THE STABILITY OF THE FUNDAMENTAL HARMONIC OF A REACTOR WITH A CLOSED COOLANT LOOP IN RELATION TO XENON OSCILLATIONS

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This paper discusses xenon oscillations of reactor power with due regard to their relationship with the other components of an atomic power plant.

The conditions for the stability of the fundamental harmonic (power as a whole) for a reactor with an open coolant loop were obtained in [1, 2]. In this case the temperature of the coolant on entry into the reactor is constant or, more precisely, does not depend on the reactor power. For brevity we will call this type of system an open reactor.

In practice, however, the coolant loop of a reactor is usually closed. This can alter the conditions for stability of the reactor as regards xenon oscillations in comparison with the corresponding conditions for an open reactor.

We will confine ourselves to the stability conditions for a reactor operating in a two-loop plant. For other possible systems (three-loop, for instance) the stability is analyzed in a similar manner.

In writing the equations for the various values characterizing the process we make the following assumptions:

1. Linearization of the equations is permissible.
2. The time constants of thermal processes in the reactor are small in comparison with those of thermal processes in the heat exchanger.
3. The reactivity of the reactor is determined by the mean temperature of the coolant and the Xe-135 concentration, calculated from the mean neutron flux.
4. The relationship connecting the reactivity with changes in the coolant temperature and the xenon concentration is linear.
5. The thermophysical properties and flow of the coolant in the primary and secondary loops are constant.
6. A lumped-parameter model is used.

Then for an elementary reactor

$$\delta n(s)/\delta k(s) = W_r(s), \tag{1}$$

an explicit expression for W_r can be found in [1, 2].

We note that in the case of xenon processes a good approximation is $1/W_r = 0$ (see [2]).

The relationship between the coolant temperature at the outlet of the reactor and the reactor power has the form

$$\delta t_{r.\,out}(s) = \Delta t_1 \delta n(s) + \delta t_{r.\,in}(s). \tag{2}$$

For the mean temperature of the coolant in the reactor we have

$$\delta t_{r.\,m}(s) = \frac{1}{2}\left[\delta t_{r.\,in}(s) + \delta t_{r.\,out}(s)\right] \tag{3}$$

and

$$\delta k_t(s) = \alpha_t \delta t_{p.cp}(s). \tag{4}$$

We introduce a transfer function connecting the reactor power with xenon concentration

$$\delta\rho_{Xe}(s)/\delta n(s) = W_{Xe}(s), \tag{5}$$

then the xenon reactivity is

$$\delta k_{Xe}(s) = \alpha_{Xe}\delta\rho_{Xe}(s) = \alpha_{Xe} W_{Xe}(s)\,\delta n(s). \tag{6}$$

An explicit expression for W_{Xe} is given in [1].

For simplicity we neglect the lag in the pipes of the primary loop and obtain

$$\delta t_{he.\,in}(s) = \delta t_{r.\,out}(s), \tag{7}$$

$$\delta t_{r.\,in}(s) = \delta t_{he.\,out}(s). \tag{8}$$

We also assume [in view of (7) and (8)]

$$\delta t_{he.\,out}(s)/\delta t_{he.\,in}(s) = \delta t_{r.\,in}(s)/\delta t_{r.\,out}(s) = W_{he}(s), \tag{9}$$

then from (3), (4), and (9) we obtain an expression for the temperature reactivity

$$\delta k_t(s) = \frac{\alpha_t \Delta t_1}{2}\,\frac{1 + W_{he}(s)}{1 - W_{he}(s)}\,\delta n(s). \tag{10}$$

Equations (1), (6), and (10) completely define the problem of xenon oscillations of the power of a reactor operating in a reactor plant. The characteristic equation has the form

$$1 - W_r(s)\left[\alpha_{Xe} W_{Xe}(s) + \alpha_t W_t(s)\right] = 0, \tag{11}$$

where

$$W_t(s) = \frac{\Delta t_1}{2}\,\frac{1 + W_{he}(s)}{1 - W_{he}(s)}. \tag{12}$$

Considering a specific reactor plant, we must obtain in explicit form the heat-exchanger transfer function W_{he} and, using (11), determine the conditions for stability of the reactor power.

We will confine ourselves to a determination of the effect of closure of the primary loop on the conditions for stability of the reactor power in the case of a two-loop plant. Hence, we use the simplest equations, based on a lumped parameter model, which describe the thermal processes in the heat exchanger:

$$M_1 c_1 \frac{dt_{he.\,out}}{d\tau} = G_1 c_1 t_{he.\,in} - G_1 c_1 t_{he.\,out} - kF\left(\frac{t_{he.\,in} + t_{he.\,out}}{2} - \frac{T_{in} + T_{out}}{2}\right), \tag{13}$$

$$M_2c_2\frac{dT_{out}}{d\tau}=G_2c_2T_{in}-G_2i_{out}+$$
$$+kF\left(\frac{t_{he,in}+t_{he,out}}{2}-\frac{T_{in}+T_{out}}{2}\right). \quad (14)$$

It is obvious that the entry of heat into the heat exchanger with the secondary coolant must be prescribed or determined by the corresponding equations. We assume $G_2c_2T_{in}$ = const.

We will examine two cases:

1. The removal of heat by the secondary coolant leaving the heat exchanger is proportional to its temperature,

$$G_2i_{out}=G_2c_2T_{out}, \quad (15)$$

which is the case, for instance, when the secondary loop is open.

2. The removal of heat by the secondary coolant leaving the heat exchanger is constant,

$$G_2i_{out}=\text{const}, \quad (16)$$

which is the case, for instance, if the heat consumer is a turbine with an efficiency independent of the parameters of the working substance and with an ideal regulator of the number of revolutions.

Then for case 1 from Eqs. (13)–(15) we obtain

$$W_{he}(s)=[1-a_1+a_2+s\tau_2(1-a_1)]\times$$
$$\times\{1+a_1+a_2+s[(1+a_1)\tau_2+(1+a_2)\tau_1]+s^2\tau_1\tau_2\}, \quad (17)$$

where

$$\tau_1=M_1c_1/G_1c_1; \quad \tau_2=M_2c_2/G_2c_2; \quad (18)$$

$$a_1=\frac{kF}{2G_1c_1}=\frac{\Delta t_1}{2\Delta T_{12}}; \quad a_2=\frac{kF}{2G_2c_2}=\frac{\Delta T_2}{2\Delta T_{12}}. \quad (19)$$

Similarly, from Eqs. (13), (14), and (16) for case 2 we have

$$W_{he}(s)=\frac{1+2s\tau_2^*(1-a_1)}{1+s[\tau_1+2\tau_2^*(1+a_1)]+2s^2\tau_1\tau_2^*}, \quad (20)$$

where

$$\tau_2^*=M_2c_2/kF \quad (21)$$

and τ, a_1, and a_2 are determined from (18) and (19).

For an open reactor (in the case W_{he} = 0) the conditions for stability of the fundamental harmonic are

$$\alpha_t<0, \quad |\alpha_t|>\alpha_{cr}. \quad (22)$$

In this case the critical value of the temperature coefficient of the reactivity α_{cr} depends on the reactor parameters. For a reactor, considered together with the plant, the conditions for stability have the same form as (22), but the value of α_{cr} is changed. We estimate this change by considering the limiting case $\tau_1\to 0$, $\tau_2\to 0$, and $\tau_2^*\to 0$. On these assumptions

$$W_{he}\to\frac{1-a_1+a_2}{1+a_1+a_2}=\frac{2\Delta T_{12}+\Delta T_2}{\Delta t_1} \quad (23)$$

for case 1 and

$$W_{he}\to 1 \quad (24)$$

for case 2.

Thus, in the considered limiting case the temperature feedback reactivity (10) has the same form for an open and closed reactor and the only difference lies in the value of the numerical factor $(1+W_{he})/(1-W_{he})$, which for an open reactor is equal to 1, and for a closed one is determined from expressions (23) or (24). Hence, on the basis of (10), (23), and (24) we can obtain the ratio of the α_{cr} values for a closed and open reactor:

in case 1

$$\frac{\alpha_{cr,cl}}{\alpha_{cr,op}}\to\frac{\Delta t_1}{2\Delta T_{12}+\Delta T_2}\leqslant 1, \quad (25)$$

in case 2

$$\frac{\alpha_{cr,cl}}{\alpha_{cr,op}}\to 0. \quad (26)$$

Expressions (25) and (26) show that a reactor with a closed coolant loop becomes more stable as regards xenon oscillations of power than an open one with the same parameters. The difference is particularly pronounced in case 2, where the stability of the reactor with $\tau_1=\tau_2^*=0$ requires only the negativity of the temperature coefficient of the reactivity.

For a reactor with a closed loop and where the heat withdrawal from the secondary loop is proportional to the temperature of the secondary coolant at the outlet of the heat exchanger (case 1), the effect of closure of the primary loop on the power stability is less. In comparison with an open reactor even in the case of $\tau_1=\tau_2=0$ the value of α_{cr} is reduced a finite number of times.

NOTATION

Here n denotes the relative reactor power; δk is the reactivity; W is the transfer function; t is the temperature of the primary coolant; ρ_{Xe} is the xenon concentrations; α is the reactivity coefficient; M is the mass of the coolant; c is the specific heat of coolant; G is the flow of the coolant; i is the heat content of the secondary coolant; k is the heat transfer coefficient in the heat exchanger; F is the surface of the heat exchanger; R is the temperature of the secondary coolant; Δt_1 is the steady-state heating of the coolant in the reactor; ΔT_2 is the steady-state heating of the secondary coolant in the heat exchanger; ΔT_{12} is the mean temperature difference between the primary and secondary loops in the heat exchanger in the steady-state; s is the variable transforms; δ is the deviation from the steady-state value; τ is the time. Subscripts: 1 represents the primary loop; 2 is the secondary loop; the in is the inlet; out is the outlet; r is the reactor; he is the heat exchanger; t is the temperature; Xe is xenon; cr is critical; op is open; cl is closed; m is mean.

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