Modeling and Validation of Pump Coast-down Flow for Research Reactor Application

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1. Introduction

Research reactor tend to be enlarged to improve economic efficiency and application in various fields. Although the size of the reactor core in the research reactor is smaller than that of the nuclear power plant, the piping and components of the primary cooling system are designed to be large to perform heat removal with a small temperature difference. As a result, it has disadvantages such as the possibility of breakage due to an increase in the pipe length and an increase in construction cost. In order to compensate for these shortcomings, research and development related to the reduction of piping and components of the research reactors is being conducted.

In order to reduce the size of pipes and devices, it is necessary to optimize the fluid components (such as heat exchanger, pump, decay tank) and develop a precise prediction model that can predict the performance [1,2]. In this study, a model was developed that improved the predictive ability of the pump coast-down flow in the compact primary cooling system. Most of the previous studies have focused on predicting the coast-down flow in the initial section [3,4]. Therefore, the error of the theoretical model tends to increase in the late section of coast-down flow. To supplement the disadvantages of the previous models, a model with improved predictive ability at low flow rates was proposed. The proposed model presents the pump efficiency as a correlation between normalized angular velocity and head, and has a characteristic that the efficiency changes in the transient state. As a similar approach, there is a model that proposes efficiency as a correlation equation for angular velocity, but it has the disadvantage that the correlation equation changes depending on the section [5], as shown in Table I. To verify the proposed model, comparison with previous studies and verification test were performed. As a result, it was confirmed that the proposed model showed higher predictive ability in the low-flow section than the previous models.

Table I: Previous theoretical model for coast-down flow

Authors	Model
H. Gao et al. (2011) [3]	$Q(t) = \frac{1}{2(\beta t+1)}(\beta + \tanh(\frac{1}{2}\frac{(\ln(\beta t+1)\sqrt{\beta^2+4}-2\operatorname{arctanh}(\frac{-2+\beta}{\sqrt{\beta^2+4}})\beta}{\beta}\sqrt{\beta^2+4})$ $,\beta = \frac{t_{1/2}}{\tau_{1/2}}$
K. Farhadi (2010) [4]	$\frac{1}{2}\frac{dQ}{dT} + Q^2 = \frac{1}{(2\epsilon T+1)^2}$ $\epsilon = \frac{KE_f}{KE_p\eta}, KE_f = \frac{1}{2}I_p n_{ss}^2, KE_p = \frac{1}{2}\Sigma\frac{L}{A}(\frac{w}{g})q_{ss}^2$
H. Yoon et al. (2018) [5]	$\frac{L}{A}\frac{d\dot{m}}{dt} + \frac{1}{2}k_{sys}\rho(\frac{\dot{m}}{\rho A})^2 - \rho g h = 0$ Pump efficiency (η) $\eta = 1-(1-\eta_0)\left(\frac{\omega_0}{\omega}\right)^{0.1}, 0.3 < \frac{\omega}{\omega_0} \le 1$ $\eta = 1-(1-\eta_0)\left(\frac{\omega_0}{\omega}\right)^{0.1}\left(\frac{\omega_0}{\frac{\omega}{0.3}}\right)^{0.8}, 0 \le \frac{\omega}{\omega_0} \le 0.3$

2. Theoretical model

To predict the transient flow, it is necessary to define the governing equations for the pump and fluid system. As shown in Equation (1), the overall differential pressure in the system can be defined as the flow inertia, the friction loss, and the pump head. From the force balance of the pump, the angular velocity can be defined as the torque due to the electromagnetic force, the hydraulic torque, and the torque due to the mechanical friction, as shown in equation (2).

$$\Sigma(\frac{L}{A})\frac{dq}{dt} + \Sigma k\frac{q^2}{2\bar{\rho}A^2} - \bar{\rho}gh_p = 0 \qquad (1)$$

$$I\frac{d\omega}{dt} = M_{em}(\omega) - M_h(\omega) - M_f(\omega) \qquad (2)$$

In the governing equation, when the pump is stopped, the torque due to the electromagnetic force of the pump and the pump head become 0. Assuming that the torque for the mechanical friction is 0, the change in the angular velocity can be defined as the hydraulic torque.

$$I\frac{d\omega}{dt} = -M_h(\omega) \qquad (3)$$

Assuming a steady state in Equation (1), the flow inertia becomes 0.

$$\bar{\rho}gh_{p0} = \Sigma k\frac{q_0^2}{2\bar{\rho}} \qquad (4)$$

By substituting Equation (4) into Equation (1), it can be expressed as in Equation (5)

$$\frac{\Sigma(\frac{L}{A})}{\bar{\rho}g\hbar_{p0}}\frac{dq}{dt} + \frac{q^2}{q_0^2} = \frac{\hbar_p}{h_{p0}} \qquad (5)$$

Normalizing the expression with respect to time, flow rate, and head, it can be derived as follows.

$$\frac{\Sigma(\frac{L}{A})}{\bar{\rho}g\hbar_{p0}}\frac{dQ}{dT} + Q^2 = H$$

$$\alpha = \frac{t_{1/4}}{\tau_{1/4}}, T = \frac{t}{t_{1/4}}, Q = \frac{q}{q_0}, H = \frac{h}{h_{p0}} \qquad (6)$$

In the transient state, pump is stopped and the pump head become 0. Assuming that the hydraulic torque is proportional to the square of the angular velocity, the following equation can be derived using Equation (3) and (6).

$$\frac{1}{3}\frac{dQ}{dT} + Q^2 = \frac{1}{(1+3\alpha T)^2} \quad (7)$$

In general, the efficiency of the pump can be defined as in Equation (8).

$$\eta = \frac{g h_0 q_0}{M_0 \omega_0} \quad (8)$$

In the efficiency equation, the efficiency in the transient state was defined as equation (9) regarding normalized head and angular velocity.

$$\eta = \eta_0 \frac{H^{3/2}}{W^3}, W = \frac{\omega}{\omega_0} \quad (9)$$

3. Validation

To verify the present model, experiment was performed using the test facility built for the primary cooling system of the research reactor [6, 7]. Table II shows the experimental conditions performed for model validation.

Fig. 1 shows the experimental results and the calculation results of the previous models and the present model. It can be confirmed that the present model and the previous models similarly predict the initial section of coast-down flow. However, from the point where the coast-down flow becomes 30% of the steady-state flow, the error between the previous models and the calculation result tends to increase. It can be confirmed that the models of H. Gao(2011) and K. Karhadi(2010) overestimate the mass flow compared to the test results. The reason is that the pump efficiency is reduced by the mechanical friction of the pump, but it is not considered in the theoretical model. H. Yoon(2018)'s model predicted slightly low, but it is judged that the effect of the reduction in efficiency was predicted significantly. The model proposed in this study predicted the experimental results similarly in overall period of the coast-down flow. Through the results, it was confirmed that the present model predicts the coast-down flow well.

In addition, verification was performed using the experiments of the previous literature [8], as shown in Fig. 2. It can be confirmed that the test results are predicted similarly to the calculated results of the present model.

Table II: Test condition for model validation

Parameter	Value	Unit
Mass flow rate	60	*kg/s*
Pump speed	1165	*RPM*
$\sum L/A$	52	m^{-1}
Pump head	15.53	m
Pump moment of inertia	16	$kg \cdot m^2$

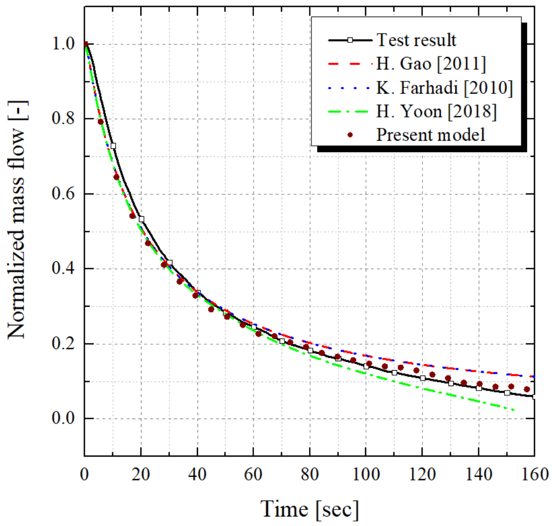

Fig. 1 Validation of theoretical model with previous theoretical models

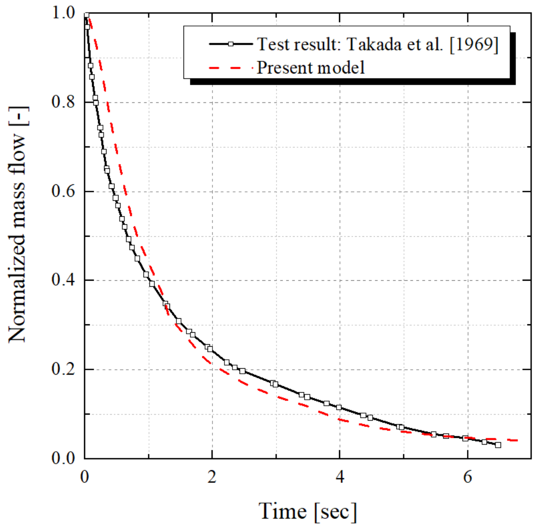

Fig. 2 Previous test results and present model [8]

4. Conclusions and Plans

As a result, an improved theoretical model was developed that can predict the coast-down flow by the pump flywheel. The coast-down flow test was performed to verify that the theoretical model predicts the experimental results well. In addition, the verification of the present model was additionally performed using the previous models and tests. The research results are expected to be utilized for the transient flow prediction and pump optimal design in the research reactor.

In the future, we plan to confirm the predictive performance of the theoretical model by securing additional tests and previous experimental data

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REFERENCES

[1] H.B. Park, K.W. Seo, "Flow design of primary cooling system against LOCA in a research reactor", The Korean Society for Energy Autumn Meeting, jeju, Korea, November 3-5, 2021

[2] H.B. Park, K.W. Seo, S.H. Kim, "Concept of primary cooling system against LOCA in a research reactor", The Korean Society for Energy Spring Meeting, Daegu, Korea, April 28-30, 2021

[3] H Gao, F. Gao, X. Zhao, J. Chen, X. Cao, "Transient flow analysis in reactor coolant pump systems during flow coastdown period", Nuclear Engineering and Design Vol.241, p.509-514, 2011

[4] K. Farhadi, "Analysis of flow coastdown for an MTR-pool type research reactor", Progress in Nuclear Energy Vol.52, p.573-579, 2010

[5] H.G. Yoon, K.W. Seo, S.H. Kim, "Primary cooling system pump and flywheel design in a research reactor." The KSFM Journal of Fluid Machinery Vol.21(6), p.54-63, 2018

[6] I.G. Kim, K-J Park, M. K. Jung, H.J. Kim, K.W. Seo, S-H. Kim, "Study on a Scaling Method and Design of an Air-Water Flow Test Facility", Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 23-24, 2019

[7] I.G. Kim, M.K. Jung, K-J Park, K.W. Seo, "Preliminary analysis of negative pressure pipe break test using MARS-KS", Transactions of the Korean Nuclear Society Autumn Meeting, Changwon, Korea, October 21-22, 2021

[8] Y. Takada, T. Yokomura, A. Kurosawa, "Thermo-hydraulic model test of the first nuclear ship reactor in Japan". Nuclear Engineering and Design Vol.10, p.126–147, 1969