameter D_2. Figure 2b shows the plane projection. The impeller blades are 2-D arc curved. Thus, the vane spine line can be shaped by the blade inlet angle β_1 and blade outlet angle β_2. In addition, thickness is one of the manufacturing constraints. Therefore, the blade thickness distributions were frozen in optimization process. Finally, four design variables (Fig. 2) are employed as the decision parameters: impeller inlet diameter D_0, impeller outer diameter D_2, blade inlet angle β_1, blade outlet angle β_2.