National Research University

"Moscow Power Engineering Institute"«MPEI»

PRESENTATION :

THE DYNAMIC MODELS OF WATER-WATER NUCLEAR REACTOR WITH TEMPERATURE REACTIVITY COEFFICIENTS AND DISSIPATION

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DEAR COLLEAGUES!

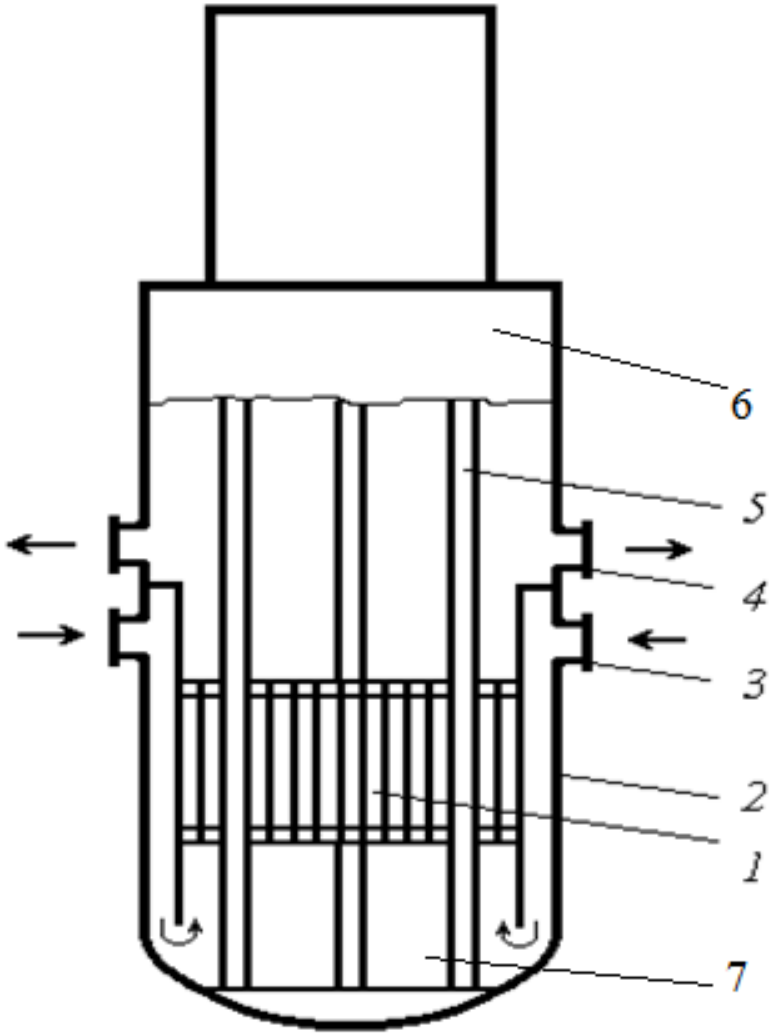
“The dynamic models with temperature reactivity coefficient for reactor type WWER and with dissipation” to water in the reactor are developed here. Unlike conventional engineering models with concentrated parameters and one group of delayed neutrons, in the work takes into account: the fluid and heat flow parameters distribution of the active zone height, six groups of delayed neutrons, the impact on the processes of inactive metal, water volumes below and above the active area. The transfer functions across all major channels are obtained.

INTRODUCTION

Limited opportunities for obtaining experimental dynamic characteristics of the reactors for the synthesis of automatic control systems have led to the need to develop analytical models. The automatic control theory methods are oriented to the linear models (or a set of linear models), are given by their transfer functions. On the one hand, these models must be as simple as possible, on the other hand, they should be adequate, i.e. reflecting all important properties for the control object. The dynamic models of WWER reactor with temperature reactivity coefficients and distributed or concentrated parameters were derived. However, these models do not take into account the effect of dissipation — the part of heat, emitting directly in the heat-transfer-agent, which is associated with the neutron flux slowdown in its.

The task of accounting dissipation and assessment of its influence on the reactor dynamic characteristics is set in this paper.

The model of reactor WWER



1 — active zone;
2 —housing (corpus);
3 — input of heat-transfer agent;
4 — output of heat-transfer agent;
5 — pipes for control driving
6 — water volume above the active zone;
7 — water volume under the active zone;

Reactor WWER

The deferent systems with 5 physical elements

- $$\frac{1}{N_0}\left(\frac{d\Delta N_0}{dt}\right)=\frac{1}{\beta}\left[\left(\frac{d\Delta k}{dt}\right)+\lambda\Delta k\right];$$
- $$\rho_{\text{fel}}c_{\text{fel}}\delta_{\text{fel}}\frac{\mathrm{d}\Delta\vartheta_{\text{fel}}}{\mathrm{d}t}=0.9\Delta q_{\text{r}}-\alpha(\Delta\vartheta_{\text{fel}}-\Delta\theta);$$
- $$\tau\frac{\partial\Delta\theta}{\partial t}+\frac{\partial\Delta\theta}{\partial z_{\text{n}}}+(\text{St}+\text{St}_{\text{v}})\Delta\theta=\frac{0.1\Delta q_{\text{r}}H}{D\ c_{\text{P}}}+\text{St}\,\Delta\vartheta_{\text{fel}}+\text{St}_{\text{v}}\,\Delta\vartheta_{\text{v}};$$
- $$T_{\text{v}}\frac{\partial\Delta\vartheta_{\text{v}}}{\partial t}+\Delta\vartheta_{\text{v}}=\Delta\theta;$$
- $$\tau_{\text{un}}\frac{\mathrm{d}\Delta\theta^{\text{ini}}}{\mathrm{d}t}+\Delta\theta^{\text{ini}}+\text{St}_{\text{un}}\Delta\theta^{\text{ini}}=\Delta\theta_{\text{in}}+\text{St}_{\text{un}}\Delta\vartheta_{\text{un}};$$
- $$T_{\text{v}}\frac{\partial\Delta\vartheta_{\text{un}}}{\partial t}+\Delta\vartheta_{\text{un}}=\Delta\theta^{\text{ini}};$$
- $$\tau_{\text{ab}}\frac{\mathrm{d}\Delta\theta_{\text{out}}}{\mathrm{d}t}+\Delta\theta_{\text{out}}+\text{St}_{\text{ab}}\Delta\theta_{\text{out}}=\Delta\theta^{\text{end}}+\text{St}_{\text{ab}}\Delta\vartheta_{\text{ab}};$$
- $$T_{\text{v}}\frac{\partial\Delta\vartheta_{\text{ab}}}{\partial t}+\Delta\vartheta_{\text{ab}}=\Delta\theta_{\text{out}}.$$

Distributed (DP) model of reactor pre-conducted system relatively the double

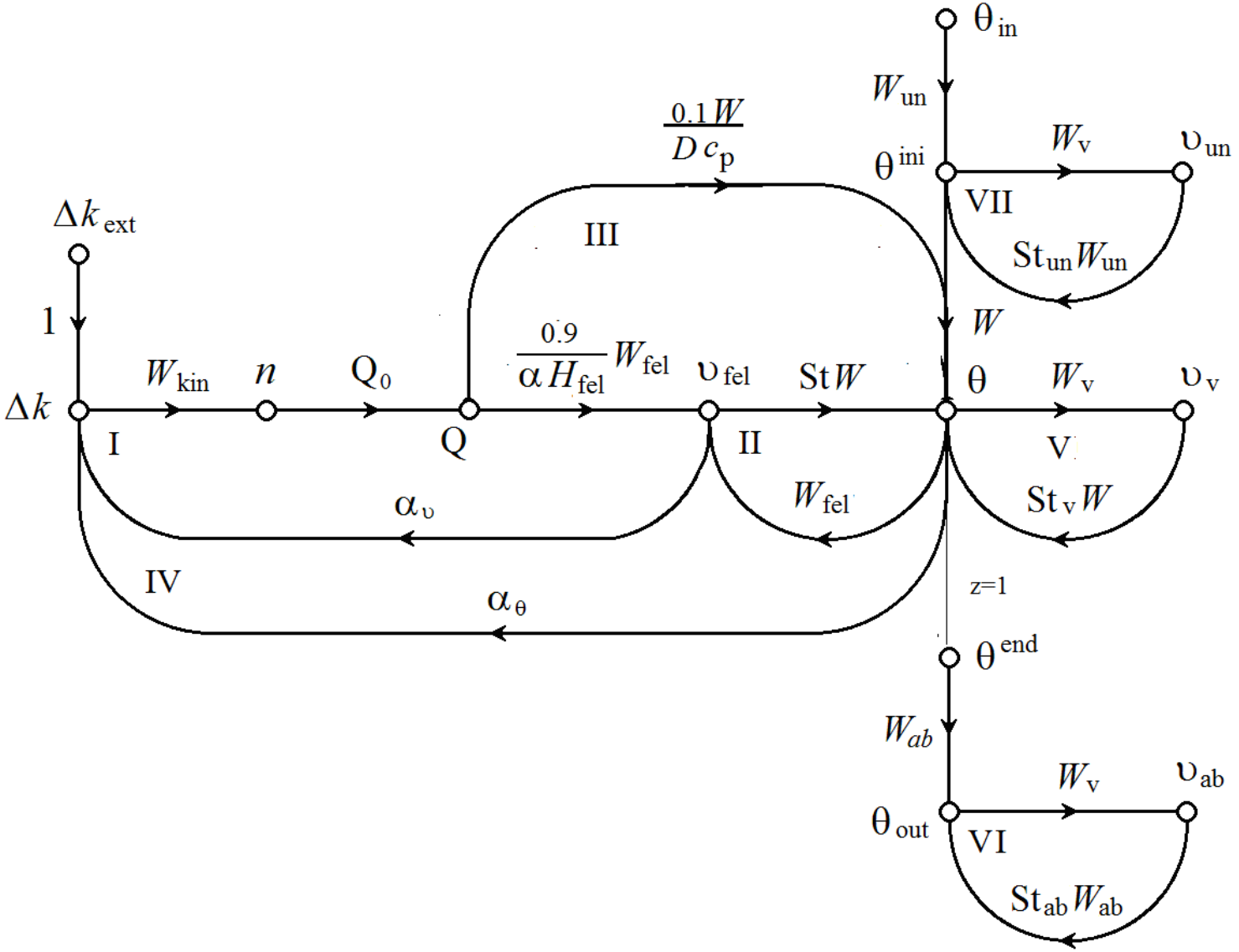
- $Q(p,s) = Q_0 n(p,s);$
- $q_{\mathrm{p}}(p,s) = \dfrac{Q_0}{H_{\mathrm{fel}}} n(p,s)\ ;$
- $k(p,s) = k_{\mathrm{ex}}\ (p,s) + \alpha_{\vartheta}\vartheta_{\mathrm{fel}}(p,s) + \alpha_{\theta}\theta(p,s)\ ;$
- $n(p) = W_{kin}(p)\Delta k(p);$
- $\vartheta_{\mathrm{fel}}(p,s) = \dfrac{0.9}{\alpha} W_{\mathrm{fel}}(p) q_{\mathrm{p}}(p,s) + W_{\mathrm{fel}}(p)\theta(p,s);$
- $\theta(p,s) = W(p,s)\theta^{\mathrm{ini}}(p) + \mathrm{St} W(p,s)\vartheta_{\mathrm{fel}}(p,s) + \mathrm{St}_{\mathrm{v}} W(p,s)\vartheta_{\mathrm{v}}(p,\mathrm{s}) + \dfrac{0.1}{D\, c_{\mathrm{P}}} W(p,s)\mathrm{Q}(p,s);$
- $\vartheta_{\mathrm{v}}(p,s) = W_{\mathrm{v}}(p)\theta(p,s);$
- $\theta^{\mathrm{ini}}(p) = W_{\mathrm{un}}(p)\theta_{\mathrm{in}}(p) + \mathrm{St}_{\mathrm{un}} W_{\mathrm{un}}(p)\vartheta_{\mathrm{un}}(p);$
- $\vartheta_{\mathrm{un}}(p) = W_{\mathrm{v}}(p)\theta^{\mathrm{ini}}(p);$
- $\theta_{\mathrm{out}}(p) = W_{\mathrm{ab}}(p)\theta^{\mathrm{end}}(p) + \mathrm{St}_{\mathrm{ab}} W_{\mathrm{ab}}(p)\vartheta_{\mathrm{ab}}(p);$
- $\vartheta_{\mathrm{ab}}(p) = W_{\mathrm{v}}(p)\theta_{\mathrm{out}}(p).$

The parameters of Distributed (DP) model of reactor pre-conducted system relatively the double transform of Laplace equation.

- $W_{\text{kin}}(p)=\dfrac{1}{lp+\sum_{i=1}^{6}\dfrac{\beta_i p}{p+\lambda_i}}$;
- $W_{\theta\vartheta_{\text{fel}}}(p)=W_{\text{fel}}(p)=\dfrac{1}{T_{\text{fel}}p+1}$; $\quad T_{\text{fel}}=\dfrac{\rho_{\text{fel}}c_{\text{fel}}\delta_{\text{fel}}}{\alpha}$;
- $W(p,s)=\dfrac{1}{\tau p+s+(\text{St}+\text{St}_{\text{v}})}$; $\quad \tau=\dfrac{V\rho_0}{D_0}$; $\text{St}=\dfrac{\alpha H}{c_P D_0}$; $\text{St}_{\text{v}}=\dfrac{\alpha_{\text{v}}H_{\text{v}}}{c_P D_0}$
- $W(p)=\dfrac{1}{\tau p+(1+\text{St}+\text{St}_{\text{v}})}$;

- $W_{\text{v}}(p)=\dfrac{1}{T_{\text{v}}p+1}$; $\quad T_{\text{v}}=\rho_{\text{v}}c_{\text{v}}\delta_{\text{v}}/\alpha_{\text{v}}$;
- $W_{\text{un}}(p)=\dfrac{1}{\tau_{\text{un}}p+1+\text{St}_{\text{un}}}$; $\quad \text{St}_{\text{un}}=\dfrac{\alpha_{\text{v}}H_{\text{un}}}{c_P D_0}$; $\tau_{\text{un}}=\dfrac{V_{\text{un}}\rho_{\text{un}}}{D_0}$;
- $W_{\text{ab}}(p)=1/(\tau_{\text{ab}}p+1+\text{St}_{\text{ab}})$; $\quad \tau_{\text{ab}}=\dfrac{V_{\text{ab}}\rho_{\text{ab}}}{D_0}$; $\text{St}_{\text{ab}}=\dfrac{\alpha_{\text{v}}H_{\text{ab}}}{c_P D_0}$

Signal graph model with temperature coefficients of reactivity



Mason's gain formula

$$G = \frac{y_{\text{out}}}{y_{\text{in}}} = \frac{\sum_{k=1}^{N} G_k \Delta_k}{\Delta}$$

$$\Delta = 1 - \sum L_i + \sum L_i L_j - \sum L_i L_j L_k + \cdots + (-1)^m \sum \cdots + \cdots$$

Where :

Δ = the determinant of the graph.

y_{in} = input-node variable

y_{out} = output-node variable

G = complete gain between y_{in} and y_{out}

N = total number of forward paths between y_{in} and y_{out}

G_k = path gain of the kth forward path

L_i = loop gain of each closed loop in the system

L_iL_j , $L_iL_jL_k$= product of the loop gains of any two,three non-touching loops

Δ_k = the cofactor value of Δ for the k^{th} forward path, with the loops touching the k^{th} forward path removed

Transfer functions of five interconnected loops

- $K_{\text{I}}(p) = W_{\text{kin}}(p)\dfrac{0.9Q_0}{\alpha H_{\text{fel}}}W_{\text{fel}}(p)\alpha_{\vartheta}$;
- $K_{\text{II}}(p,s) = \text{St}\,W(p,s)W_{\text{fel}}(p)$;
- $K_{\text{III}}(p,s) = W_{\text{kin}}Q_0(p)\dfrac{0.1}{D\,c_{\text{P}}}W(p,s)\alpha_{\theta}$;
- $K_{\text{IV}}(p,s) = W_{\text{kin}}(p)\dfrac{0.9Q_0}{\alpha H_{\text{fel}}}W_{\text{fel}}(p)\text{St}\,W(p,s)\alpha_{\theta}$;
- $K_{\text{V}}(p,s) = \text{St}_{\text{v}}\,W(p,s)W_{\text{v}}(p)$.

The transfer function of the channel "external reactivity Δk — density neutron flux n"

$$W_{\Delta k n}(p,s)=\frac{W_{\text{kin}}(p)\Delta_n(p,s)}{\Delta(p,s)}$$

$$\Delta(p,s)=1-K_{\text{I}}(p)-K_{\text{II}}(p,s)-K_{\text{III}}(p,s)-K_{\text{IV}}(p,s)-K_{\text{V}}(p,s)+K_{\text{I}}(p)K_{\text{V}}(p,s),$$

$$\Delta_n(p,s)=1-K_{\text{II}}(p,s)-K_{\text{V}}(p,s)$$

By substitution of two-dimensional transfer function

$$W_{\Delta k n}(p,s)=\frac{W_{\text{kin}}(p)}{1-K_{\text{I}}(p)}\frac{s+B(p)}{s+A(p)}$$

where

$$B(p)=\tau p+\text{St}\left[1-W_{\text{fel}}(p)\right]+\text{St}_{\text{v}}\left[1-W_{\text{v}}(p)\right],$$

$$A(p)=\tau p+\text{St}+\text{St}_{\kappa}-\text{St}\left[\frac{W_{\text{fel}}(p)}{1-K_{\text{I}}(p)}-\frac{W_{\text{kin}}(p)Q_0}{1-K_{\text{I}}(p)}\left(\frac{0.1}{Dc_{\text{P}}}+\frac{0.9W_{\text{fel}}(p)}{\alpha H_{\text{fel}}}\right)\alpha_{\theta}\right]-\text{St}_{\text{v}}W_{\text{v}}(p).$$

The transfer function of the channel "external reactivity Δk — density neutron flux n"

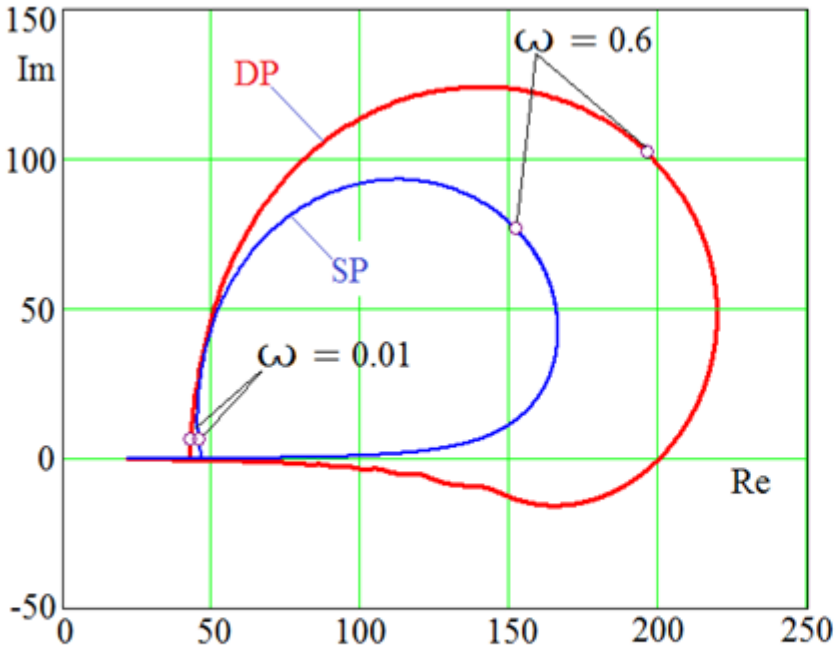
Perform an inverse Laplace transforms relatively argument *s*, taking into account the distribution in height of external reactivity, and finally get the ordinary expression of the transfer function DP-model of the considered channel

$$W_{\Delta k n}(p,z)=\frac{W_{\text{kin}}(p)}{1-K_{\text{I}}(p)}\left\{\frac{B(p)}{A(p)}+\left[1-\frac{B(p)}{A(p)}\right]\cdot e^{-A(p)z}\right\}$$

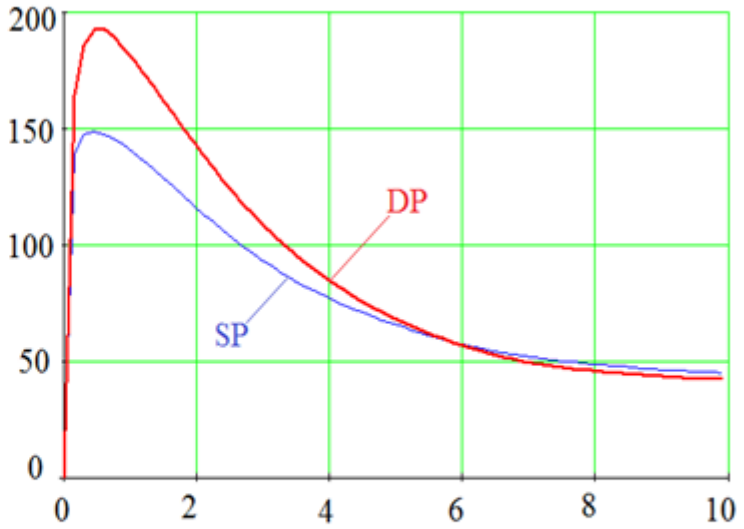
For SP model, we adopt *s* =1 and transfer function like that

$$W_{\Delta k n}(p,s)=\frac{W_{\text{kin}}(p)}{1-K_{\text{I}}(p)}\,\frac{1+B(p)}{1+A(p)}$$

Complex frequency characteristics (CFC) and time response function of channel "external reactivity — neutron flux density"



CFC of channel "external reactivity — neutron flux density"



Time response function of channel "external reactivity — neutron flux density"

The transfer functions of the channel "external reactivity Δk - coolant temperature θ "

$$W_{\Delta k\theta}(p,s)=\frac{W_{\text{kin}}(p)Q_0\left[\frac{0.9}{\alpha H_{\text{fel}}}W_{\text{fel}}(p)\,\text{St}+\frac{0.1}{Dc_{\text{p}}}\right]}{1-K_{\text{I}}(p)}\,\frac{1}{s+A(p)}$$

Take into account that with the assumptions made double Laplacian image of the input is

$$\Delta k_{\text{ext}}(p,s)=\frac{\Delta k_{\text{ext}}(p)}{s}$$

Transfer function of DP-model

$$W_{\Delta k\theta}(p,z)=\frac{W_{\text{kin}}(p)Q_0\left[\frac{0,9}{\alpha H_{\text{fel}}}W_{\text{fel}}(p)\,\text{St}+\frac{0.1}{Dc_{\text{p}}}\right]}{1-K_{\text{I}}(p)}\left[\frac{1}{A(p)}\left(1-\text{e}^{-A(p)z}\right)\right]$$

The transfer function of the channel "external reactivity — outlet water temperature"

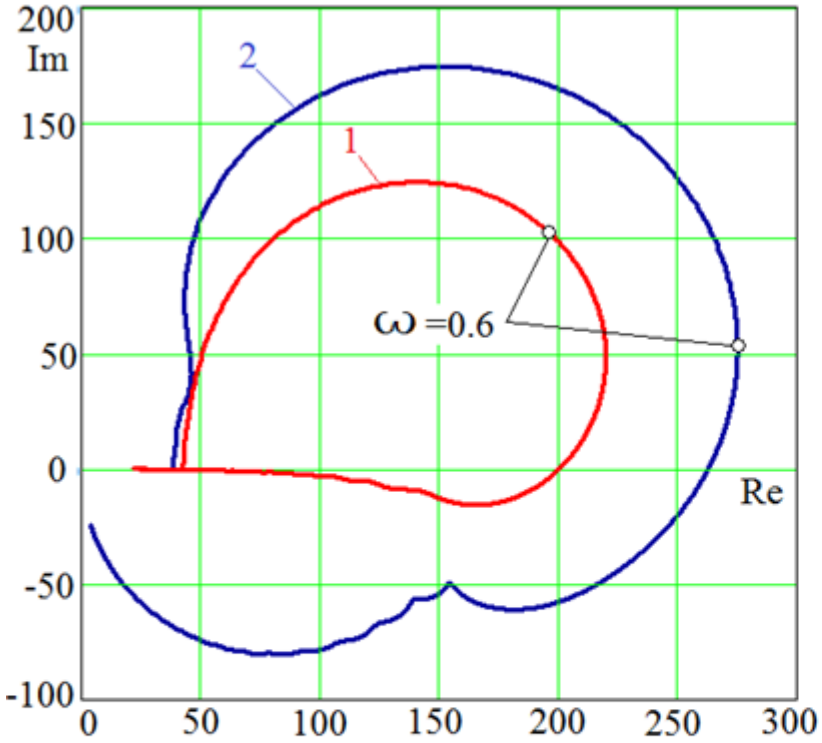
The transfer function for the temperature of the coolant in the end of the active zone where z = 1

$$W_{\Delta k\theta}(p,1) = W_{\Delta k\,\theta^{\text{end}}}(p) = \frac{W_{\text{kin}}(p)Q_0\left[\frac{0{,}9}{\alpha H_{\text{fel}}}W_{\text{fel}}(p)\ \text{St} + \frac{0.1}{Dc_{\text{p}}}\right]}{1 - K_{\text{I}}(p)}\left[\frac{1}{A(p)}\left(1 - \text{e}^{-A(p)}\right)\right]$$

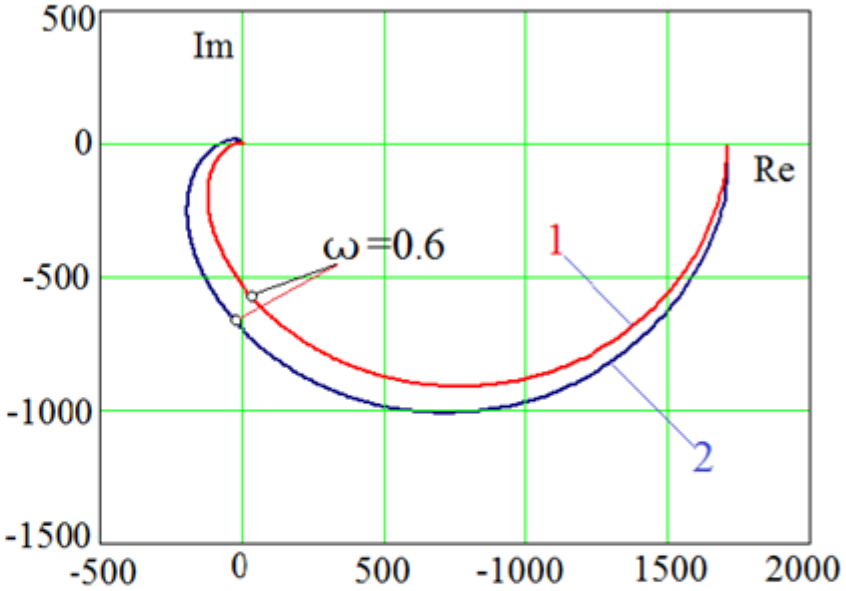
The transfer function of the DP-model for the channel "temperature of the water that enters the reactor θ^{in} — water temperature at the outlet of the reactor θ^{out} :

$$W_{\Delta k\,\theta_{\text{out}}}(p) = \frac{W_{\text{ab}}(p)}{1 - \text{St}_{\text{ab}}W_{\text{ab}}(p)W_{\text{v}}(p)}W_{\Delta k\,\theta^{\text{end}}}(p)$$

Models comparison on the WWER-1000 example



CFC DP models of the channel
"external reactivity —neutron flux density":
1 — model with dissipation
2 — model without dissipation



CFC DP models of the channel
"external reactivity— outlet water temperature":
1 — model with dissipation
2 — model without dissipation

CONCLUSION

Unlike conventional engineering models of the dynamics in this work the obtained models with distributed along the height of the active zone parameters of fluid and heat flow from the reaction of fission. To improve the accuracy taken the kinetics model with six groups of delayed neutrons, takes into account the effect on process inactive metal (measuring channels, vessel, screen etc). Adding descriptions of volumes of water below and above the active area allowed us to obtain a model of the entire reactor, and not only his active zone.

A variant of the feedback by the temperature of the fuel elements and heat-transfer-agent, with or without dissipation is looked here. Using double Laplace transform theory and signal graphs, transfer functions on the main channels, necessary for the synthesis of automatic control systems of thermal load WWER-1000 power are received.

The influence of dissipation and parameters' distribution on the dynamic characteristics are revealed. These models have the same extreme views, but at the extremum value of the DP model anymore. Calculation results show that for the automatic control synthesis of the power unit thermal load it is advisable to take a model with distributed parameters DP, because CP models have unacceptable errors in a significant range of frequencies.

The effect of dissipation should be considered if control system is designed for the basic mode of power unit because in basic mode the density of the neutron flux is stabilized. For synthesis in variable mode power unit, the final decision on account of dissipation can be taken only by the results of the joint modeling reactor-steam generator-control system.

THANKS FOR YOUR ATTENTION