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Study of temperature distribution of fuel, clad and coolant in the VVER-1000 reactor core during group-10 control rod scram by using diffusion and point kinetic methods

Mahammad Rahgoshay, Yashar Rahmani

Abstract. In this paper, through the application of two different methods (point kinetic and diffusion), the temperature distribution of fuel, clad and coolant has been studied and calculated during group-10 control rod scram, in the Bushehr Nuclear Power Plant (Iran) with a VVER-1000 reactor core. In the reactor core of Bushehr NPP, 10 groups of control rods are used of which, group-10 control rods contain the highest amount of injected negative reactivity in terms of quantity as compared to other groups of control rods. In this paper we explain impacts of negative reactivity, caused by a complete or minor scram of group-10 control rods, on thermoneutronic parameters of the VVER-1000 nuclear reactor core. It should be noted that through these calculations and by using the results, we can develop a sound understanding of impacts of this controlling element in optimum control of the reactor core and, on this basis, with careful attention and by gaining access to a reliable simulation (on the basis of results of calculations made in this survey) we can monitor the VVER-1000 reactor core through a smart control system. In continuation, for a more accurate survey and for comparing results of different calculation systems (point kinetic and diffusion), by using COSTANZA-R,Z calculation code (in which neutronic calculations are based on diffusion model) and using WIMS code at different areas and temperatures (for calculation of constant physical coefficients and temperature coefficients needed in COSTANZA-R,Z code) for the VVER-1000 reactor core of Bushehr NPP, calculation of temperature distribution of fuel elements and coolant by using diffusion model is made in the course of group-10 control rods scram and afterwards.

Key words: point kinetic • diffusion • COSTANZA-R,Z • VVER-1000 • control rod • RELAP5

Introduction

Through the application of a point kinetic method [1, 4], we can study changes of thermoneutronic parameters in the VVER-1000 reactor core of Bushehr Nuclear Power Plant (Iran) irrespective of space and merely as a time function. But, in the diffusion method [7] by modeling the Bushehr reactor core through COSTANZA-R,Z calculation code, a study of temperature distribution in fuel, clad and coolant will take place as combined spatial-time functions.

In Fig. 1 we schematically explain the applied calculative flow chart (by using point kinetic model).

Procedure

First, we explain the process of calculation of total thermal power of the Bushehr VVER-1000 reactor core by using a point kinetic model. Obviously, the total thermal power is the sum of immediate fission power, decay heat power and power resulted by decay of actinides [1, 4]. By ignoring a comprehensive and descriptive explanation of solving the equations for each mentioned components, we will only suffice to mentioning equations and basic correlations that are used in our calculations.

M. Rahgoshay, Y. Rahmani✉
Department of Nuclear Engineering,
Faculty of Engineering,
Science and Research Branch,
Islamic Azad University,
Tehran, Iran,
Tel.: 009821 44817166, Fax: 009821 44817194,
E-mail: yashar.rahmani@gmail.com

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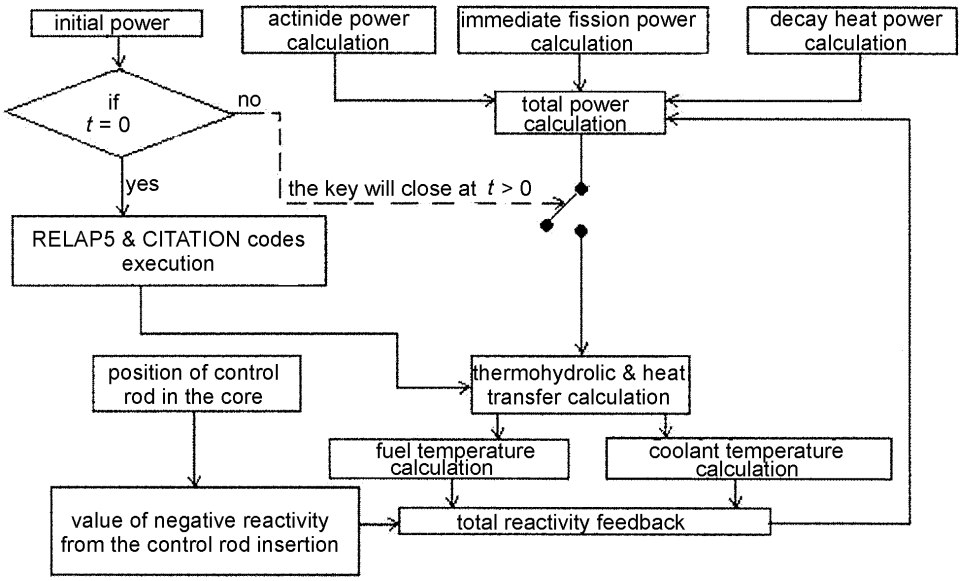

Fig. 1. Applied calculative flow chart by using point kinetic model.

By simplifying and using substitutions, equations will be changed to the following final form [1, 4]:

$$(1)\quad \frac{d}{dt}\Psi'(t)=\frac{\beta}{\Lambda}\left[\left[r(t)-1\right]\Psi'(t)+\sum_{i=1}^{N_d} f_i W_i(t)+S'\right]$$

$$(2)\quad \frac{d}{dt}W_i(t)=\lambda_i\Psi'(t)-\lambda_i W_i(t)$$

$$(3)\quad \frac{d}{dt}Z_j(t)=\lambda_{\alpha_j}\Psi'(t)-\lambda_{\alpha_j}Z_j(t)$$

$$(4)\quad \frac{d}{dt}Z_U(t)=\lambda_U\Psi'(t)-\lambda_U Z_U(t)$$

$$(5)\quad \frac{d}{dt}Z_N(t)=F_U Z_U(t)-\lambda_N Z_N(t)$$

and the total thermal power of the reactor core will be calculated by using the following equation:

$$(6)\quad P_T(t)=Q_f\Psi'(t)+G(t)\sum_{\alpha=1}^{3}\sum_{j=1}^{N_\alpha}\frac{F_\gamma a_{\alpha_j}F_\alpha Z_{\alpha_j}(t)}{\lambda_{\alpha_j}}+F_U\eta_U Z_U(t)+\eta_N\lambda_N Z_N(t)$$

Substitution parameters that are used in the above equations (for convenience solution) are defined as follows [1, 4]:

$$(7)\quad \Psi(t)=\Sigma_f\varphi(t)$$

$$(8)\quad \Psi'(t)=X\Psi(t)$$

$$(9)\quad W_i(t)=\frac{X\Sigma_f C_i(t)\Lambda\lambda_i}{\beta f_i}$$

$$(10)\quad Z_U(t)=\frac{X\gamma_U(t)\lambda_U}{F_U}$$

$$(11)\quad Z_{\alpha_j}(t)=\frac{X\gamma_{\alpha_j}(t)\lambda^2_{\alpha_j}}{F_\gamma a_{\alpha_j}F_\alpha}$$

$$(12)\quad Z_N(t)=X\gamma_N(t)$$

$$(13)\quad S'=\frac{X\Sigma_f\Lambda S}{\beta}$$

$$(14)\quad r(t)=\frac{\rho(t)}{\beta}$$

$$(15)\quad G(t)=1.0+(3.24\times10^{-6}+5.23\times10^{-10}t)\,T^{0.4}\Psi_g$$

The parameters used in equations are defined as follows: Λ – prompt neutron generation time; $\rho(t)$ – reactivity (only the time dependences has been indicated; f_i – fraction of delayed neutrons of group i; F_α – fraction of fissions from isotope α; C_i – number of delayed neutron precursors of group; β – effective delayed neutron fraction; $\lambda\alpha_j$, α_{α_j} – decay constants as obtained from ANS-1979; Σ_f – macroscopic fission cross-section (cm^{-1}); Ψ_g – number of fission vs. initial fissile atoms; F_U – number of atoms of ^{239}U produced by neutron capture in ^{238}U per fission from all isotopes; T – reactor operation time (s); η_U, η_N – the rate of energy released by decay of ^{239}U, ^{239}Np (MeV); φ – neutron flux (#/cm^2·s); Q_f – immediate fission energy per fission in MeV; F_γ – input factor to allow easy specification of a conservative calculation; t – time (s); λ_i – decay constant of group i of delayed neutrons.

Considering that prior to the group-10 control rod scram, in a lengthy period of time, the reactor has been operating at a stable power, therefore, due to the stable and balanced state, for solving equations we use the following initial conditions [1, 4]:

$$(16)\quad W_i(0)=\Psi'(0),\quad i=1,2,3,\ldots,N_d$$

$$(17)\quad Z_{\alpha_j}(0)=\Psi'(0),\quad \alpha=1,2,3;\ i=1,2,3,\ldots,N_\alpha$$

(18) $$S' = -r(0)\Psi'(0)$$

(19) $$Z_N(0) = \frac{F_U}{\lambda_N}\ \Psi'(0)$$

(20) $$Z_U(0) = \Psi'(0)$$

The total energy produced as a result of fission (Q), is calculated by using the following correlation:

(21) $$Q = Q_f + \sum_{\alpha=1}^{3}\sum_{j=1}^{N_a} F_\gamma a_{\alpha_j} F_\alpha + F_U\eta_U + F_U\eta_N$$

and the total power at the initial time is calculated through the following equation:

(22) $$P_T(0) = \begin{bmatrix} Q_f + G(0)\sum_{\alpha=1}^{3}\sum_{j=1}^{N_a}\frac{F_\gamma a_{\alpha_j} F_\alpha}{\lambda_{\alpha_j}} \\ +F_U\eta_U + \eta_N F_U \end{bmatrix}\Psi'(0)$$

by knowing that Q = 200 MeV, we can replace the parameters in correlation (21) and thereby calculate Q_f, and, in continuation, with regard to the fact that the total thermal power is 3000 MW_{th} at the initial calculation moment, therefore, by parametric replacing in correlations (22), the $\psi'(0)$ parameter is thereby calculated.

Now, in continuation, by using a finite difference method in solving Eqs. (1), (2), (3), (4) and (5) and applying initial conditions, we can calculate total thermal power and neutronic parameters of the Bushehr VVER-1000 reactor core at any time step, by using the point kinetic neutronic model.

It should be noted that the amount of $r(0)$ parameter is also considered as being zero for the reason that at the time of scram, the reactor is in its stable mode.

Now, in order to complete the calculation cycle shown in the flow chart of Fig. 1, the reactivity feedback model, which is used in calculations of this study work, is hereby explained.

With regard to the following feedback equation:

(23) $$r(t) = r_0 - r_B + r_{cr}^{(t)} + r_{Br}^{(t)} + W_\rho R_\rho\left(\rho(t) + a_{\text{cool}}T_{\text{cool}}(t) + W_F R_F(T_{\text{fuel}}(t))\right) + a_F T_{\text{fuel}}(t)$$

where: r_0 – reactivity corresponding to assumed steady-state reactor power at t = 0; r_B – bias reactivity; $r_{cr}(t)$ – time dependent control rod reactivity insertion; $r_{Br}(t)$ – boric acid reactivity; W_ρ – density weighting factor; W_F – fuel temperature weighting factor; R_ρ – reactivity as a function of current density of water; a_F – fuel temperature coefficient; R_F – reactivity as a function of fuel temperature; a_{cool} – coolant temperature coefficient and by considering the Final Safety Analysis Report of ATOMENERGOPROEKT Institute [2] (the Russian manufacturer company of VVER-1000 reactor in Bushehr NPP), for measuring the amount of injected negative reactivity according to the height of group-10 control rod scram, by applying the parameter of speed at the time of control rod scram, we managed to create a rational relation between the height of injection of the control rods and the factor of time.

Here, we explain the heat transfer process used for calculating temperature distribution in this study work.

By using the first thermodynamic law and writing down energy equation for control volumes considered for fuel, clad and coolant elements [3, 5, 6], we will have:

(24) $$M_f C_f = \frac{\partial T_f}{\partial t}\ P - 4\pi K_f L_{tot}\left(T_{\text{fuel}_{in}}(t) - T_{\text{fuel}_{out}}(t)\right)$$

(25) $$M_{\text{clad}}C_{\text{clad}}\frac{\partial t_{\text{clad}}}{\partial t} = \left(t_{\text{fuel}_{out}}(t)T_{\text{clad}_{in}}(t)\right)(2\pi R_{\text{gap}}h_{\text{gap}}L_{tot}) - \left(T_{\text{clad}_{out}}(t) - T_{\text{cool}_{ave}}(t)\right)\cdot(2\pi h_{\text{cool}}R_{co}L_{tot})$$

(26) $$M_{\text{cool}}C_{\text{cool}}\frac{dT_{\text{cool}}}{dt} = \dot{m}_{\text{cool}}C_{\text{cool}}\left(T_{\text{cool}_{in}}(t) - T_{\text{cool}_{out}}(t)\right) + h_{\text{cool}}A\left[T_{\text{clad}_{out}}(t) - T_{\text{cool}}(t)\right] + \dot{m}\left(Z_{in} - Z_{out}\right) + \frac{1}{2}\dot{m}_{\text{cool}}\left[\frac{\dot{m}_{\text{cool}}}{A_2^2}\left(\frac{1}{\rho_{in}^2} - \frac{1}{\rho_{out}^2}\right)\right]$$

in which, by ignoring details about solving energy balance equations for each control volumes, we only sufficed to explain the final equations.

M_{clad} – total mass of clad (kg); A_2 – total area of outer surface of clad; C_{clad} – clad specific heat capacity; M_f – total mass of fuel (kg); L_{tot} – total length of fuel rods (m); C_f – fuel specific heat capacity; M_{cool} – total mass of coolant (kg); $T_{\text{fuel}_{in}}$ – central fuel temperature; A – area of coolant passing through the channel; ρ_{in} – coolant density at the core inlet state; ρ_{out} – coolant density at the core outlet state; Z_{in} – height of core lower boundary; Z_{out} – height of core upper boundary.

However, for solving the above-mentioned equations by using the finite difference method, we needed to calculate the initial temperatures at the time when calculations started, and the process for the said calculations is as follows.

For calculating temperature of the coolant at the initial calculation moment, by applying CITATION and RELAP5 calculation codes, we calculated the total thermal power in 10000 sub-volumes in axial direction of the reactor core. Then by applying correlation (27) in each sub-volumes and with regard to the fact that the amount of temperature of the incoming coolant to the reactor core is 291°C and other parameters used in Eq. (27) are known, we calculated temperature of the coolant in the first sub-volume (at the initial moment of calculations) as follows:

(27) $$P = \dot{m}C_{\text{cool}}[T_{\text{cool}}(0) - T_{\text{cool}_{in}}]$$

Now, after completing all calculations in the first sub-volume by using the following correlation:

(28) $$T_{out}(t) = 2T_{\text{cool}_{ave}}(t) - T_{in}$$

We calculate temperature of the coolant at the outgoing point of the sub-volume, and by replacing it in the next sub-volume as the temperature of the incoming coolant, repeat the calculations and continue the process until

we reach the 10,000th sub-volume, and finally by volumetric integration we calculate the average temperature of the coolant at the initial time of calculations.

Here, after calculating temperature of the coolant at the initial calculation moment, by using the DITTUS BOELTER thermohydraulic model, we calculate h_{coolant} parameter and thereby calculate temperature of the outer surface of the clad at the initial moment (start of calculations) by using the following correlation [6]:

$$(29) \quad T_{\text{clad}_{out}}(0) = \frac{q_0'}{2\pi R_{co} H_{\text{cool}}(0)} + T_{\text{cool}_{ave}}(0)$$

In the next step, by using the following formula, we calculate average temperature of the clad at the initial calculation time [6]:

$$(30) \quad T_{\text{clad}_{ave}}(0) = q_0' \left(\frac{1}{2\pi R_{co} h_{\text{cool}}} + \frac{\ln\left(\frac{R_{co}}{R_{ci}}\right)}{4\pi K_{\text{clad}}} \right) + T_{\text{cool}}(0)$$

Temperature of the inner surface of the clad is calculated through the following correlation [6]:

$$(31) \quad T_{\text{clad}_{in}}(0) = q_0' \left(\frac{1}{2\pi R_{co} h_{\text{cool}}} + \frac{\ln\left(\frac{R_{co}}{R_{ci}}\right)}{2\pi K_{\text{clad}}} \right) + T_{\text{cool}}(0)$$

Temperature of the outer surface of fuel will be calculated by using the following equation [6]:

$$(32) \quad T_{\text{fuel}_{out}}(0) = q_0' \left(\frac{1}{2\pi R_{\text{gap}} h_{\text{gap}}} + \frac{1}{2\pi R_{co} h_{\text{cool}}} + \frac{\ln\left(\frac{R_{co}}{R_{ci}}\right)}{4\pi K_{\text{clad}}} \right) + T_{\text{cool}}(0)$$

It should be noted that by using the results of FSAR [2] report and by applying DIGITIZER 3.3[1)] software, we can find out the accurate heat conduction coefficient of gap according to the linear power changes, and by placing it in Eq. (32) we can easily calculate temperature of the outer surface of fuel.

In the next step, considering correlation (33), we calculate average fuel temperature in the following way [6]:

$$(33) \quad T_{\text{fuel}_{ave}}(0) = \frac{0.5 q_0'}{4\pi K_f} + T_{\text{fuel}_{out}}$$

[1)] Digitizer 3.3 is a type of software which by taking a picture of a curve capable to give all the points on the curve (x,y) with high precision. It should be noted that this software produced by Mark Mitchell Marisoft Company in 1997, and has been used for receiving experimental data relevant to h_{gap} from the chart about gap conductance according to linear power of the reactor that existed in FSAR of Bushehr NPP [2].

And, as the final stage, we use the following correlation in order to calculate the central temperature of fuel at the initial moment:

$$(34) \quad T_{\text{fuel}_{in}}(0) = \frac{q_0'}{4\pi K_f} + T_{\text{fuel}_{out}}(0)$$

Now, after completing temperature calculations at the initial moment, by applying the finite difference method for calculations in Eqs. (24), (25) and (26), and with regard to changes in reactor's linear power (caused by group-10 control rods scram) and by taking into consideration impacts of contraction in clad and fuel elements and using Eqs. (29) up to (34), (on time-change basis), we can calculate fuel, clad and coolant temperature during group-10 control rod scram of the Bushehr VVER-1000 reactor.

In Fig. 2 of the applied flow chart, the process of heat transfer calculations has been shown by using the Control Volume Model which has been used in this paper and was earlier explained.

In the final stage of this research work and by using COSTANZA-R,Z calculation code [7] and thereby modeling Bushehr reactor core, we calculate thermo-neutronic parameters by using diffusion calculation method.

To this end, first, by using WIMS [8] calculation code and applying it to different zones of the reactor core (at different temperatures), including fuel assemblies with the enrichment of 1.6, 2.4 and 3.62%, the reflector zone and control rods, we calculate the required physical constants in COSTANZA-R,Z code and thereby obtain the quadruplet temperature coefficient for each physical constant at each different zone of the reactor core (which are needed in modeling by using COSTANZA-R,Z code).

As we already know, we can show temperature dependence of different physical constants in the form of an expanded equation (with the help of Taylor series) [7]

$$(35) \quad C = C_0 + \alpha(T_{\text{fuel}} - T_{\text{fuel}_0}) + \beta(T_{\text{coolant}} - T_{\text{coolant}_0}) + \gamma(T_{\text{fuel}} - T_{\text{fuel}_0})^2 + \delta(T_{\text{coolant}} - T_{\text{coolant}_0})^2$$

where: $\alpha, \beta, \gamma, \delta$ – temperature coefficients; C – physical constant value (at T_{fuel}, T_{coolant}); C_0 – physical constant initial value (at T_{fuel_0}, T_{coolant_0}); T_{fuel}, T_{coolant} – new values of fuel and coolant temperature values; T_{fuel_0}, T_{coolant_0} – reference temperatures related to fuel and coolant.

Now, as an example, we define the calculation method (for obtaining the quadruplet temperature coefficient) for the fast diffusion parameter (D_f) in the fuel assembly zone with 1.6% enrichment.

By applying WIMS calculation code [8] in this zone at 5 different temperatures, we calculate the amount of D_f in these 5 temperature samples and place them in 4 equations with 4 unknown quantities and then complete calculations as follows:

$$(36) \quad D_{f_1} = D_{f_0} = \alpha(T_{\text{fuel}_1} - T_{\text{fuel}_0}) + \beta(T_{\text{coolant}_1} - T_{\text{coolant}_0}) + \gamma(T_{\text{fuel}_1} - T_{\text{fuel}_0})^2 + \delta(T_{\text{coolant}_1} - T_{\text{coolant}_0})^2$$

$$(37) \quad D_{f_2} = D_{f_0} = \alpha(T_{\text{fuel}_2} - T_{\text{fuel}_0}) + \beta(T_{\text{coolant}_2} - T_{\text{coolant}_0}) + \gamma(T_{\text{fuel}_2} - T_{\text{fuel}_0})^2 + \delta(T_{\text{coolant}_2} - T_{\text{coolant}_0})^2$$

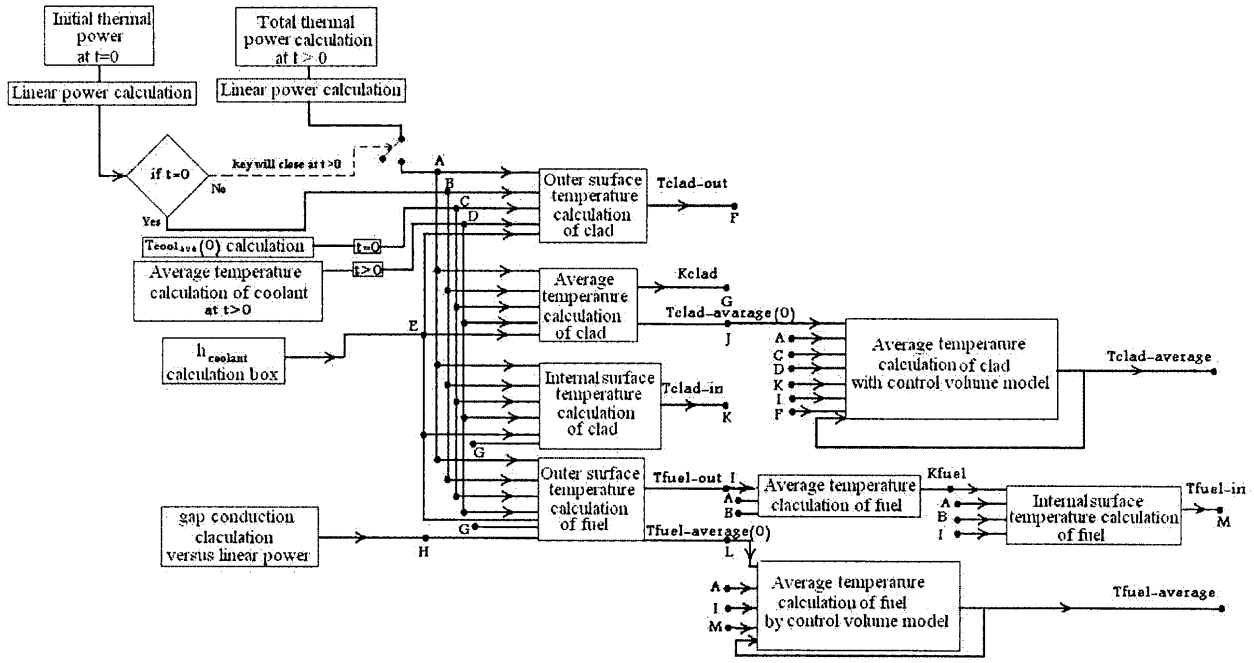

Fig. 2. Applied flow chart for heat transfer calculation in this paper by using control volume thermohydraulic model.

$$(38)\quad D_{f_3} = D_{f_0} = \alpha(T_{\text{fuel}_3} - T_{\text{fuel}_0}) + \beta(T_{\text{coolant}_3} - T_{\text{coolant}_0}) + \gamma(T_{\text{fuel}_3} - T_{\text{fuel}_0})^2 + \delta(T_{\text{coolant}_3} - T_{\text{coolant}_0})^2$$

$$(39)\quad D_{f_4} = D_{f_0} = \alpha(T_{\text{fuel}_4} - T_{\text{fuel}_0}) + \beta(T_{\text{coolant}_4} - T_{\text{coolant}_0}) + \gamma(T_{\text{fuel}_4} - T_{\text{fuel}_0})^2 + \delta(T_{\text{coolant}_4} - T_{\text{coolant}_0})^2$$

With the complimentary calculations and programming, which have been conducted in line with this research work, temperature coefficient of different physical constants (at different zone of the reactor core) will be calculated through a smart system and then will be linked to COSTANZA-R,Z code. In order to better define the calculation process, we explain the calculation flow chart according to diffusion model by using COSTANZA-R,Z code in Fig. 3.

By doing these sub-calculations (in line with applying COSTANZA-R,Z code) and modeling reactor core (within the framework of diffusion calculation) through the relevant code, we compare results for temperature distribution obtained through application of this model with results obtained from calculations through using Point Kinetic Model. Results obtained from the said two models are shown in Figs. 4 to 10.

Results

In charts 4 to 10, rates for temperature changes of different elements of fuel, clad and coolant during the time that group-10 control rod scram and afterwards are shown by using the two point kinetic and diffusion calculation methods.

With regard to the experimental data provided by FSAR report [2], some 3.52 s will last till the control

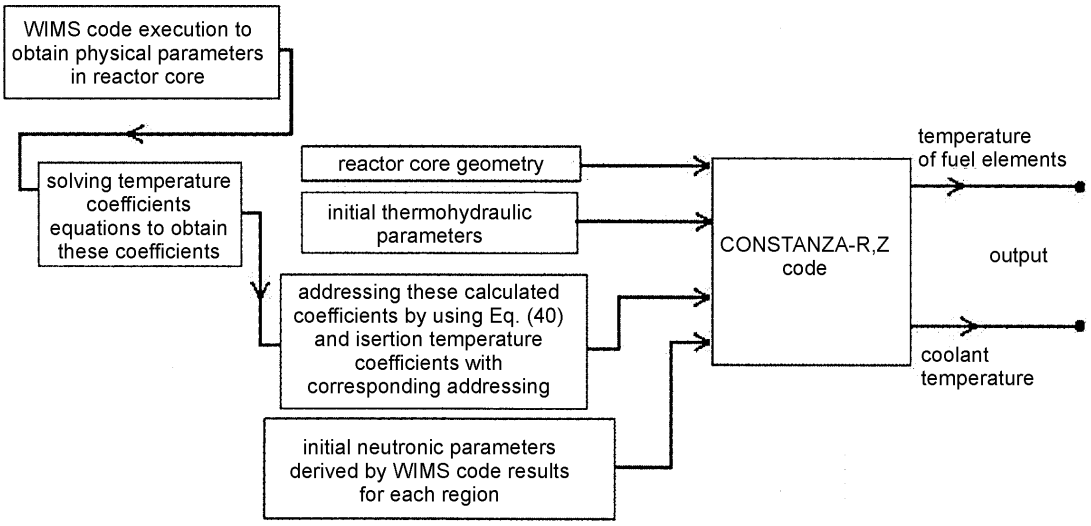

Fig. 3. Flow chart for calculating thermoneutronic parameters according to diffusion model by using COSTANZA-R,Z code.

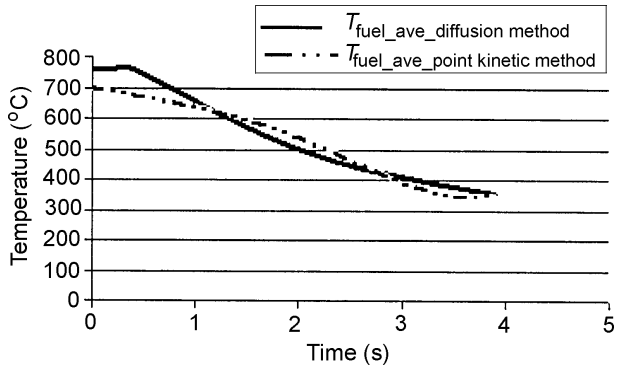

Fig. 4. Comparison of results of average fuel pellet temperature (diffusion and point kinetic methods).

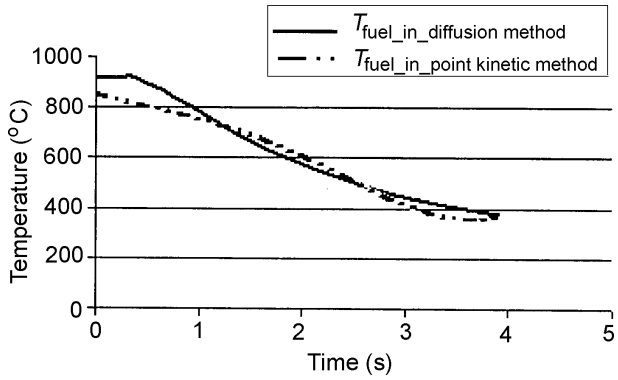

Fig. 5. Comparison of results of inner fuel pellet temperature (diffusion and point kinetic methods).

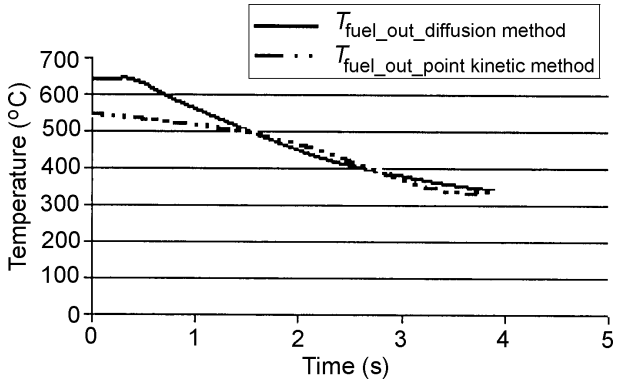

Fig. 6. Comparison of results of outer fuel pellet temperature (diffusion and point kinetic methods).

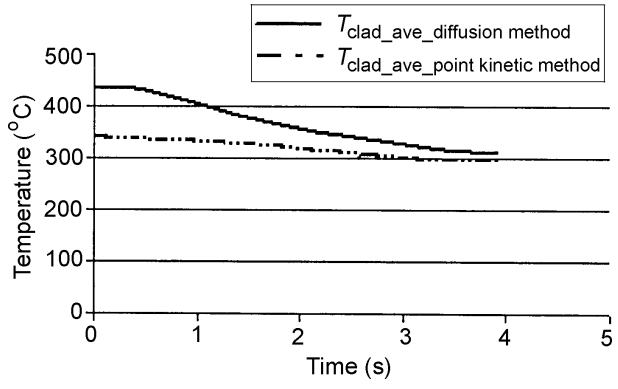

Fig. 7. Comparison of results of average temperature of clad (diffusion and point kinetic methods).

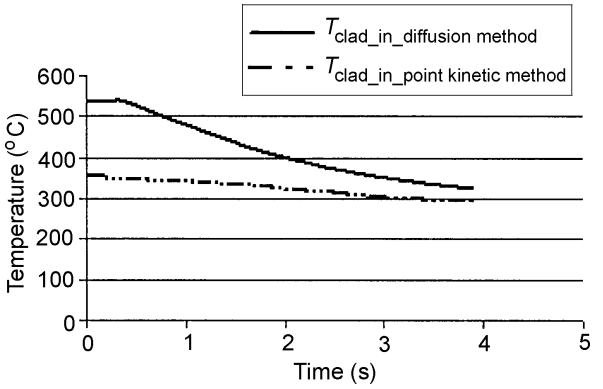

Fig. 8. Comparison of results of internal temperature of clad (diffusion and point kinetic methods).

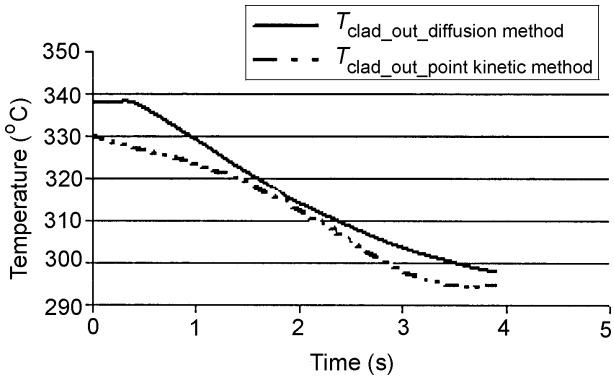

Fig. 9. Comparison of results of external temperature of clad (diffusion and point kinetic methods).

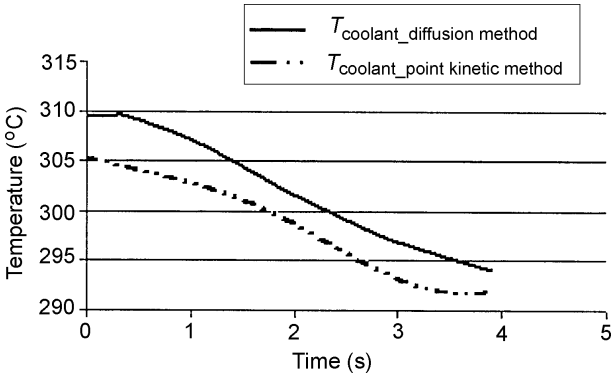

Fig. 10. Comparison of results of temperature of coolant (diffusion and point kinetic methods).

rods in group-10 scram into the reactor core and given that at the beginning of calculations 10% of the height of the rods is inside the reactor core, therefore, the time span will reduce to 3.168 s (the velocity of group-10 control rods scram = 1 m/s) [2].

In order to increase the accuracy of calculations, the span for each time step has been calculated at 0.000001 s, which slow down the computer calculations. Therefore, with regard to the fact that this research work aims to study temperature distribution in fuel and coolant elements during the scram of group-10 control rods, we sufficed to continuing calculations until to 4 s.

Conclusion

By doing the calculations and applying the obtained results we can develop a sound understanding of impacts of the injected negative reactivity caused by group-10 control rod scram in optimum control of the reactor core and on that basis, and by having access to a reliable modeling (according to the results of calculations available in this survey) we can carefully control the VVER-1000 reactor core through a smart system. By comparing results of the two calculation models – point kinetic and diffusion (Figs. 4 to 10) – we find out that the rate of temperature changes in fuel, clad and coolant are similar to each other to a great extent. Considering that the two applied models – point kinetic and diffusion – are different from each other, the similarity in the results of the two neutronic models further prove authenticity of the calculations and results gained thereby in this survey.

It should be noted that based on the results of the above-mentioned calculations, we can find out impacts of different parameters such as fuel elements contraction, negative reactivity caused by group-10 control rod scram and temperature feedback reactivity caused by fuel and clad, on the thermoneutronic parameters of VVER-1000 Bushehr nuclear reactor core.

Study of COSTANZA-R,Z programming, and the method of heat transfer calculation, has shown that this code is weak in terms of calculation of gap conduction coefficient and that accurate results cannot be achieved by this code in h_{gap} calculations with regard to weak estimation on impacts of thermal contraction of fuel and clad as well as other parameters. The difference shown in comparing temperature results of inner surface of the clad in these two calculation methods is due to ignoring these important factors in COSTANZA-R,Z programming which increases the average temperature and the inner surface temperature of clad in COSTANZA-R,Z code as compared to results obtained through point kinetic calculations.

At least this important point should be brought into attention here that point kinetics is a simple model of reactor core neutronic calculations, but by optimizing authenticity of the required initial calculations in this neutronic model, the results showed a suitable rate of accuracy.

In conclusion, it is proposed that in order to increase accuracy of calculations of VVER-1000 reactor core with the diffusion model, the number of available energy groups in neutronic calculations should be increased to a multiple group system and a more accurate modeling of the reactor core geometry should be applied in neutronic calculations. Meanwhile, a more advanced model should be used in the calculation of gap convention coefficient.

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