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Real-time simulation of response to load variation for a ship reactor based on point-reactor double regions and lumped parameter model

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ABSTRACT

Based on the point-reactor double regions and lumped parameter model, while the nuclear power plant second loop load is increased or decreased quickly, the Simulink calculation software (SCS) is adopted to calculate the variation of main physical and thermal–hydraulic parameters of the reactor core. The calculation results are compared with those of three-dimensional simulation program. It is indicated that the SCS can deal well with the stiff problem of the point-reactor kinetics equations and the coupled problem of neutronics and thermal–hydraulics. The high calculation precision can be reached with less time, and the quick calculation of parameters of response to load disturbance for the ship reactor can be achieved. The clear image of the calculation results can also be displayed quickly by the SCS, which is very significant and important to guarantee the reactor safety operation.

1. Introduction

The nuclear power plant (NPP) is made up of many complex systems. To safely operate the NPP seems to become more difficult than to operate the conventional fossil-fuelled power plant because of the characteristic of NPP's high temperature, intense radioactivity and large power density. Specially for the ship NPP, it often needs to change operating condition in addition to the startup and shutdown, such as frequently and quickly to load from low power to full power or to unload from full power to low power. Compared with the real reactor and experiment, the simulation software has the merits of low cost with no risk in the research process. At present, the large-scale safety analysis and simulation software for reactors, such as RELAP5 and THEATRE (The RELAP5 Code Development Team, 2001; GSE Power System, 1999) which are mostly in FORTRAN language, have been widely applied to calculate the main physical and thermal–hydraulic parameters in the NNP. But these software adopt the statement form of the input card, and they have thousands of statements only for calculating the thermal–hydraulic parameters of the reactor core. The calling program of every statement is intricate and has serious problems, such as large numbers of calculation work, strict calculation step size, discommodious manipulation interface, non-modular structure, bad readability, great difficulty of debugging and high error rate (Li et al., 2008). However, the Simulink calculation software (SCS) adopts the program form of the diagrammatic module, which has the friendly man–machine interface and very clear logic structure. Specially, the SCS includes the variable step size solver Ode15s that is suitable for treating stiff problems, so it will dispose the stiff point-reactor kinetics equations well under the condition of less total step size and calculation time, and the function of the quick calculation, even a forecast faster that real time process, can be materialized. The clear real-time image can be easily displayed by the Simulink output module to provide the variety regularity of the simulated and calculated parameters for the local reactor operators (Holzhüter, 1998; Ionescu et al., 1997), which is very important to guarantee the ship reactor safety operation.

2. Calculation model

2.1. Model for core physics

Consider the six-group delayed neutron point-reactor kinetics equations as follows:

$$\frac{dn(t)}{dt} = \frac{\rho(t) - \beta}{l} n(t) + \sum_{i=1}^{6} \lambda_i C_i(t) + q \tag{1}$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{l} n(t) - \lambda_i C_i(t) \tag{2}$$

where $n(t)$ is the reactor power, kW; $\rho(t)$ is the reactor reactivity; β is the total delayed neutron fraction for six-group; β_i is the delayed neutron fraction for group i, $i = 1, 2, \ldots, 6$; l is the average generation time of the prompt neutron, s; λ_i is the decay constant for a

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precursor group i, $i = 1, 2, \ldots, 6$, s^{-1}; $C_i(t)$ is the potential power generated by the delayed neutron precursor group i, $i = 1, 2, \ldots, 6$, kW; q is the unit time power generated by the external neutron source, kW/s.

Assuming the initial reactor state is steady and $n(0) = n_0$, $C_i(0) = C_{i,0}$, then $dC_i(t)/dt = 0$. By using the assumption and Eq. (2), we have:

$$C_{i,0} = \frac{\beta_i}{\lambda_i l} n_0 \tag{3}$$

2.2. Model for core thermal–hydraulics

After the insertion of reactivity $\Delta\rho$, the reactor power and temperature will change. Consider the temperature feedback effect as follows:

(a) the reactivity $\Delta\rho_{fe}$ by the change of average temperature of the core fuel,
(b) the reactivity $\Delta\rho_l$ by the change of average temperature of the coolant.

Based on these two types of reactivity caused by the temperature feedback effect, the double regions and lumped parameter model are adopted in this paper, i.e. taking all the fuel elements and claddings as one region and all the coolant as another. The heat created by the reactor core is transferred to the secondary side of the steam generator. The heat-transfer equations can be obtained as follows (Lewis, 1977; Tong, 1988):

$$M_{fe}C_{fe}\frac{dT_{fe}(t)}{dt} = n(t) - \frac{1}{R}[T_{fe}(t) - T_l(t)] \tag{4}$$

$$M_l C_l \frac{dT_l(t)}{dt} = \frac{1}{R}[T_{fe}(t) - T_l(t)] - 2W(t)C_l[T_l(t) - T_{l,in}(t)] \tag{5}$$

$$(M_l' C_l' + M_p C_p)\frac{dT_p(t)}{dt} = 2W(t)C_l[T_l(t) - T_{l,in}(t)] - kF[T_p(t) - T_s(t)] \tag{6}$$

$$M_c C_c \frac{dT_s}{dt} = kF[T_p(t) - T_s(t)] - N_0 \tag{7}$$

where $M_{fe}, M_l, M_l', M_p, M_c$ are the mass of the fuel elements, the core coolant, the primary loop coolant, the primary side coolant of the steam generator, the secondary side coolant of the steam generator, respectively, in kg; C_{fe}, C_l, C_l', C_p, C_c are the specific heat of the fuel elements, the core coolant, the primary loop coolant, the primary side coolant of the steam generator, the secondary side coolant of the steam generator, respectively, in kJ/(kg °C); $T_{fe}(t), T_l(t), T_p(t)$ are the average temperature of the fuel elements, the core coolant, the primary loop coolant, respectively, °C; $T_{l,in}(t)$ is the temperature of the core inlet coolant, °C; $T_s(t)$ is the saturation steam temperature of secondary side of the steam generator, in °C; R is the core heat resistance, in °C/kW; $W(t)$ is the mass flux of the core coolant, in kg/s; k, F are the heat transfer coefficient and area, respectively, in kW/(m^2 °C), m^2; and N_0 is the transported power by the secondary side steam of the steam generator, in kW. In this model, because the ship reactor analyzed in the paper is relatively small, the time delay between heat generation from the core and heat removal through the steam generators is small, and overshooting degrees of operational variables are reduced.

The inserted reactivity by the average temperature variation of the core fuel and coolant is given as follows:

$$\Delta\rho_{fe} = \alpha_{fe}[T_{fe}(t) - T_{fe,0}] \tag{8}$$

$$\Delta\rho_l = \alpha_l[T_l(t) - T_{l,0}] \tag{9}$$

where α_{fe}, α_l are the temperature coefficient of the fuel and coolant, respectively, in 1/°C; $T_{fe,0}$, $T_{l,0}$ are the initial average temperature of the fuel and core coolant, respectively, in °C.

When the reactivity $\Delta\rho$ is inserted, the real reactivity of reactor with temperature feedback is:

$$\rho(t) = \Delta\rho + \Delta\rho_{fe} + \Delta\rho_l \tag{10}$$

3. Simulink simulation

3.1. Simulation frame

Based on the point-reactor double regions and lumped parameter model built above, two types of load variations for a certain ship reactor are considered respectively, (1) loading from the operating condition I to the full power quickly, (2) unloading from the full power to the operating condition II quickly. For the ship reactor, the power is 200 MW, the mass flow rate is 800 kg/s, the operating pressure is 15 MPa. The variations of main physical and thermal–hydraulic parameters are simulated and calculated with the Simulink simulation software. Because the variation of the secondary loop load will lead to the imbalance between the heat generation and transportation, the temperature of the reactor fuel and coolant will change. The reactivity will be introduced into the reactor by the temperature feedback effect. Assuming that the variation of the differential worth, integral worth and position of every control rod are known, then the reactivity inserted by the control rod can be calculated accurately. Inputting the variation values of the reactivity and secondary loop load into the Simulink calculation software, the system simulation and calculation model can be framed as shown in Fig. 1a, which is mainly made up of four parts, the physical part, the thermal–hydraulic part, the variation part of the reactivity inserted by the control rod and the variation part of the secondary loop required power. In order to compare the results and validate the correctness of the simulation, we also employ the large-scale three-dimensional simulation software. The three-dimensional simulation software, which contains the three-dimensional physical real time simulation software, the thermal–hydraulic simulation software and the auxiliary equipment simulation software, is developed according to the characteristics of the small reactor. The three-dimensional simulation software also considers the coupling of the physical and thermal–hydraulic parameters in the reactor, see Fig. 1b.

3.2. Selection of solver and simulation step size

As an example, the secondary loop load is increased step by step from the operating condition I to the full power. The power response results, which are calculated respectively by the general differential equation solver Ode45 with 0.01 s as the max simulation step size and by the stiff equation solver Ode15s with the automatic selection simulation step size, are compared as shown in Fig. 2. From Fig. 2 it can be found that the two curves are in accord well with each other, which shows that the stiff equation solver Ode15s with the automatic selection simulation step size can obtain the satisfactory precision. In 915 simulated seconds, the general differential equation solver Ode45s needs to calculate 91,676 steps in all with the minimal simulation step size 7.2713×10^{-5} second, and the computer consumes 15.58 s. (This time may be different for different computers.) However, the stiff equation solver Ode15s only needs 0.13 s to calculate 864 steps in all with the maximal simulation step size 12.1482 s. The variation of simulation step size with time is drawn in Figs. 3 and 4 by the two different solvers. From Fig. 4, it can be found that the solver Ode15s is suitable for solving the stiff equation and can