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The software for simulating the operation of the spherical nuclear reactor

Danila Zaronov[1], *Ivan* Provorny[1], *Ivan* Chumakov[1], *Mariia* Pokushko[1,2,3,4*], and *Margarita* Karaseva[1,2]

[1]Reshetnev Siberian State University of Science and Technology, Department of System Analysis and Operations Research, 660037, 31, Krasnoyarsky Rabochy av., Krasnoyarsk, Russian Federation
[2]Siberian Federal University, Department of Digital Management Technologies, 660041, 79, Svobodny av., Krasnoyarsk, Russian Federation
[3]University of Cadiz, Department of Computer Engineering, 11519, 10, street University of Cadiz, Puerto Real, Spain
[4]BITS Pilani K. K. Birla Goa Campus, Department of Mathematics, 403726, NH17B, Bypass Road, Sancoale, Zuarinagar, Goa, India

Abstract. The paper presents simulation of the processes of starting, operating and stopping a spherical nuclear reactor. A software package was developed. This makes it possible to visualize reactor's dynamics and evaluate its characteristics. Mathematical models describing the behavior of the reactor in various operating modes were investigated. Key physical processes were analyzed, such as neutron generation and diffusion, heat transfer, and control rod dynamics. Parameters affecting the stability and safety of the system's operation were identified. Methods for using the model for design, analysis and training in the field of nuclear energy are identified.

1 Introduction

Nuclear reactors are central to modern energy systems, providing stable and efficient energy production. In an era of striving to decarbonize the economy and search for alternatives to traditional energy sources, nuclear energy remains one of the most promising fields. Since the internal processes occurring in nuclear reactors are very complex, in-depth analysis is a necessary to ensure their safe and reliable operation. Therefore, computer simulation of nuclear reactors has become an indispensable tool for their design, control and analysis.

Modern nuclear reactors operate through a controlled nuclear chain reaction accompanied by the release of a huge amount of energy. This is possible due to the interaction of neutrons with atomic nuclei which leads to their division and the release of new neutrons. Physical and engineering parameters of the system, such as neutron concentration, heat transfer, and power handling, must be extremely precise tuned to maintain a stable reaction. All these aspects complicate the manual calculation of reactor parameters. It makes simulation to be an important tool.

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* Corresponding author: mvp1984@mail.ru

Digitalization of control processes becomes more involved in our everyday lives every year. A great number of processes have already been simulated as a digital twin such as enterprise processes, education, etc.

Simulation of nuclear reactors makes it possible not only to predict their behavior under various conditions, but also to optimize operating parameters, ensure safety and develop new approaches to their control. The application of mathematical models and specialized software helps engineers and scientists gain a deeper understanding of processes such as neutron generation and diffusion, core heat transfer, and the effects of control rods. Moreover, simulation allows testing emergency scenarios, predicting their consequences and developing prevention mechanisms.

The aim of this work is to create a software package for simulating processes of starting, operating and stopping a spherical nuclear reactor applying mathematical methods and algorithms in the Python language.

The following tasks are solved to achieve this goal:

1. development of the mathematical model describing the main physical processes in the reactor, including: generation and diffusion of neutrons; heat transfer and control of coolant temperature; motion of control rods.
2. model implementation in the form of program code applying modern programming tools.
3. visualization of key parameters (temperature, neutron concentration, rod immersion depth) to demonstrate the dynamics of reactor's operation;
4. estimation of the control parameters' influence on the stability and safety of the reactor.

2 Theory

The structure of the reactor includes the following basic elements:

- chamber surrounded by a protective shell where nuclear fuel and a neutron moderator are placed;
- control rods, moved by the engine, regulating the intensity of the reaction by absorbing excess neutrons;
- coolant pumped through the core that transfers then thermal energy to water vapor to rotate the turbine.
- control system that monitors the reactor's operation with temperature and radioactivity sensors. The control system regulates the rods' immersion depth based on signals from the sensors.

The reactor operates on the basis of a nuclear chain reaction when the fission of atomic nuclei is accompanied by the emission of neutrons and the release of energy. The mass of fuel must exceed the critical mass to start the reaction. Immediate and delayed neutrons are released during the nuclear fission process. Control rods can be applied to slow down or speed up this reaction.

Nuclear fuel is loaded into the reactor so that its mass exceeds the critical value. A nuclear chain reaction starts. In average, $K = 2.5$ neutrons are formed as a result of the absorption of a neutron by the nucleus and its fission. After nuclear fission, 99% of neutrons appear immediately. They are called immediate neutrons. The rest are emitted in some time (10-50 seconds) after one or two beta decays of the resulting fission fragments. Some of neutrons are captured by other nuclei, which also causes them to be divided. Control rods are introduced into the active zone to absorb neutrons to reduce the intensity of the nuclear reaction [1, 2].

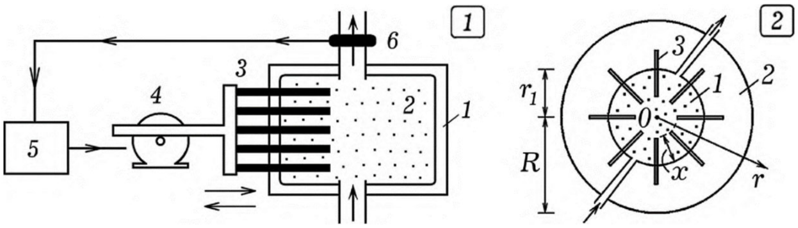


Fig. 1. Structure of a nuclear reactor.

Let us consider a spherical nuclear reactor (Fig. 1), consisting of nuclear fuel 1, protection 2 and control rods 3 [1]. The model must take into account the formation of neutrons as a result of nuclear decay, their diffusion and the thermal conductivity of the environment. The equation in spherical coordinates for this reactor is as follows [3-5]:

$$\frac{\partial n}{\partial t} = k_1\left(\frac{\partial^2 n}{\partial r^2} + \frac{2}{r}\frac{\partial n}{\partial r}\right) + k_2(1-\beta)n + \lambda C - S \tag{1}$$

where *n* is neutron concentration at a distance r from a center *O, β* is a fraction of delayed neutrons arising from the decay of precursor nuclei, *(1- β)* is a fraction of immediate neutrons, C is concentration of precursor nuclei, *λ* is decay constant of precursor nuclei, *S* is rate of change of neutron concentration due to their absorption by the control rods;

$$\frac{\partial C}{\partial t} = k_3\beta n - \lambda C \tag{2}$$

where *T* is temperature, *q* is heat released as a result of nuclear decay;

$$\frac{\partial T}{\partial t} = k_4\left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r}\right) + \frac{q}{c\rho} \tag{3}$$

where *c* and ***ρ*** are the specific heat capacity and density of the environment (nuclear fuel, neutron moderator and coolant);

$$q = k_5 n. \tag{4}$$

3 Results and discussion

The program demonstrates how neutron concentration, temperature of the coolant passing through the core, and a distance of the extended rods are changing. The applied program includes a time loop *t* when the above-listed quantities are calculated and graphs *x(t), T(t)* and *n(t)* are constructed [4].

The *Matplotlib library* was applied to create the simulation graphs. It is designed to visualize data in two-dimensional and three-dimensional graphics.

Table 1 presents the required constant values to perform the system simulation.

Table 1. Constants of the software program for simulation reactor's operation.

Constant	Value	UoM	Description
dt	0.002	sec	Time step
r	50	sm	Distance of neutrons from the center O
B	0.1	-	Delayed Neutron Fraction
L1	0,05	s-1	Decay constant of precursor nuclei
k1	250	unit	Number of neutrons produced
rs	1.5	unit	Resistance coefficient of rods

All parameters were selected based on the physical properties of thermal reactors. For the accuracy of the simulation, the time step *Δt* was chosen equal to *0.002 s*, which satisfies the stability condition of the numerical scheme.

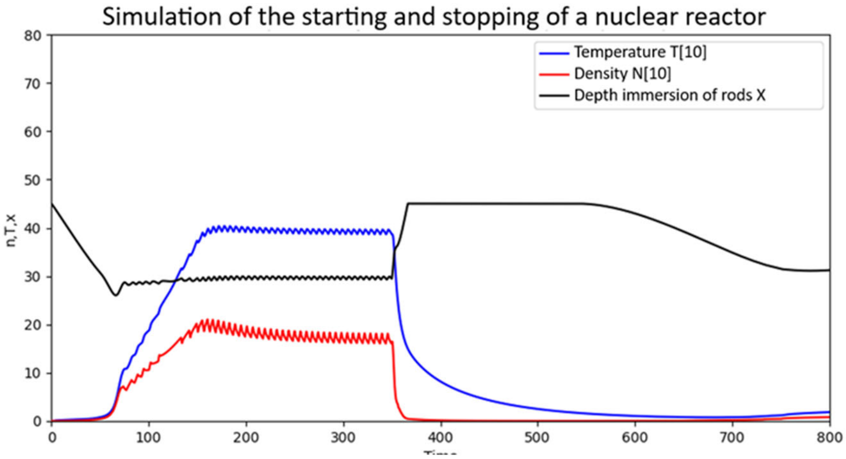


Fig. 2. Simulation of the starting and stopping of a nuclear reactor.

The graphs of the dependencies *n(t), T(t)* and *x(t)* during the starting operation and stopping of the reactor are presented in Fig. 3. This graph demonstrates that in the steady state the system is in dynamic equilibrium, control rods, and with them the neutron concentration n and temperature T, fluctuate with a small amplitude. At the moment $t2=360$ the given level U_0 drops to zero, rods are immersed to the maximum depth, the nuclear reaction decays quickly, the temperature drops to the temperature of the environment [7, 8].

An explicit difference scheme is applied to calculate the neutron diffusion equation. It provides sufficient accuracy for a small-time step Δt. The stability condition of the scheme is satisfied when:

$$\Delta t < \frac{h^2}{2D} \tag{5}$$

where D is the neutron diffusion coefficient.

The simulation results showed that the system operates properly, however, the observed dynamics of temperature and neutron concentration, characterized by fluctuations even in steady state, are undesirable from the point of view of reactor safety and efficiency. The practice proves that significant temperature fluctuations can lead to overheating of structural elements, and instability of neutron concentration can lead to unpredictable consequences. Therefore, it is required to have a control system based on precise regulation of the coolant temperature to ensure stable and safe operation.

In the future, a system with adjustable rods will be implemented to solve this problem. It will maintain the reactor in a stabilized state, despite fluctuations in temperature and neutron concentration [8]. With sharp changes in the intensity of the reaction, for example, with a decrease in the voltage level U_0, the rods will quickly plunge into the active zone, which will allow the reaction to be effectively quenched. With sharp changes in the intensity of the reaction, for example, with a decrease in the voltage level U_0, the rods will quickly plunge into the active zone, which will allow the reaction to be effectively quenched. This confirms the importance of establishing an efficient control system for reactor safety.

Also, one of the main restrictions of the presented model is the use of spherical symmetry, which simplifies calculations, however, in reality the reactor has a more complex geometry. This factor can significantly affect the temperature and neutron distribution, especially in large reactors with complex designs. In the future, it is necessary to take into account the influence of inhomogeneities in the distribution of temperature and neutron density, as well as to take into account turbulence in the coolant flow.

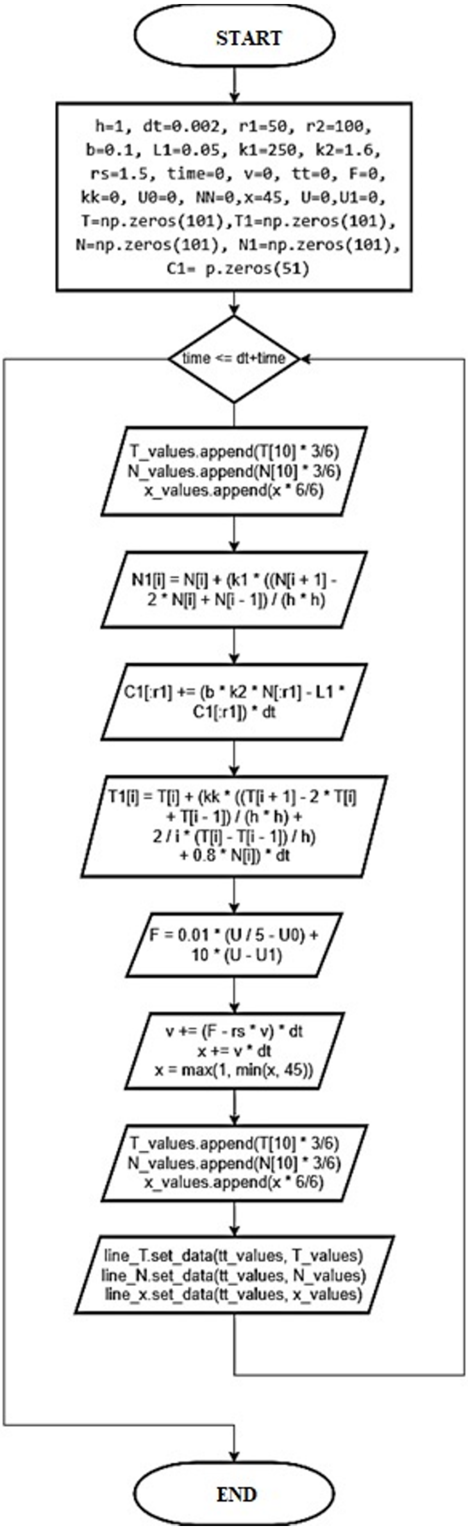
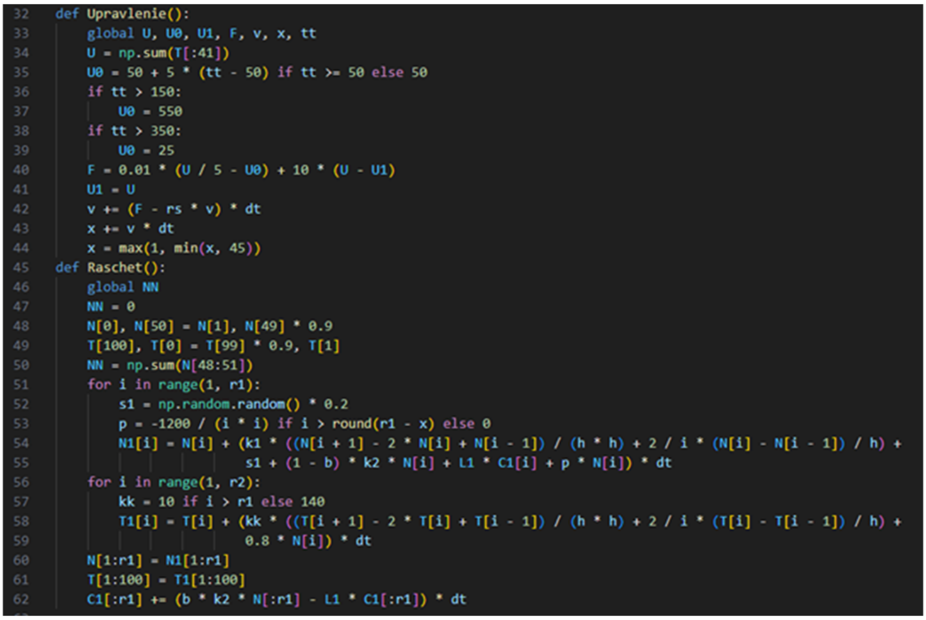


Fig. 3. Block diagram of the functioning of the program for simulating a feedback system.



```python
def Upravlenie():
    global U, U0, U1, F, v, x, tt
    U = np.sum(T[:41])
    U0 = 50 + 5 * (tt - 50) if tt >= 50 else 50
    if tt > 150:
        U0 = 550
    if tt > 350:
        U0 = 25
    F = 0.01 * (U / 5 - U0) + 10 * (U - U1)
    U1 = U
    v += (F - rs * v) * dt
    x += v * dt
    x = max(1, min(x, 45))
def Raschet():
    global NN
    NN = 0
    N[0], N[50] = N[1], N[49] * 0.9
    T[100], T[0] = T[99] * 0.9, T[1]
    NN = np.sum(N[48:51])
    for i in range(1, r1):
        s1 = np.random.random() * 0.2
        p = -1200 / (i * i) if i > round(r1 - x) else 0
        N1[i] = N[i] + (k1 * ((N[i + 1] - 2 * N[i] + N[i - 1]) / (h * h) + 2 / i * (N[i] - N[i - 1]) / h) +
                        s1 + (1 - b) * k2 * N[i] + L1 * C1[i] + p * N[i]) * dt
    for i in range(1, r2):
        kk = 10 if i > r1 else 140
        T1[i] = T[i] + (kk * ((T[i + 1] - 2 * T[i] + T[i - 1]) / (h * h) + 2 / i * (T[i] - T[i - 1]) / h) +
                        0.8 * N[i]) * dt
    N[1:r1] = N1[1:r1]
    T[1:100] = T1[1:100]
    C1[:r1] += (b * k2 * N[:r1] - L1 * C1[:r1]) * dt
```

Fig. 4. Software program in Python.

Another limitation is the use of a fixed time step *Δt=0.002*. It may not be accurate enough to simulate reactors with rapidly changing parameters. It is possible to reduce a time step and apply more complex numerical solution methods to improve the accuracy of calculations.

4 Conclusion

The paper presents the software that was developed and implemented for simulating starting, operating and stopping processes in a nuclear reactor applying mathematical models and numerical methods. Simulation in the software program makes it possible to fulfill the following operations such as analysis of neutron generation processes, heat transfer and control rod dynamics, prediction of reactor behavior under various scenarios, such as normal starting, acceleration and emergency stopping, taking into account all key factors affecting its operation.

In the future, it will be possible to improve the computer model taking into account the creation of more complex reactor operating modes, as well as the addition of new physical effects, such as coolant turbulence. These improvements will increase the accuracy and applicability of the model for various reactor types and situations.

The proposed model is a useful tool for educational purposes such as reactor design and accident analysis. Also, it can serve as a basis for further research on safety and clean energy production in the field of nuclear power and nuclear reactor control.

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