The chaotic dynamics of boiling-water reactors is investigated on the basis of a one-dimensional integral model of momentum for the boiling-water channel and point equation of kinetics. It is shown that chaotic oscillations during which the sign of the coolant velocity in the boiling channel changes occur in the case of strong feedback on steam content with the parameters of the boiling channel deep in the region of instability occur in boiling-water reactors with natural and forced circulation of the coolant. It is determined that such oscillations can occur with the standard reactor arrangement when the core entrance is open for water to enter the core and for back circulation of the coolant as well as with an arrangement where the entrance is half open – closed for back circulation of the coolant. A numerical calculation of the chaotic oscillations is performed. The mechanism of pulsed chaos is described. Regions of stability and stochasticity are separated in the plane of the parameters characterizing the underheating of water to the saturation temperature at the entrance to the reactor and stationary average steam content in the core. One-dimensional point mappings determining the chaotic dynamics of the boiling water reactor are constructed. The properties of the mappings and the bifurcation of their stationary points are investigated.

Chaotic oscillations of the density and velocity of two-phase flow in boiling-water heated channels, including in the channels of boiling-water reactors, are investigated in [1–10].

A very simplified model of a boiling-water reactor is studied in [1, 2]; the model uses point equations of kinetics and a system of three ordinary differential equations to describe thermohydraulic processes in a reactor and the density feedback on reactivity. It is determined that as the coefficient of feedback on the steam content increases, the stationary regime of the reactor becomes unstable and stable periodic oscillations arise in the reactor and are replaced by chaotic oscillations according to Feigenbaum’s scenario via a cascade of period-doubling bifurcations.

It is shown in [3] that the chaotic density oscillations of a two-phase flow arise with periodic variation of the pressure differential on the channel.

A mechanism for chaos in boiling channels that is different from that in [1, 2] is found and investigated in [4, 5]. It occurs with natural circulation of the coolant when a long unheated section where there is a large underheating of the water at the channel entrance up to the saturation temperature and low steam content in the channel is present. Here, in contrast to [1, 2], chaos is not associated with the interaction of the neutron-physical and thermohydraulic processes and can occur even with a constant heat flux in the coolant.

The mechanism of chaos found in [1, 2] is confirmed in [6–9] using more complex models, where one-dimensional distributed equations of heat-and-mass transfer are used to describe the thermohydraulic process in the boiling channels.

We note that only self-oscillation during which the coolant velocity at the channel entrance does not change sign are studied in [4–9]. They occur when the parameters of the reactor are not too far from the boundary of the region of stability of the stationary regime.
In [10], it was determined for the first time that in the case of sufficiently strong feedback on the steam content there arise pulsed stochastic regimes with reversal of the coolant circulation at the entrance into the reactor arise when the coolant parameters are deep in the region of instability. Circulation reversal occurs at moment of the neutron pulses when the coolant, heated and boiled up as a result of the pulse, is displaced from the core through the core entrance and exit. Self-quenching neutron pulses occur when the reactor reaches instantaneous criticality. A thorough study of such regimes is a topical problem, since their appearance in boiling-water reactors could turn out to be admissible and desirable [10]. Specifically, by allowing such regimes it is possible to increase the dimensions and power of boiling water reactors substantially [10].

In the present work, new results are presented concerning the study of chaotic oscillations during which the sign of the coolant velocity changes in the boiling channel. New cases where such oscillations arise are found – a reactor with forced circulation of the coolant, which remains unstable with feedback on steam content switched off (with constant neutron density), and a reactor with a half-open entrance, when the entrance into the core is open allowing water to flow into the core and closed for back flow of the coolant. Regions of stochasticity are separated for the first time in the plane of parameters characterizing the underheating of water at the entrance into the reactor to saturation temperature and the stationary average steam content in the core. How the neutron pulses, the number of oscillations of the variables between pulses (time interval between pulses), occurring during the chaotic oscillations, change when these parameters change is investigated. The characteristics of impulsive chaos in boiling-water reactors, whose dynamics is described by a complicated nonlinear distributed model, are investigated for the first time; this is reduced to an analysis of the properties of specially constructed one-dimensional point mapping.

The investigations are performed within a one-dimensional integral momentum model for a boiling channel and point equations of kinetics. The results are obtained by a direct computer calculation of the self-oscillations, numerical construction of diagrams of the maxima and minima of a reactor variable which occur during the oscillations, as well as numerical construction of one-dimensional mappings and bifurcation analysis of their stationary points.

**Mathematical Model of a Reactor.** The core of height \( H \) and the immediately following unheated thrust of height \( H_1 \) will be represented as a single equivalent channel. Assuming the pressure drop over the channel to be small compared with the pressure set at the exit, which we shall assume to be constant and equal to \( P_0 \), and no phase slip, we write the equation of conservation of energy and the equation of continuity for an equilibrium steam–water mixture as follows:

\[
\frac{\partial i}{\partial t} + u \frac{\partial i}{\partial z} = q v; \quad i(0, t) = i_0 \quad \text{for} \quad u(0, t) > 0; \tag{1}
\]

\[
\frac{\partial u}{\partial z} = \frac{q v}{\partial i}, \tag{2}
\]

where \( i, u, \) and \( v \) are, respectively, the enthalpy, velocity, and specific volume of the steam–water mixture; \( q \) is the heat flux; \( i_0 \) is the coolant enthalpy at the entrance into the reactor; \( t \) is the time; \( z \in [0, H + H_1] \); the point \( H \) corresponds to the exit from the core and the start of the pulling section; and the point \( H + H_1 \) is the exit of the thrust section.

The specific volume of the coolant is assumed to depend only on the enthalpy:

\[
v(i) = \begin{cases} v' \quad \text{for} \quad i < i'; \\ v' + (v'' - v')(i - i')(i'' - i') \quad \text{for} \quad i > i'. \end{cases} \tag{3}
\]

where \( i', i'', v', \) and \( v'' \) are the enthalpy and specific volume of the water and steam on the saturation line at pressure \( P_0 \). The volume steam content \( \varphi = 0 \) at \( v = v' \), \( \varphi = 1 \) for \( v > v'' \), and

\[
\varphi = \frac{(v'' - v')(v - v')}{(v'' - v')} \quad \text{for} \quad v' < v < v''. \tag{4}
\]

The boundary condition on the coolant velocity for Eqs. (1), (2) is the equation of conservation of momentum integrated over the length of the channel:

\[
d \frac{d}{dt} \left[ \int_0^{H+H_1} (u/v) \, dz \right] + u^2 \sqrt{\int_0^{H+H_1} (g - v) \, dz} + \int_0^{H+H_1} |\lambda_d(z)u| |u|/(2v) \, dz = P_{in} - P_{out}. \tag{5}
\]

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