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Analyses for Primary Coolant Pump Coastdown Phenomena for Jordan Research and Training Reactor

Yazan M. Alatrash, Han-ok Kang, Hyun-gi Yoon, Shen Zhang,Juhyeon Yoon

Abstract**—**Flow coastdown phenomena are very important to secure nuclear fuel integrity during loss of off-site power accidents. In this study, primary coolant flow coastdown phenomena are investigated for the Jordan Research and Training Reactor (JRTR) using a simulation software package, Modular Modeling System (MMS). Two MMS models are built. The first one is a simple model to investigate the characteristics of the primary coolant pump only. The second one is a model for a simulation of the Primary Coolant System (PCS) loop, in which all the detailed design data of the JRTR PCS system are modeled, including the geometrical arrangement data. The same design data for a PCS pump are used for both models. Coastdown curves obtained from the two models are compared to study the PCS loop coolant inertia effect on a flow coastdown. Results showed that the loop coolant inertia effect is found to be small in the JRTR PCS loop, i.e., about one second increases in a coastdown half time required to halve the coolant flow rate. The effects of different flywheel inertia on the flow coastdown are also investigated. It is demonstrated that the coastdown half time increases with the flywheel inertia linearly. The designed coastdown half time is proved to be well above the design requirement for the fuel integrity.

Keywords**—** Flow Coastdown, Loop Coolant Inertia, Modeling, Research Reactor.

I. INTRODUCTION

AN adequate coolant flow rate should be provided to a reactor core in order to secure nuclear fuel integrity. During normal operation mode ofthe Jordan Research and Training Reactor (JRTR), the downward coolant flow rate inside the core is provided by the primary coolant pumps. If the pumps stop due to a loss of electricity accident, the downward primary coolant flow rate will decrease rapidly.

If the decreasing rate of the core flow rate is higher than the core decay heat decreasing rate, nuclear fuel integrity cannot be guaranteed. To prevent this kind of situation in the initial stage of the loss of electricity accident, a flywheel is installed on a shaft of the primary coolant pump.

Yakomura [10] studied the coastdown phenomena in centrifugal pumps. His method is applicable to a system with one reactor and any number of centrifugal pumps. Power failure was assumed. Electrical energy was out of consideration, and the kinetic energy of rotating parts of pumps and motors was considered. Detailed information of the pumps characteristics is not required for his method.

Takada et al. [9] carried out a series of fluid flow model tests to confirm the first nuclear ship reactor thermal hydraulic design. Flow rates calculated by his method were compared with the experimental results. In the first half of the flow coastdown, the calculated flow rate was larger than measured rates. In the later half, the experimental values were considerably smaller than the calculated ones. He stated that the instruments were not accurate enough to allow further discussion to be made on this point.

Farhadi [3] developed a mathematical model for analyzing a flow coastdown transient. He derived the differential equations for the diminishing fluid flow in the piping system and a retarding motion of the rotating parts of the centrifugal pump. Influence of the kinetic energy in the piping system and kinetic energy of the pump is considered in the form of a ratio that he called the effective energy ratio. His model showed that the inertia of the rotating parts and inertia of the coolant fluid are the most important variables influencing flow coastdown transients.

Farhadi [5] developed a model to model flow coastdown phenomenon for the Tehran Research Reactor (TRR). In his model, all physical parameters that can influence the disturbing torque are defined and formulated. Mechanical loss of an induction motor was measured and included in the model for predicting a coastdown curve more accurately.

In another paper, Farhadi [4] presented a physical model for analyzing a flow transient phenomenon. The model developed was used to study the influence of a motor retarding the torque on the reactor flow transients. Preliminary measurements and calculations for motor mechanical losses showed that the retarding torque resulting from a loss of electricity to a canned motor is significant.

Gao et al. [7] derived a mathematical model for analyzing the flow coastdown transient in a reactor coolant pump system. Their model was developed based on a momentum conservation equation of the primary coolant and moment balance relation of the pump. The non-dimensional flow rate and non-dimensional pump speed for a speed coastdown are solved analytically. Their analytical solution showed that the

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Y. Alatrash is a master student at Advanced Nuclear Engineering Department, University of Science and Technology,217 Gajeong-Ro Yuseong-Gu, Daejeon305-350, Republic of Korea (e-mail: Yazan.atrash@gmail.com).

H. Kangis with Korea Atomic Energy Institute, 1045 Daeduk-daero, Yuseong-Gu, Daejeon 305-353, Republic of Korea (phone: +82-42-868-2758; e-mail: hanokang@kaeri.re.kr).

H. Yoon is with Korea Atomic Energy Institute, 1045 Daeduk-daero, Yuseong-Gu, Daejeon 305-353, Republic of Korea (Phone: +82-42-868-4460; e-mail: hyungi@kaeri.re.kr).

S. Zhang is a simulation engineer at nhance technology, Inc.122 corner stone St. Lynchburg, VA 245 USA (phone:(434) 582-6110; e-mail: shen.zhang@nhancetech.com).

J. Yoon is with Korea Atomic Energy Institute, 989-111 Daedeok-daero, Yuseong, Daejeon 305-353, Republic of Korea (corresponding author to provide phone: +82-42868-8319; fax:F=82-42-868-8622; e-mail: yoonj@kaeri.re.kr).

non-dimensional flow rate is determined by the energy ratio, which is the ratio of initial kinetic energy of the loop coolant fluid to the effective initial kinetic energy of the pump rotating parts. The calculated results were compared with the experimental results of two nuclear power plants, and the agreement is satisfactory.

In this paper, flow coastdown phenomena of the JRTR Primary Coolant System (PCS) loop are analyzed for different sizes flywheels, the effect of the PCS loop fluid inertia, and the coastdown half time required halving the coolant flow rate.

II. A SimpleMMS Model for Pump Loop Simulation

MMS is a Windows-based visual software system for modeling the dynamic characteristics of power plant systems and studying various designs, performances, and operation aspects [8]. A MMS model is composed of predefined modules for various power plant components which areconnected together to define the inter-relationships. MMS provides the capability of real-time simulation and many flexible features which give the user the ability to modify their model and study the effect of adding or removing components on system performance. To investigate the JRTR PCS loop fluid inertia effect on a flow coastdown curve during a loss of off-site power accident, two MMS models are developed. One of them is a simple model for pump loop simulation to investigate the characteristics of a JRTR primary coolant pump only with a minimum coolant inventory inside the loop. The second model is for a JRTR PCS loop simulation. The configuration of the simple MMS model for pump loop simulation is shown in Fig. 1. The model consists of two centrifugal pumps, pipes, and two code blocks in which the moment balance relation of the pumps during a coastdown is programmed.

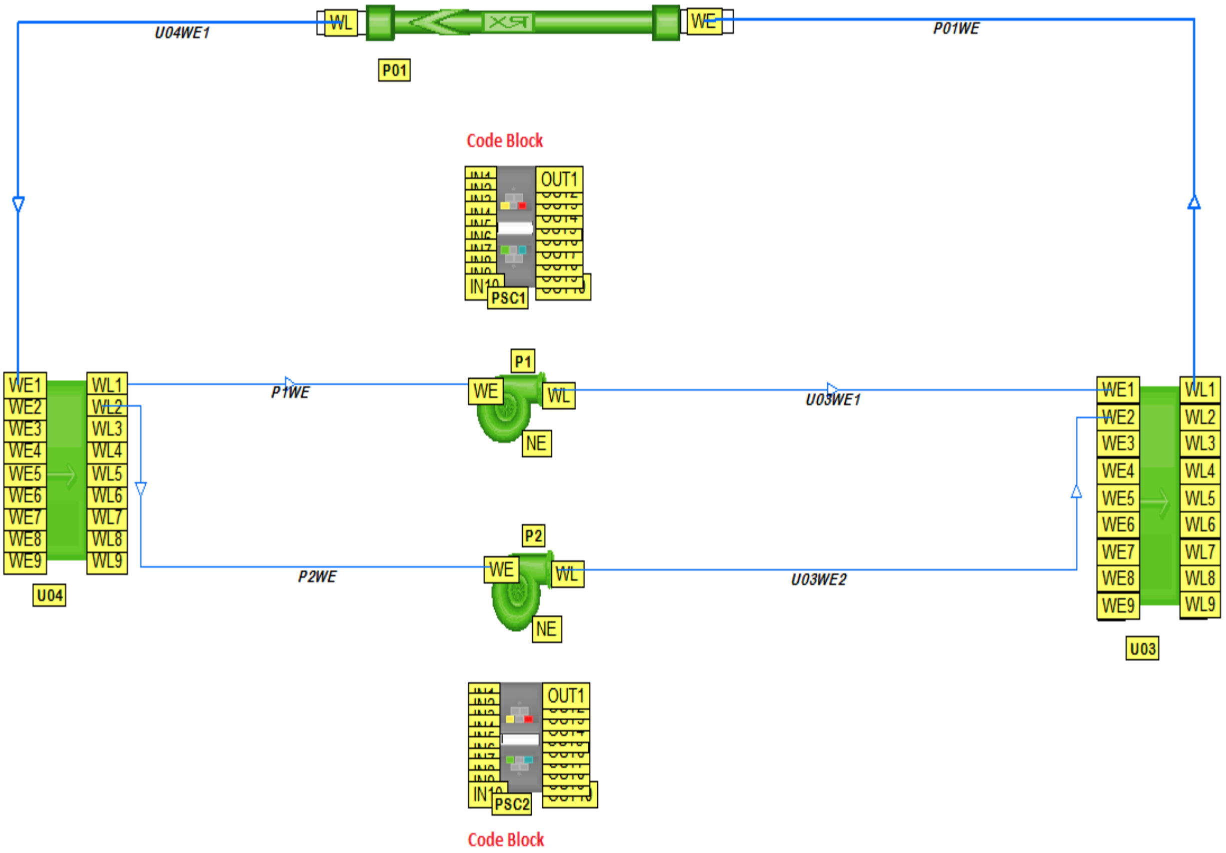

Fig. 1 The configuration of MMS simple model for pump loop simulation

III. MMS Model for a JRTR PCS Simulation

The JRTR is an open-tank-in-pool type research reactor with a 5MWt capacity. The JRTR is currently under construction. It will be Jordan and region leading center for nuclear research, training and radioisotope production. As shown in Fig. 2, the MMS model for JRTR PCS simulation consists of two centrifugal pumps, two plate type heat exchangers, valves, pipes, decay tank, and three code blocks. In the model, governing equations necessary for a loss-of-electricity accident simulation are programmed in MMS code blocks [1]. Code block (A) in Fig. 2 contains a model for a core power decay curve after a reactor trip. Code blocks (b) and (C) model the moment balance relation of the pumps during a coastdown. No neutronics equations are modeled for the core. During the normal operation mode, a 5 MWt power is added to the primary coolant inside the reactor core as a constant heat source. The solid lines represent hot water from the reactor core which flows into a decay tank and is then divided into two parallel lines where the heat dissipates through two plate type heat exchangers. Cold water represented by dotted lines flows back to a reactor pool. In this model, all isometric components are appropriately modeled.

IV. SOLUTION METHOD

A. MMS Governing Equations

The pressure loss coefficient of an individual MMS thermo-hydraulic module is input by specifying pressures at the input andoutput ports of each MMS module such as pipes, pumps, heat exchangers, and tanksthrough an input worksheet for each module [6]. MMS solver assembles all the design data from these modules and calculates the pressure, flow rate and enthalpy distribution in the MMS model by solving the following governing equations [8]:

$$\frac{d}{dt} = \frac{1}{\left(\frac{L}{A}\right)}\left((P_e - P_l - \rho K_{dz}) - k_{fr}|\,|\right) \tag{1}$$

where (kg/s) is the coolant flow rate,$\left(\frac{L}{A}\right)$ is the equivalent inertia length for the system (m^{-1}), P_e is the pressure at the entering port (Pa), $P_l$is the pressure at the leaving port (Pa), ρ is the coolant density (kg/m^3), K_{dz} is the elevation rise (m), andk_{fr} is the flow resistance (Pa/(kg/s) ^{2}).

$$\frac{dh}{dt} = \frac{_e(h_e - h) - _l(h_l - h) + q}{\rho V_t} + \frac{1}{\rho}\frac{dp}{dt} \tag{2}$$

where h is the specific enthalpy (J/kg), $_e$ is the flow rate at entering port (kg/s), h_e is the specific enthalpy at entering port (J/kg),$_l$ is the flow rate at the leaving port (kg/s), h_l is the specific enthalpy at the leaving port (J/kg), q is the heat added (W), and $V_t$is the total volume (m^3).

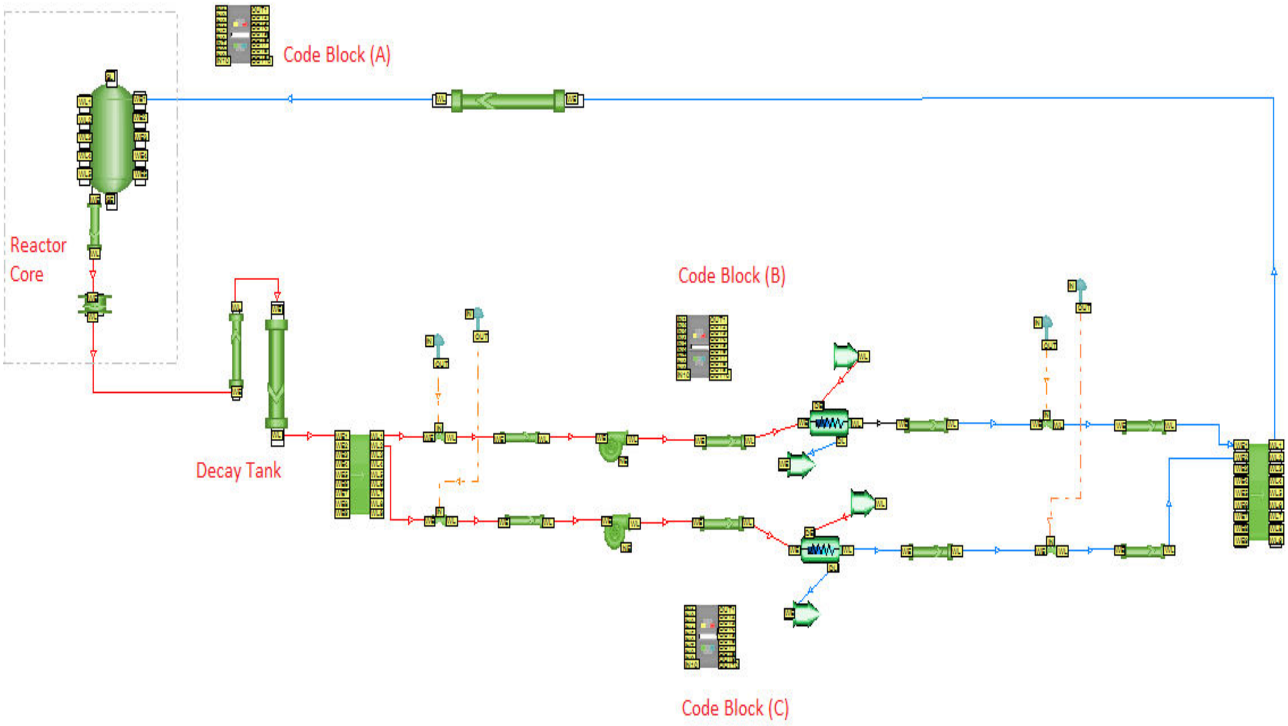

Fig. 2 The configuration of the MMS model for JRTR PCS simulation

B. MMS Pump Module

The Pump Module models the pump by calculating the pressure rise as a function of the pump speed.

$$\Delta P_{rise} = \rho_{av} K_{hz} g \left(\frac{\omega}{\omega_{rated}}\right)^2 \tag{3}$$

where $\Delta P_{rise}$is the pressure rise from the inlet to the outlet (Pa)$_{,}\rho_{av}$istheaverage fluid density (kg/m^3), $K_{hz}$is the pump head at zero flow and rated speed (m),g is the acceleration of gravity (9.8065 m/s^2) ,$\omega_{rated}$is the rated pump speed (rad/sec), andω is the pump speed (rad/sec).

$$\boldsymbol{P}_{shaft} = \frac{\Delta P_{rise}}{\eta \rho_{av}} \tag{4}$$

where$\boldsymbol{P}_{shaft}$isthe pump shaft power (W),ΔP_{rise} is the pressure increase (Pa), (kg/s)is mass flow rate,and η is the pump efficiency.

$$\eta = \eta_{rated}\left(1-\left(1-\frac{1}{K_{np}}\frac{}{\rho_{av}Q_{rated}}\frac{\omega_{rated}}{\omega}\right)^2\right) \qquad (5)$$

whereη is the pump efficiency, η_{rated} is the pump efficiency at the rated conditions, $K_{np}$is the number of pumps in parallel and Q_{rated} is therated volumetric flow rate (m^3/s).

C. Pump Coastdown Equation

Themoment balance equation of a primary coolant pump is shown in (6).

$$I\frac{d\omega}{dt} = T_{em}(\omega) - T_h(\omega) - T_f(\omega) \qquad (6)$$

where $I\frac{d\omega}{dt}$is the rotor inertia torque, I is the moment of inertia of the pump flywheel (kg.m^2),$T_{em}(\omega)$ is the electromagnetic torque of the pump motor (N.m), $T_h(\omega)$ is the hydraulic torque (N.m), and$T_f(\omega)$ is the friction torque (N.m). The electromagnetic torque T_{em} becomes zero during a coastdown, and assuming the retarding torque is proportional to the square of the pump speed, (6) can be simplified as

$$I\frac{d\omega}{dt} + C\omega^2 = 0 \qquad (7)$$

where C is a proportional constant assuming that the steady state retarding torque (T_0) is proportional to the square of the steady state pump impeller speed (ω_0).

$$T_o = C{\omega_0}^2 \qquad (8)$$

The solution of (7) using the initial condition $\omega = \omega_0$ at t=0 is given by

$$\omega = \frac{\omega_0}{1+t\left(\frac{C\omega_0}{I}\right)} \qquad (9)$$

Equation (9) is programmed in the code blocks to calculate the pump speed during a coastdown.

D. MMS Code Blocks for Simulation of Core Decay Power and JRTR PCS Pump Coastdown

The code blocks in the models have no influence on the coolant flow rate during a steady state operation mode. MMS calculates the pressure, flow rate and enthalpy distributions solving MMS governing equations (1) and (2) based on the input system design data. The MMS PUMP module models a pump using (3) and (4) based on input data for a pump speed and input and output pressures. Code blocks containing (9) start to calculate the pump speeds with a signal of loss of off-site power accident. As the ratio between the initial and new pump speeds decreases, the new values of ΔP rise are calculated using (3). Pshaft is calculated using (4). The coolant flow rate in the models during a flow transient is calculated by solving governing (1) and (2) using new ΔP rise values calculated in the pump modules.

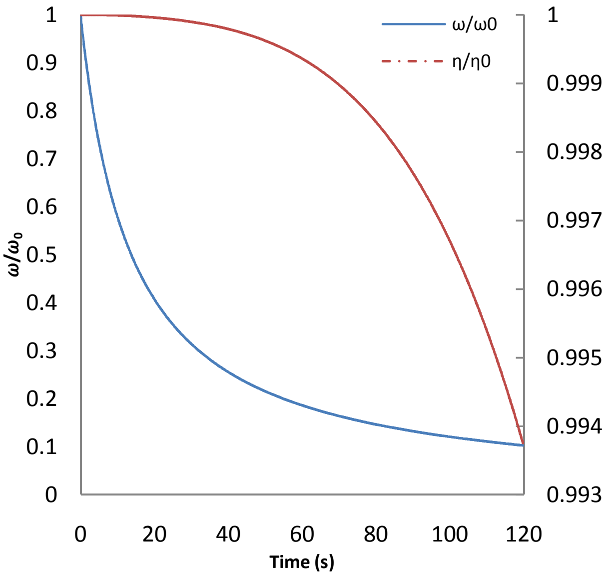

Fig. 3 Pump speed and efficiency curves during coastdown

Fig. 3 shows the pump speed and efficiency curves calculated by the code blocks and pump module during a coastdown.

V. RESULTS AND DISCUSSION

Table I shows the design data of a JRTR PCS coolant pump used as input data for a MMS PUMP Module in both models.

TABLE I
DESIGN DATA FOR A JRTR PRIMARY COOLANT PUMP

Rated Flow ($m^3.s^{-1}$)	Design Head (m)	Rated Speed (rad/s)	Moment of Inertia (kg.m^2)	Efficiency (%)	Torque (N.m)
0.092	20	101.5	30	0.8	222.23

The core decay power after a reactor trip is calculated according to the ANS-73 curve for core decay power [2] and is shown in Fig. 4.

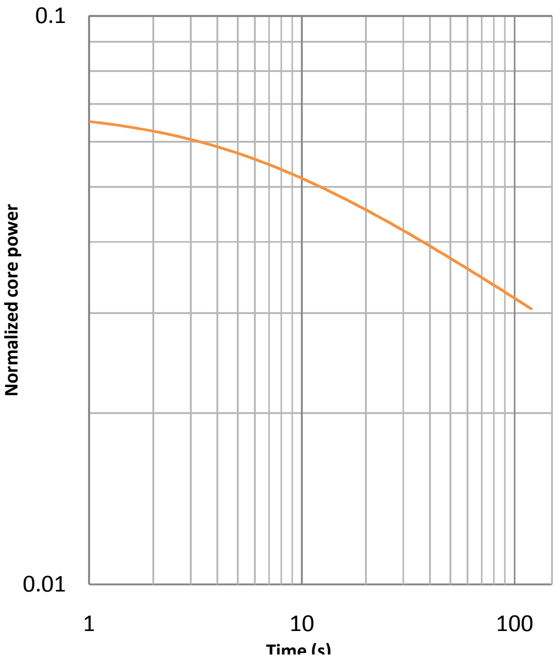

Fig.4 JRTR core power after reactor trip

When the off-site power of the JRTRis cut-off, the reactor will be tripped and the primary coolant pump will start to coastdown. Fig. 5 shows the coolant inlet and outlet transient temperatures for the reactor core during a coastdown.In this study, flap valves installed in the reactor outlet PCS pipe are not modeled because the main purpose of this study is evaluating the flywheel performance. In a real situation, the flap valves will open at around 20 seconds after the PCS pumps are off and the core flow will be reversed at around 50 seconds after the PCS pump trips. As shown in Fig. 5,the core inlet temperature (temperature of the pool water) decreases slower than the core outlet temperature. This is because, in the JRTR, a large decay tank is installed after the reactor core, and the PCS dumps the coolant into the big pool water. A reactor trip is considered only in the model for the PCS simulation,because the reactor core is not modeled in the simple model for a pump loop simulation. Fig. 6 shows a comparison of the flow coastdown curves of the two models described previously.In the MMS model for PCS simulation, the coolant flow decreases slower compared with the coolant in theMMS model for the pump loop simulation. This difference in coastdown curves is due to the influence of the PCS loop coolant inertia. The influence of the PCS loop coolant inertia is found to be small, i.e., about one second increase in coastdown half time in which the coolant flow rate decreases to half its steady state value. This is because the flywheel inertia of the PCS pump is dominant (I=30 kg.m^2) compared with the inertia of the PCS loop coolant. As can be seen in Fig. 6, the loop coolant inertia effect is greater in the early stage of a coastdown. As the coolant flow rate decreases to less than 30%of its initial value, the flow coastdown curve is mainly determined by the flywheel inertia only.

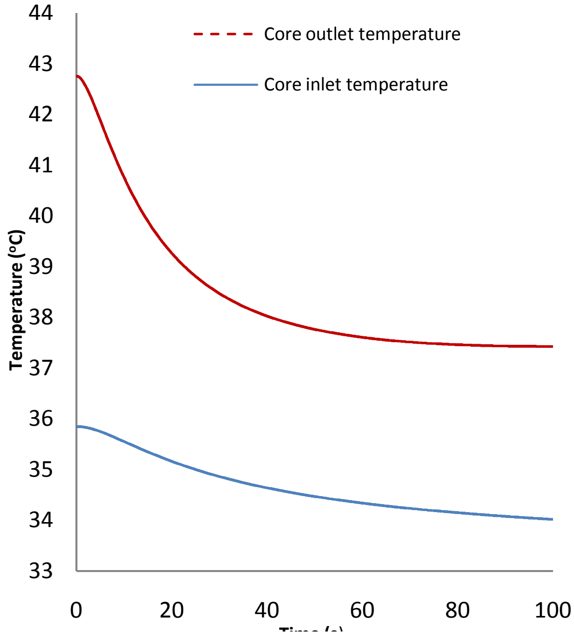

Fig. 5 Inlet and outlet core temperatures during coastdown

Fig. 7 shows the flow transient simulation results for different pump flywheel inertia during a loss-of-electricity accident in the MMS model for the PCS simulation. To study the effect of the pump flywheel size on a flow coastdown, the design data for the PCS pump in Table Iare kept constant except thevarying moment of flywheel inertia:25, 30, 35 and 40.

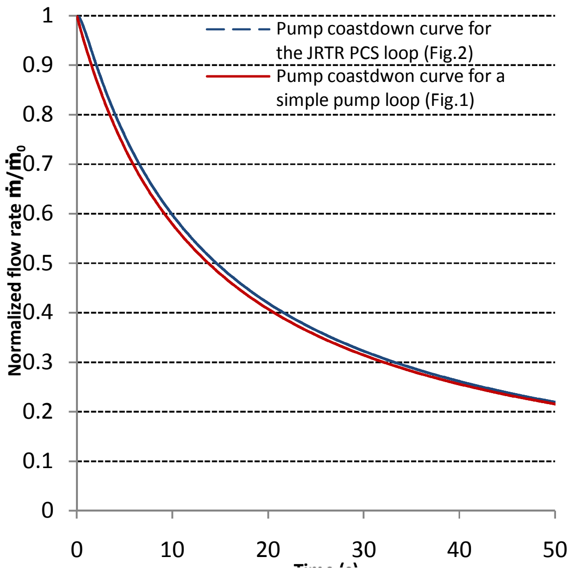

Fig. 6 Influence of the PCS loop fluid inertia on the pump coastdown curve

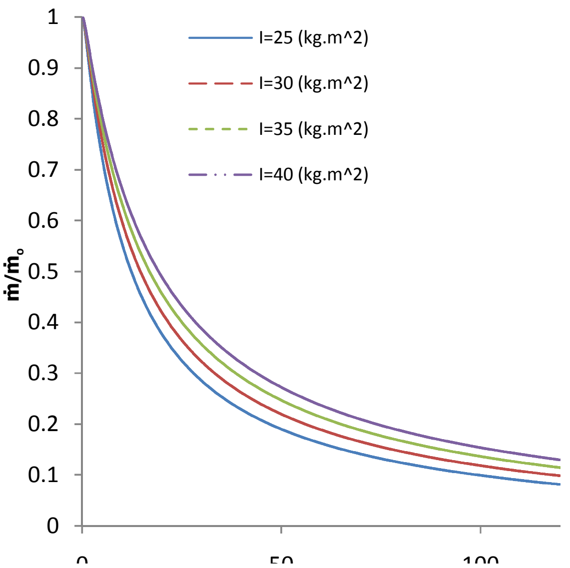

Fig. 7 PCS flow coastdown curves for different moment of flywheel inertia of the PCS pump

Fig.7shows that increasingthe moment of flywheel inertia results in a slower decrease of the primary coolant flow during a coastdown. The coastdown half time in which coolant flow rate is decreased to half its steady state value is increased when bigger flywheel sizes are used. Fig. 8 shows that the coastdown half timeincreases linearly with the moment of flywheel inertia. This linear relation can be explained using(9) to derive a formula for the half time in which the pump speed decreases to half its steady-state value ($\tau_{1/2}$):

$$\tau_{1/2} = \frac{I}{C\omega o} \qquad (10)$$

VI. Conclusion

Inertia of the pump rotating parts and inertia of the coolant fluid inside the cooling loop are the most important factors that affect the flow coastdown transients. Using two MMS models, the effect of the PCS loop coolant inertia on a flow coastdown during a loss of off-site electricity accident is investigated. Simulation results showed that the PCS loop coolantinertia effect on the coastdown curve is minor because of the dominant amount of flywheel inertia compared with the loop coolant inertia. It was confirmed that the PCS pump coastdown transient is mainly determined by the moment offlywheel inertia. The relation between the moment of flywheel inertia and the coastdown half time is found to be linear. The designed coastdown half time is confirmed to be well above the value required by the safety analysis results.

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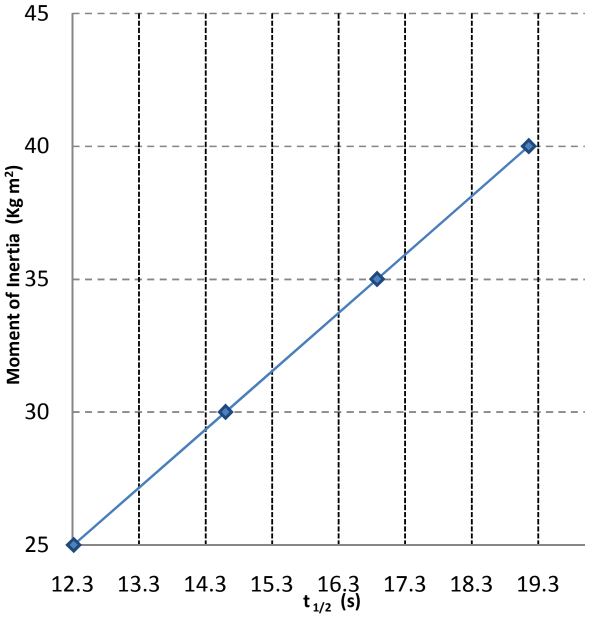

Fig. 8 Relation between moment of flywheel Inertia and coastdown half time

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