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Research paper

Hybrid model for discharge flow rate prediction of reciprocating multiphase pumps

Hongying Deng[a,b], Yi Liu[b,*], Ping Li[a], Shengchang Zhang[b]

[a] *State Key Laboratory of Industrial Control Technology, Institute of Industrial Process Control, Zhejiang University, Hangzhou 310027, China*
[b] *Institute of Process Equipment and Control Engineering, Zhejiang University of Technology, Hangzhou 310014, China*

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ABSTRACT

Accurate description of the quick and nonlinear change of the discharge flow rate in reciprocating multiphase pumps is important but difficult. To ensure the reliability of reciprocating multiphase pumps, it is necessary to model the relationship between the discharge flow rates of a stroke and multiphase transportation conditions. A hybrid modeling method is proposed for practical use in this work. First, a Gaussian process regression (GPR) model is adopted to online predict the discharge flow rates. Then, the probabilistic information of GPR is used to divide the flow rate curve of a stroke into four stages for individual modeling. Additionally, the process knowledge of multiphase pumps is integrated into the modeling process. Furthermore, to capture the nonlinear characteristics of the mutation stage with limited samples, the local relationship between the input variables change related to opening points and the flow rates is constructed. Consequently, the process knowledge and probabilistic information are integrated to formulate a practical hybrid model. Experimental results show the superiority of the hybrid modeling method.

1. Introduction

Reciprocating oil-gas multiphase pumps can efficiently increase oil and gas productions in the crude oil drilling for their good internal compression and anti-gas resistance performance [1–4]. Ideally, the periodical motions of the piston and valves make the change of the pump flow rate consistent with the volume change rate, which cause knowable flow pulsations [5]. In fact, the spools usually exhibit lag characteristics for irregular motions in the instantaneous multiphase migration flows [6]. Additionally, the gas compressibility promotes or resists the flows to develop irregular compression ratio. Consequently, unknowable backflow phenomenon in the closing lag periods and salient phenomenon in the opening moment of the discharge valve, will form to aggravate flow pulsations [7]. Furthermore, the resulting pressure fluctuation will cause noise, vibration, and reduce pump efficiency [5]. If the discharge flow rates in different multiphase transportation conditions can be predicted, the obtained important information (e.g., the maximum and mean flow rates, lag characteristics, etc.) will help the designers optimize the pump structure to improve the reliability of multiphase pumps. Therefore, it is necessary to investigate the interaction mechanism between the discharge flow rate and the multiphase transportation conditions.

During the past two decades, several mechanism models of multiphase pumps have been proposed based on mass and energy conservation equations [8–11]. Generally, mechanism models for multiphase conditions are complex because they largely vary with thermodynamic conditions and pump types. However, the engineering applications of mechanism models are still limited mainly because of the neglect of partial leakages and energy losses and the assumption of the homogeneous flows. Additionally, some variables, such as the transient pressure and temperature distribution, the flow and friction coefficient are difficult to be determined analytically or experimentally for complicated flow patterns. As a newly used multiphase pump, the mechanism model of the reciprocating multiphase pump is also difficult to be described and thus rarely investigated.

The computational fluid dynamics (CFD) method has been utilized as a useful tool in the multiphase flow fields. Most research investigated the internal flow characteristics of the screw, scroll, helico-axial, and vane multiphase pumps [12–14], while only a few studies were conducted for the reciprocating multiphase pumps [7]. Additionally, most CFD models did not consider leakages and energy losses. The internal flows were often supposed to be homogeneous. It was insufficient to

Abbreviations: CFD, computational fluid dynamics; GPR, Gaussian process regression; MACV, maximal absolute change of variance; ME, maximal error; MFRE, maximal flow rate error; MV, maximal MACV; RMSE, root-mean-square error

* Corresponding author.
E-mail address: yliuzju@zjut.edu.cn (Y. Liu).

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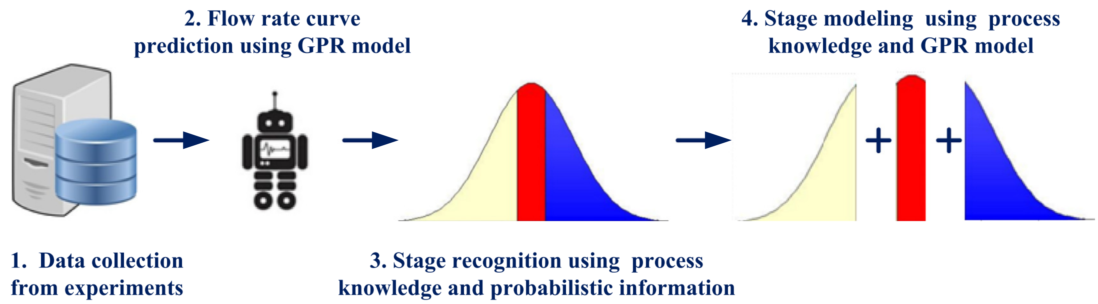

Fig. 1. A brief scheme of the hybrid modeling method for recognition and prediction of the discharge flow rate in reciprocating multiphase pumps.

describe the behavior of reciprocating multiphase pumps. Moreover, the selection of multiphase and turbulence models, dynamic grid technique and user defined functions, as important factors for the accuracy and reliability of calculation results, heavily relies on designers' experience [15]. Therefore, a practical modeling approach should be developed for complex multiphase conditions.

Recently, as an alternative method, data-driven empirical models have been developed in the mechanical and flow fields [16–18]. Compared with the mechanism models and experimental methods, the data-driven empirical models can generally be developed faster without substantial understanding of the process. In comparison with CFD models, the data-driven empirical models can be trained without requiring much experience of designers. As we know, the modeling accuracy of data-driven empirical models depends on the reliability of modeling data. However, it is difficult to collect enough samples of different multiphase conditions due to the time-consuming and costly experiment process [19–21]. Thus, develop efficient strategies to enhance prediction performance with limited data is necessary in data-driven empirical modeling methods.

In chemical processes, several applications of hybrid models integrated physical with data-driven empirical models show good prediction performance without lots of samples [22,23]. Although there has not been a physical model of the reciprocating multiphase pump, the existing process knowledge may be efficiently utilized. Remarkably, the discharge flow rate of a reciprocating pump can be calculated from one of its pump cavities. For a pump cavity, the ideal curve of the discharge flow rate in a stroke is half a sine wave. And the actual curve consists of four stages, namely known sine and opening lag stages,

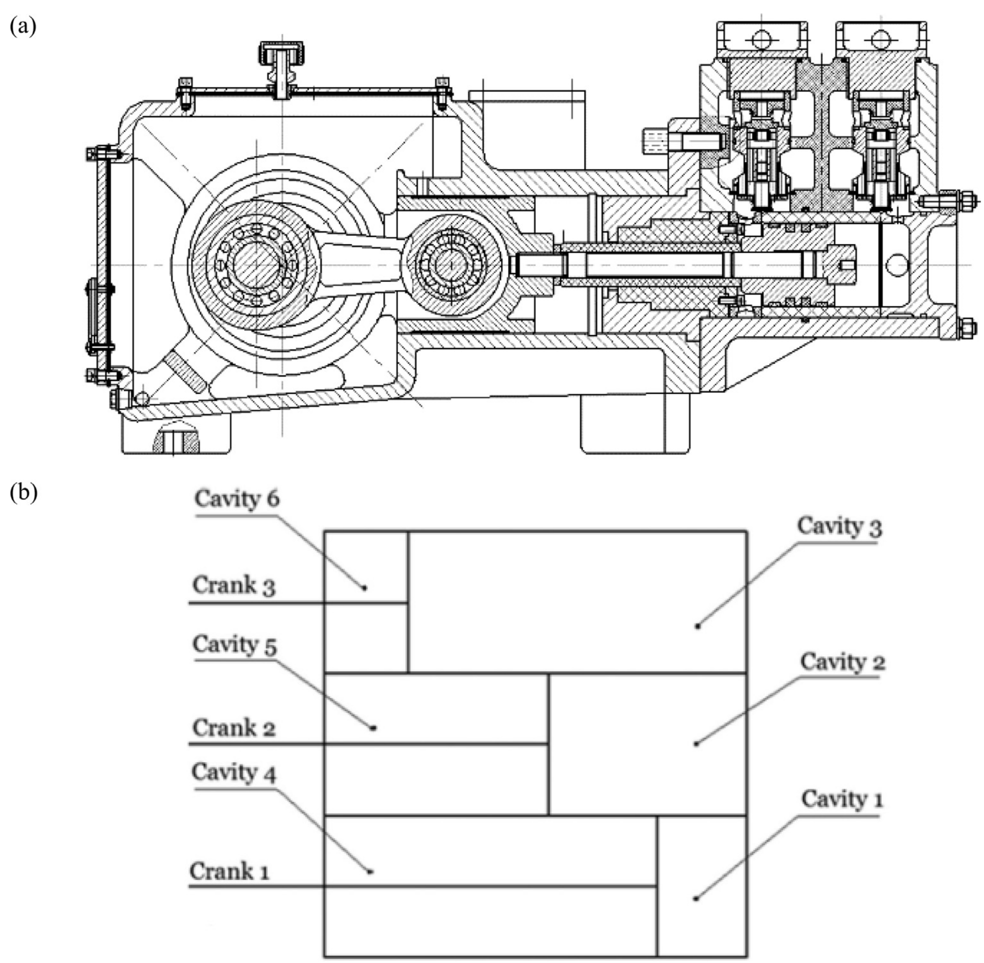

Fig. 2. (a) The diagram of the three-cylinder double-acting reciprocating multiphase pump **(b)** Six pump cavities of the three-cylinder double-acting reciprocating multiphase pump.