Modeling Study on the Centrifugal Pump for a Floating Nuclear Power Plant

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Modeling Study on the Centrifugal Pump for a Floating Nuclear Power Plant

Weitong Li[a], Lei Yu[*] and Tianhong Yuan[b]

College of Nuclear Science and Technology, Naval University of Engineering, Wuhan, China

*Corresponding author e-mail: yulei301@163.com, [a]lwt863@126.com, [b]yuantianhong.niu@163.com

Abstract. In order to study the thermal-hydraulics characteristics of a floating nuclear power plant (FNPP) system, a series of modeling studies are made for the safety analysis. By establishing a centrifugal pump model, the paper emphatically calculated a series of pump operating behaviors, such as steady-state operation, switching speed condition, starting condition and coastdown condition. The results show that the model can realize the corresponding simulation function and reflect the operation characteristics of the FNPP pump accurately. In addition, the selection of energy ratio for FNPP pump is highly demanding. The simulation model is suitable for the subsequent analysis of different FNPP reactor responses.s.

1. Introduction

As the key equipment, the centrifugal pump plays an important role in the heat transfer of reactor, which is related to the reliable operation and safety of the floating nuclear power plant (FNPP) system. The modeling work of the centrifugal pump not only provide reference basis for the design and selection of the pump, but also can be used to analyze the response of the reactor system under different transient characteristics. Therefore, it is of great importance to establish the pump model by using the numerical method. Farhadi et al. conducted mathematical models to predict the starting behavior of coolant pump. Relationships of important parameters such as pump heads, torques and flow rate are established [1, 2]. Coastdown phenomena of coolant pump were investigated by Gao et al. The analytical models proposed in the references agree well with the published experimental data [3, 4]. Alatrash et al. studied the inertial capability of coolant pump during coastdown period. A simulation model named MMS was developed to reflect the design characteristics of coolant pump [5].

Generally speaking, a detailed pump performance experiment is required in the modeling work, however, modeling is difficult to be carried out in practical application due to the lack of experimental data. Some scholars adopted similar pump data to replace the real pump data, but the results are inaccurate. What's more, researches on the marine pump used in the FNPP are few due to the special operating performance. In this paper, the whole characteristic curve of the pump is plotted based on the pump experiment, and the special operational conditions of the FNPP pump are analyzed using the established mathematical simulation model.

2. Pump simulation model

2.1. Pump full characteristic curve

The operating states of the centrifugal pump can be divided into four parts, including normal pump state, energy dissipation state, turbine state and reverse pump state. In the model a curve covering full characteristics of pump is plotted, reflecting different pump operating performance. Dimensionless parameters (ratio of actual value to rated value, i.e., flow rate ratio v, speed ratio α, torque ratio β, head ratio h) are calculated to establish the full characteristic curve, which is relatively convenient to use in the simulation. However, a lot of theoretical calculations is required in the early stage. The full characteristic curve includes eight head curves (HAN, HVN, etc.) and eight moment curves (BAN, BVN), as shown in Table 1. It can be used to simulate the starting process, normal operation and stopping process of the FNPP pump. It should be pointed out that the discussion of the pump performance is based on the single-phase flow. If two-phase is involved in the flow, empirical correction based on the experiment should be added to the current work.

Table 1. Classification of centrifugal pump operation.

Classification	Feature	Homologous curves
Normal pump	Forward flow, Forward speed	HAN/BAN
		HVN/BVN
Energy dissipation	Reverse flow, Forward speed	HAD/BAD
		HVD/BVD
Turbine	Reverse flow, Reverse speed	HAT/BAT
		HVT/BVT
Reverse pump	Forward flow, Reverse speed	HAR/BAR
		HVR/BVR

Limiting by the experiment conditions, it is difficult to obtain the experiment data in some operating regions, so the fitting and extrapolation method is adopted in the data processing. The dimensionless calculation of the experiment data is carried out by selecting fitting models, such as linear model, parabolic model, four-power model and multiple-power model. The fitting goodness of the obtained curve is greater than 0.98, indicating that the data fitting degree is very good, and the better the fitting degree is obtained based on the higher the polynomial power in the fitting model. However, if the fitting curve is extrapolated by the fitting formula to a great extent, the results of different methods will differ greatly. Taking the HAD curve as an example, the extrapolation results of four-power model and multiple-power model are shown in Fig.1.
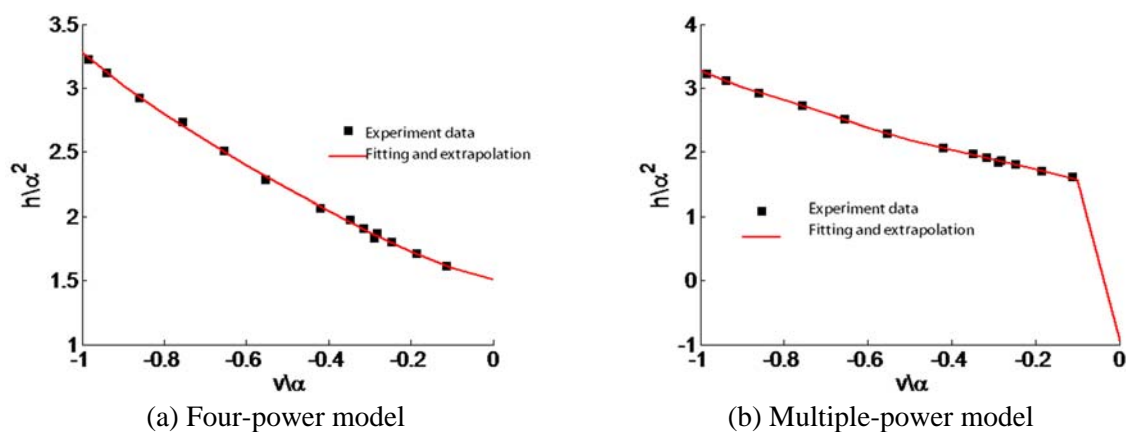

(a) Four-power model   (b) Multiple-power model

Figure 1. Comparison between different fitting methods.

For multiple-power model, the trend deviation between extrapolation point and curve is large, which should be excluded in the work. After comprehensive consideration of fitting degree and extrapolation ability of fitting model, the four-power model is selected as the basis for fitting HAD curve. Similarly, the method of obtaining other curves requires dozens of screening work of fitting models, and finally a complete and smooth full-characteristic curve is obtained, as shown in Fig.2.
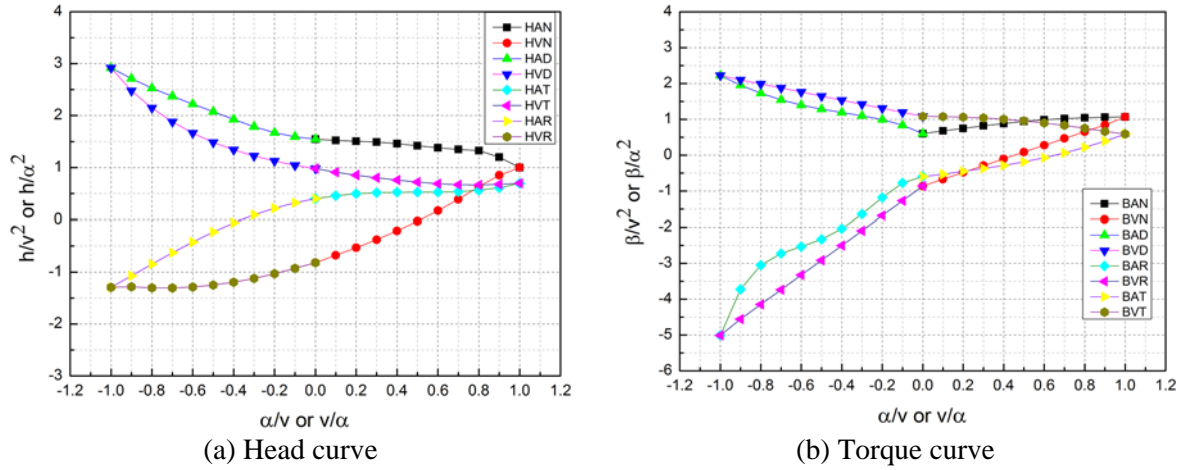

(a) Head curve   (b) Torque curve

Figure 2. Full characteristic curves of pump.

2.2. Pump speed calculation model
The basic equation of the speed of the FNPP pump is expressed as:

$$I\frac{d\omega}{dt} = M_{ej} - M_{hy} - M_{fr} \tag{1}$$

Where I refers to the rotational inertia of the pump, M_{ej}, M_{hy} and M_{fr} are electrical torque, hydraulic torque and frictional torque, respectively.

The electrical torque of the pump can be derived from the reference formula [6], in which the specific parameters are given by the pump manufacturer. The hydraulic moment is obtained by solving the full characteristic curve based on the experiment. The frictional torque is related to the inherent characteristics of the pump, and its relationship can be written as [7]:

$$M_{fr} = M_{fr0} + M_{fr1}(\frac{\omega}{\omega_R}) + M_{fr2}(\frac{\omega}{\omega_R})^2 + M_{fr3}(\frac{\omega}{\omega_R})^3 \tag{2}$$

Where M_{fr0}, M_{fr1}, M_{fr2}, M_{fr3} are the constant coefficients.
In the calculation, the simplified frictional torque term is expressed as:

$$M_{fr} = M_{fr0} + M_{fr1}(\frac{\omega}{\omega_R})^2 \tag{3}$$

A complete simulation model of the pump is established and transferred to the analytical RELAP5 code. Thus, a series of pump behaviours can be calculated by the established model.

3. Pump operating condition analysis
Reliable pump provide steady head to drive the fluid in the FNPP circulation. At present, the common operating conditions of FNPP pump include steady-state operating condition (including high speed and

low speed working modes), speed switching operating condition, starting condition and coastdown condition.

3.1. Calculation of pump steady-state condition

When the FNPP is under the operating condition of low power, a low-speed and low-flow state of pump is sufficient to maintain the heat transfer form reactor core. According to the use of multistage motor-winding, pumps can operate at both high-speed and low-speed condition. The FNPP high-speed and low-speed steady-state conditions are calculated by using pump simulation model and the main parameters include flow rate, head and speed. The results show that the error of the simulation and design under the high-speed condition is not more than 1%, the error of the simulation and design under the low-speed condition is not more than 2%. The main parameters in the reasonable scope verify the simulation model successfully.

3.2. Calculation of pump switching speed condition

The pump often switches between high-speed and low-speed in the FNPP operation. In the current design, pumps can achieve the function of direct switching, rather than switching indirectly with the standby pump mode. Fig.3 displays the speed and flow variation as a function of time parameter for the switching condition. It can be seen that the switching process is relatively smooth, and the pump flow rate is approximately linear with the pump speed. The change of pump flow rate lags behind the change of pump speed, which conforms to the pump basic change law. The results show that the simulation model can simulate the switching transient process well, and the influence of the switching process on the whole reactor system can be analyzed in the future study.
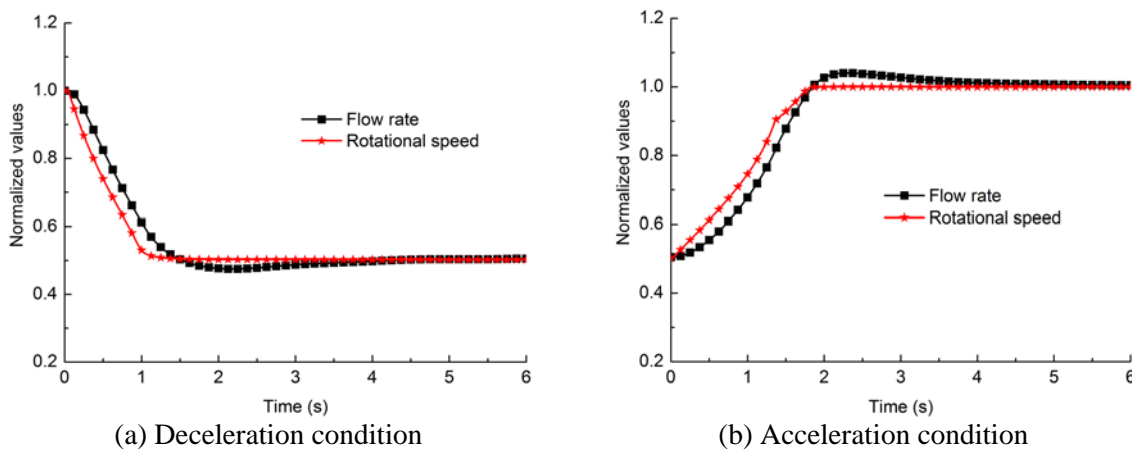

(a) Deceleration condition   (b) Acceleration condition

Figure 3. Transient performance for speed switching.

3.3. Analysis of pump starting and coastdown characteristic

The pump starting characteristics have a great influence on the reactor starting condition and switching condition of natural circulation to forced circulation. Some studies have analyzed the influence of different pump designs on the pump speed, head and torque [8]. In fact, the FNPP study pays great attention to the influence of the inertia moment on the starting process. An effective energy ratio ε is introduced as an indication to evaluate the inertia effect, taking the inertia of pump as well as the inertia of fluid into consideration:

$$\varepsilon = \frac{E_f}{E_p \eta} \tag{4}$$

Where η: efficiency; E_f and E_p represent the kinetic energy stored in coolant fluid and pump, respectively.

The starting simulation results under different inertia moments are shown in Fig.4 (a). The results show that the pump can successfully complete the starting process from static state to the low speed state, and the inertia moments has an obvious limit on the starting acceleration. The smaller the value of ε, the slower the starting process.

On the other hand, it is widely accepted that there should be a sufficient capability of coastdown in the pump design to improve the safety characteristics of reactor system. When the power failure of pump occurs, the electric torque of the pump turns to zero immediately, but the pump impeller continues to drive the coolant for a certain time due to the inertial effect which ensures that the fuel elements of reactor core will not burn up. In addition, in the case of switching condition of forced circulation to natural circulation for FNPP reactor, the coastdown effect ensures a smooth transition. Fig.4 (b) shows the analytical results of coastdown pump characteristic, indicating that a relatively small value of ε allows the impeller to offer more flow resistance.

However, it is noteworthy that a relatively small value of ε cannot satisfy the high requirement on the starting time for the marine reactor. Therefore, a moderate value of ε should be considered in the design of FNPP pump.

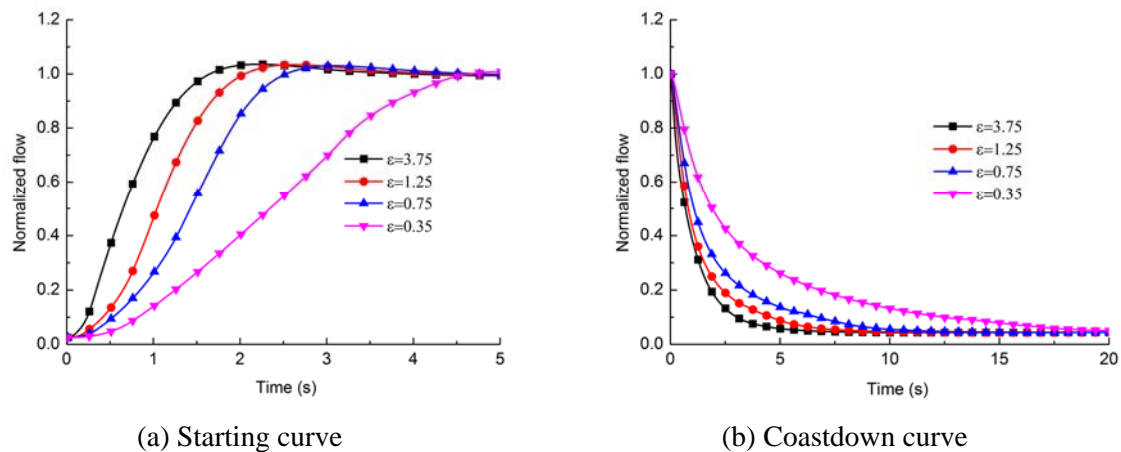(a) Starting curve   (b) Coastdown curve

Figure 4. Starting and coastdown characteristic of FNPP pump.

4. Conclusion

Based on the experiment data of FNPP pump, this paper plots the full characteristic curve of pump according to the fitting and extrapolation method. The speed calculation model of the pump is established in the RELAP5 code. Based on the simulation model, the response processes of steady-state condition, starting characteristic, coastdown characteristic and the direct switching condition of high-speed and low-speed are analyzed. The results show that the pump model can achieve the corresponding simulation function and reflect the operation characteristics accurately. What's more, the FNPP pump has a high demand for inertia, which needs to be designed suitably according to the actual situation. The pump model is applicable to the subsequent analysis of different responses of the FNPP reactor system, and results can provide reference for the pump design and optimization.

Acknowledgments

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