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Aleksey Nikolov, Vesela Pasheva, and Gergana Gerova



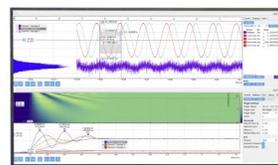
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A Simulator of Vertical U-tube Steam Generator in SCILAB Environment

Aleksey Nikolov^{1,a)}, Vesela Pasheva^{1,b)} and Gergana Gerova^{2,c)}

¹*Technical University of Sofia
Faculty of Applied Mathematics and Informatics
Department of Mathematical Analysis and Differential Equations
8, Kl.Ohridski Blvd., 1000 Sofia, Bulgaria*

²*Technical University of Sofia
Faculty of Power Engineering and Power Machines
Department of Thermal and Nuclear Power Engineering
8, Kl.Ohridski Blvd., 1000 Sofia, Bulgaria*

^{a)} Corresponding author: ajn@tu-sofia.bg

^{b)} vvp@tu-sofia.bg

^{c)} ggg@tu-sofia.bg

Abstract. The goal of this project is the development of a Simplified Simulator for Student Training for one of the nuclear power plant's main equipment, namely the steam generator. The TRIPLE S simulator is designed for basic understanding of undergraduate students in nuclear engineering educational programs. Scilab is used to implement a simulation model and to develop a graphical user interface and it run on a personal computer.

INTRODUCTION

The simulators have a great role in education of students in the nuclear technology field worldwide by providing them a very attractive virtual place. This allows students to explore and operate a nuclear power plant in a safe way. This is a significant improvement over the classroom teaching of NPP systems. The other advantage of such an improvement is that it attracts and motivates students in nuclear science. Depending on their fidelity simulators provides realistic plant responses during normal and abnormal operations, power maneuvers, malfunctions, operational transients, and allows training in emergency procedures.

The simulators can also be used to teach students the fundamentals of human factors and how human machine interfaces can influence the decision making process of the operator. Human actions are an essential part of the operation and maintenance of a nuclear power plant and human factors play an essential role in determining human actions [1].

Last but not least the simulators can be used to teach students the fundamentals of university disciplines as mathematics, heat transfer, material science, thermodynamics, and etc.

SIMULATION AND SIMULATORS IN NUCLEAR INDUSTRY

Simulation is the imitation or replication of a real system, activity, operation or situation. Simulation often is used to simulate the reality which is either too complex, or too danger for actual training [2].

Simulators by definition are the physical devices that replicate actual devices operationally or physically. These representations depict the dynamic behavior of actual systems and provide a means to experiment and test new ideas and research to evaluate human performance without the necessity of conducting impractical tests in real nuclear power plants, airplane cockpits and etc.

Historically, simulator technology for domains such as aviation emerged in the 1930s with the invention of the Link Trainer, a mockup plane. Further advancements in the fields of computers and mathematical models have led to the development of more realistic flight simulators [1, 3, 4]

A similar course was followed for nuclear power plants (NPPs). NPPs initially utilized hardware mock panels of control rooms which were used by the US nuclear Navy and plant vendors. For the last half a century, the simulator technologies have changed significantly due to the rapid advances in computer hardware and software. Until 30 years ago, computers that were used to simulate a complete nuclear power plant down to the last electrical fuse occupied a full room and cost millions of dollars. However, nowadays nuclear power plant simulators have become necessities and fundamental tool for education and training, design, development, modifications, analysis, design of control strategies and safety aspects among nuclear utilities worldwide to ensure safe and reliable operation of nuclear power plants. They are proved to be an effective and efficient training tool for imparting plant knowledge as well as recognized of the utmost relevance [1, 4, 5]

In the nuclear industry simulators can be used for various purposes providing a wider range of services. Some of them are listed below:

- for NPP operator simulators are one of the most important parts of his/her training program because of an extensive “hands-on” experience that they provide during normal and abnormal operations, power maneuvers, malfunctions, operational transients, and allows training in emergency procedures startups, power maneuvering and shutdown operations;
- they also play an important role in during licensing examination and in the development of operating procedures;
- simulators can also be used for teaching of human factors fundamentals and how human machine interfaces can influence the decision making process of the operator;
- last but not least – computer-based tools are becoming standard components and an essential tool of training programs for student fundamentals’ training which is an essential for their future growth and development in nuclear energy field. The simulators provide training tools for university professors and engineers involved in teaching topics in nuclear energy and are also supplied directly to students, junior engineers, and senior engineers and scientists interested in broadening their understanding of the topic. Simulator training has enabled participants to become fairly skilled in operating the simulation codes. It was clear that the combination of lectures on the physics and control of reactors together with the opportunity to test out the understanding on simulators was very effective in keeping up the interest of participants and of imparting knowledge about the operational characteristics of the various reactor systems. In a number of cases, the simulators are being or will be incorporated in national university syllabi or training courses. [5, 6, 7, 8, 9, 10]

SIMULATORS CLASSIFICATION

There are various types of nuclear reactor simulator. Their roles in the training process are well established. In general, they can be briefly classified as follows:

- *Basic Principle Simulator* may describe the main function of the plant, or only a subsystem (turbine, generator, feedwater system, core control, etc.). Basic principle simulators are excellent for improving the basic understanding and fundamentals training because they provide an overview of plant behaviour and a basic understanding of the main operating modes. They can be used as desktop classroom training tool since illustrates general concepts, demonstrating and displaying the fundamental physical processes of the plant. Basic Principle Simulator main goal is to help trainees understand fundamental physical processes, basic operation of complex systems, and the general operating procedures of a nuclear reactor without providing a faithful mockup of a specific plant. The simulation scope focuses on the main systems; auxiliary or support systems are often not simulated, or are simulated in a very limited way [1, 2, 3, 11, 12, 13, 14];
- *Part-Task Simulator* are also used for improving the basic understanding and fundamentals training. This type simulates only specific systems of a plant or merely some systems or portions of systems, thereby enabling a trainee to be trained specifically on only parts of a job or task [1, 2, 3, 13];

- *Full-Scope Simulator* – a simulator incorporating detailed modelling of all systems of the referenced plant replicating the real control room and includes all the models needed to reproduce the functionality of the real plant and an accurate representation of the real-time process that can be operated or observed from the control room [1, 2, 3, 13, 14, 15];
- *Other-than-full-scope control room simulator*— a simulator that does not provide the same human-machine interface as does the plant to which it is referenced. Generally, for a simulator of this type, the human-machine interface is provided through computer driven displays and either touchscreen or mouse-control of on-screen buttons. These displays and controls may be similar to those of the referenced plant, or may be simplified. Examples of the names given to such simulators have included: Analytical Simulator, Functional Simulator, Graphics Simulator, and Multi-functional Simulator [1, 2, 3, 13];
- *Plant Analyser* is a training device to study complicated plant transients or accidents in detail. This simulator is not required to operate in real-time nor display all actual operating data [12, 14];
- *Compact simulators* provide a means of training on operating procedures in a simplified form. A control desk is often provided to display significant parameters. They are powerful tools for the basic training of new operators, field operators and personnel not working in the control room. These simulators become multi-functional if provide a graphical representation of the control parameters and the operating environment. [12].

BRIEF THERMO-HYDRAULIC DESCRIPTION OF STEAM GENERATOR UNDER CONSIDERATION

For steam generator (SG) modeling as a part of nuclear plant it is necessary to reproduce the inlet and outlet facility parameters in a proper way [16, 17]. Since the steam generator, shown in Fig. 1 is the link between primary and secondary circuit of nuclear power plant with pressurized water reactor its primary side temperature data gives information about heat generated in the core whereas secondary side temperature data – about power consumption of this circuit taking into account the heat accumulated in the entire SG volume. When the nuclear power plant is in operation steam turbine load and or nuclear reactor power changes may affect the operational parameters (temperatures and mass flow rates) at the SG inlet in both primary as well as secondary sides. Moreover, the SG inlet temperature changes by a nuclear reactor thermal power variation while the SG outlet temperature depends on both inlet and saturation temperatures. The saturation temperature is determined by saturation pressure which is affected from the steam consumption that characterizes secondary side power [18, 19]. To monitor how the change in inlet parameters affects the outlet ones can be accomplished via simplified simulation SG model development which will work at steady-state mode. Although the model is simplified its development is not an easy task due to various reasons some of which are – its complex structure, feed water phase changes, fluid flows different directions and so on.

Furthermore, in the lower part of SG heat is transferred from water to water while in the upper part – from water to steam mixture. On the secondary side, the feed water first flows downward, and then – upward, collects the heat and evaporates. Non-evaporated water droplets are separated in cyclones separators, and flow downward for reheating. The dehumidified steam flows to the steam turbine. On the primary side, the direction of the fluid flow is also changeable. The water from the primary side flows through the steam generator tubes first co-currently with the steam and water mixture, and then counter currently. The complexity of different phenomena that take place in SG requires a problem simplification to accurate simulator development. To achieve this simplification SG is considered as a “black box” ensuring primary circuit heat removal and steam generation by this heat. The aim is to examines how the changes of the inlet parameters affect the changes of the outlet ones.

STEAM GENERATOR MATHEMATICAL MODEL

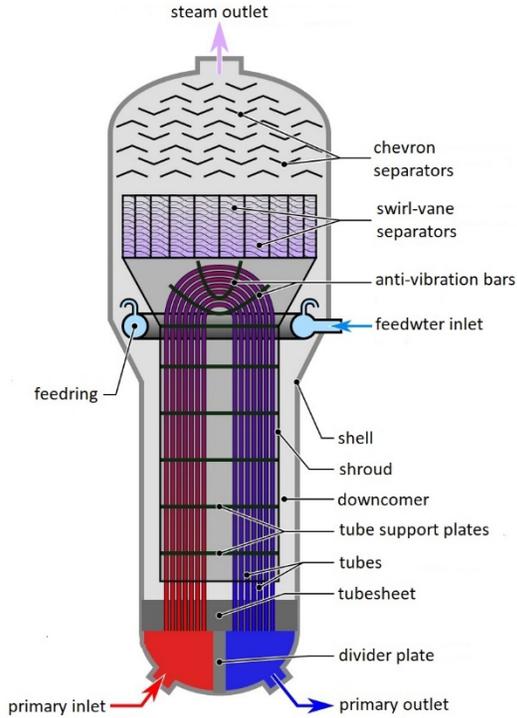


FIGURE 1. Steam generator scheme.

The processes that take place in the vertical steam generator under consideration can be briefly described in the following way – the reactor coolant flows into the SG metal tubes with mass flow W_{pr} and the temperature T_{in} . It passes to tubes some of its heat which leads to changes of its temperature to T_{pr} . The metal is heated up to T_m while the coolant leaving SG with temperature T_{out} go back to the reactor core. The metal tubes give their heat to the secondary water (feed water) which turns into water-steam mixture and enters the separator where the vapor with mass flow W_{st} is separated. The separated water is mixed with feed water with mass flow W_{fw} then the mixture is heated to saturation temperature turning into water-steam mixture and thus goes with mass flow W_d in the separator again.

The system of ordinary differential equations (ODE), derived below present SG mathematical model. The model will be almost the same regardless of SG type that is studied. Since for a real simulation of SG processes various geometric parameters (lengths and areas) are used they must be known and specified in advance. In [20, 21] the numerical values for these parameters are given for vertical U-tube steam generator. Thus, the model and the numerical simulations based on it are carried out for that SG type.

In SG mathematical model derived the relations of the specific volumes v' and v'' of the water and the steam correspondingly, and their specific enthalpies h' and h'' on the pressure P are used. Usually such relations can be found for particular intervals of the pressure in tables with thermodynamic properties of water and steam. However, a search directly in these tables would make the computer simulation too ineffective with respect to time and program realization. Thus, the development of approximating formula is necessary. More than that, in the presented model the relations of the derivatives of the parameters on the pressure also take place. This imposes the necessity of using simple relations in which these derivatives are found directly. Thereby linear approximating formula is used here.

Let f is whoever it is from the quantities v', v'', h' and h'' . The corresponding relation is looked for the type $f = A.P + B$. The derivative with respect to pressure is determined directly as $\frac{\partial f}{\partial P} = A$. In Table 1 values of A and B are presented. They are found by using the least squares method. Data for application of the method are taken from [22].

TABLE 1. Linear model coefficients

	v'	v''	h'	h''
A	3.6294×10^{-5}	-2.7×10^{-3}	45.08	-17.93
B	1.1×10^{-3}	4.68×10^{-2}	949.92	2896

The model which is presented here is with discrete parameters. The steam generator is divided into separate nodes and interaction between them reflects the processes in it. In the framework of one node the quantities are function of time only and they are presented by the mean values in the space of the node.

The model is for single phase fluid and is derived from the balance equations for energy, mass and momentum by interaction between the nodes. The nodalization is presented in Fig.2, where with thick arrows is shown heat transfer and with thin– mass flow.

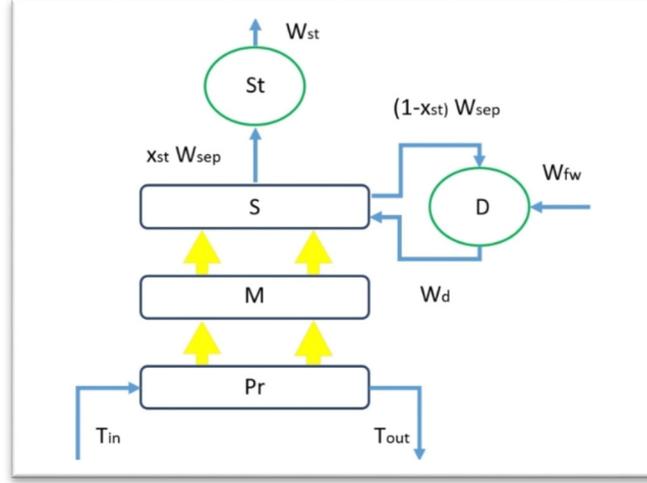


FIGURE 2. Steam generator model nodalization scheme.

The nonlinear ODEs, derived in [23] will be briefly shown here

$$\rho_{pr} V_{pr} \frac{dT_{pr}}{dt} = 2c_{pr} W_{pr} (T_{in} - T_{pr}) - \alpha_{pr} A_{pr} (T_{pr} - T_m) \quad (1)$$

$$c_m \rho_m V_m \frac{dT_m}{dt} = \alpha_{pr} A_{pr} (T_{pr} - T_m) - \alpha_{se} A_{se} (T_m - T_{sat}) \quad (2)$$

$$\frac{A_d}{v_d} \frac{dL_d}{dt} + x_r \frac{V_{st}}{v^{''2}} \frac{dv''}{dp} \frac{dp}{dt} = x_r W_{st} + W_{fw} - W_d \quad (3)$$

$$h_d \frac{A_d}{v_d} \frac{dL_d}{dt} + \frac{V_d}{v_d} \frac{dh_d}{dt} + x_r \frac{h' V_{st}}{v^{''2}} \frac{dv''}{dp} \frac{dp}{dt} = h_{fw} W_{fw} + x_r h' W_{st} - h_d W_d \quad (4)$$

$$-\frac{V_s}{v_s^2} v'' \frac{dx_{st}}{dt} - \left[\frac{V_s}{v_s^2} \left(\frac{dv'}{dp} + x_{st} \frac{dv''}{dp} \right) - \frac{V_{st}}{v^{''2} x_{st}} \frac{dv''}{dp} \right] \frac{dp}{dt} = W_d - \frac{W_{st}}{x_{st}} \quad (5)$$

$$\frac{V_s}{v_s} \left(h'' - h_s \frac{v''}{v_s} \right) \frac{dx_{st}}{dt} - \left\{ \frac{V_s}{v_s} \left[\frac{h_s}{v_s} \left(\frac{dv'}{dp} + x_{st} \frac{dv''}{dp} \right) - \frac{dh'}{dp} - x_{st} \frac{dh''}{dp} \right] + \frac{V_{st}}{v^{''2} x_{st}} \frac{dv''}{dp} \right\} \frac{dp}{dt} =$$

$$= \alpha_{se} A_{se} (T_m - T_{sat}) + h_d W_d + h_{fw} W_{fw} - \frac{h_s W_{st}}{x_{st}}$$

The equations represent a system of ODE with respect to the state variables T_{pr} , T_m , L_d , h_d , P , and x_{st} . The first two equations are linear differential equations solved with respect to the derivatives of the unknown functions. The situation is not the same for the rest of the equations. They are nonlinear with respect to the state variables and they can be considered as a linear system of equations with respect to derivatives of these variables. But instead of solving a system of four equations it is more convenient to divide them into two pair of equations – (3) and (4) on one hand and (5) and (6) from the other. After solving these systems by using Cramer's rule for example, four nonlinear equations will be obtained. Thereby, they will be solved with respect to derivatives of unknown functions L_d , h_d , P , and x_{st} .

Next step is clarifying the quantities W_d and W_{st} . Mass flow W_d will be defined by using feedwater natural circulation i.e. balance of momentum. According [20] an equivalence of momentum balance leads to assumption that W_d is proportional to the square root of the water heads difference at nodes D and S.

$$W_d = \alpha \sqrt{\frac{L_d - L_w}{v_d} - \frac{L_w}{v'}} \quad (7)$$

The water level L_w in the separator is determined by the ratio between water and steam at this node $1 - x_{st} = \frac{M}{M_s} = \frac{A_w L_w}{v'} \frac{v_s}{A_1 L_2}$, where $A_w = A_1 - \frac{V_{pr} + V_m}{L_1}$. Here A_1 is the separator area, L_2 is its length, and L_1 is metal tubes length. The proportionality coefficient α in (7) is determined at steady-state and is taken from [20].

The steam flow W_{st} is determined by using the assumption made in [21], namely:

$$W_{st} = c_o P_{sat}$$

The system of equations (1) to (6) is nonlinear. It is necessary to use numerical procedures to solve it. As a base of such procedures different numerical method can be used. The fourth order Runge-Kutta method is applied here. It allows both effectiveness as well as accuracy which are necessary in numerical simulation.

TABLE 2. Model variables and coefficients

Symbol	Meaning	SI unit
A_1	separator area	m^2
A_d	downcomer area	m^2
A_{pr}	inner area of U-tubes	m^2
A_{se}	outer area of U-tubes	m^2
A_w	associated area	m^2
c_o	proportionality coefficient	\square
c_m	specific heat capacity of metal	$J / kg K$
c_{pr}	specific heat capacity of primary water	$J / kg K$
h'	specific enthalpy of saturated water	J / kg
h''	specific enthalpy of steam	J / kg
h_d	specific enthalpy of downcomer water	J / kg
h_{fw}	specific enthalpy of feedwater	J / kg
h_s	specific enthalpy of separator water	J / kg
L_1	metal tubes length	m
L_2	separator length	m
L_d	water level in downcomer	m

TABLE 2 (Continued). Model variables and coefficients

<i>Symbol</i>	<i>Meaning</i>	<i>SI unit</i>
L_w	water level in separator	<i>m</i>
M	water mass in separator	
M_s	mass of steam in separator	<i>kg</i>
P	live steam pressure	<i>Pa</i>
P_{sat}	saturation pressure	<i>Pa</i>
t	time	<i>s</i>
T_{in}	temperature of primary water steam generator inlet	<i>K</i>
T_m	temperature of metal tubes	<i>K</i>
T_{pr}	temperature of primary water in steam generator	<i>K</i>
T_{sat}	saturation temperature	<i>K</i>
v'	specific volume of water in separator	<i>m³ / kg</i>
v''	specific volume of steam in separator	<i>m³ / kg</i>
v_d	specific volume of water in downcomer	<i>m³ / kg</i>
v_s	specific volume of water in separator	<i>m³ / kg</i>
V_m	volume of U-tube metal	<i>m³</i>
V_{pr}	volume of primary water	<i>m³</i>
V_s	separator volume	<i>m³</i>
V_{st}	steam volume	<i>m³</i>
W_d	downcomer flow	<i>kg / s</i>
W_{fw}	feedwater flow	<i>kg / s</i>
W_{pr}	primary water flow	<i>kg / s</i>
W_{st}	steam flow	<i>kg / s</i>
x_{st}	steam quality at the exit of separator	\square
α	coefficient	\square
α_{pr}	proportionality coefficient	\square
α_{se}	coefficient	\square
ρ_m	density of U-tube metal	<i>kg / m³</i>
ρ_{pr}	density of primary water	<i>kg / m³</i>

GRAPHICAL USER INTERFACE OF THE SIMULATOR

The program implementation of this method is realized in the Scilab environment. The choice of the Scilab program is not random. From one hand it allows easily programming of numerical procedures, convenient structuring of whole model separate functions and it has very good graphics. On the other hand, it is an open source product and any student can install it free of charge. Moreover, Scilab has some opportunity for GUI development.

More information about modeling and simulation with Scilab can be found for example in [24].

With the graphical interface before the simulation the user may set the initial values of the state variables as well as he may change the values of input variables (Fig. 3-4).

The results of simulation appear as real-time animated graphs of the state variables T_{pr} , T_m and P (Fig.5). The user may set control time of simulation to reach steady-state, after which the simulation stops and the program suggests to change some of the following parameters T_{in} , A_{pr} and W_{st} before continuing the integration.

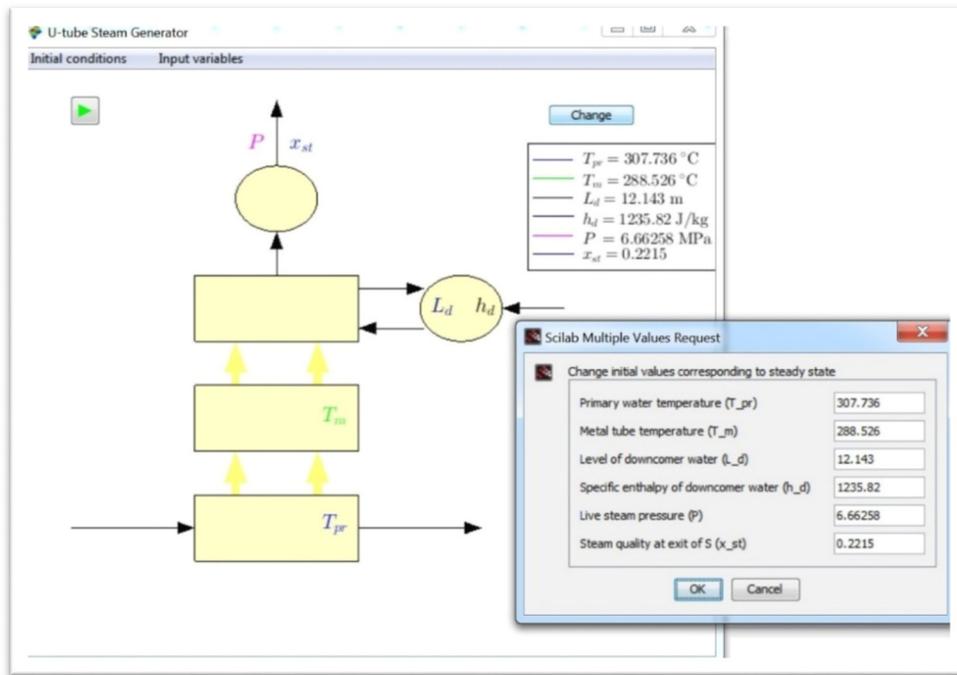


FIGURE 3. Inserting the initial conditions.

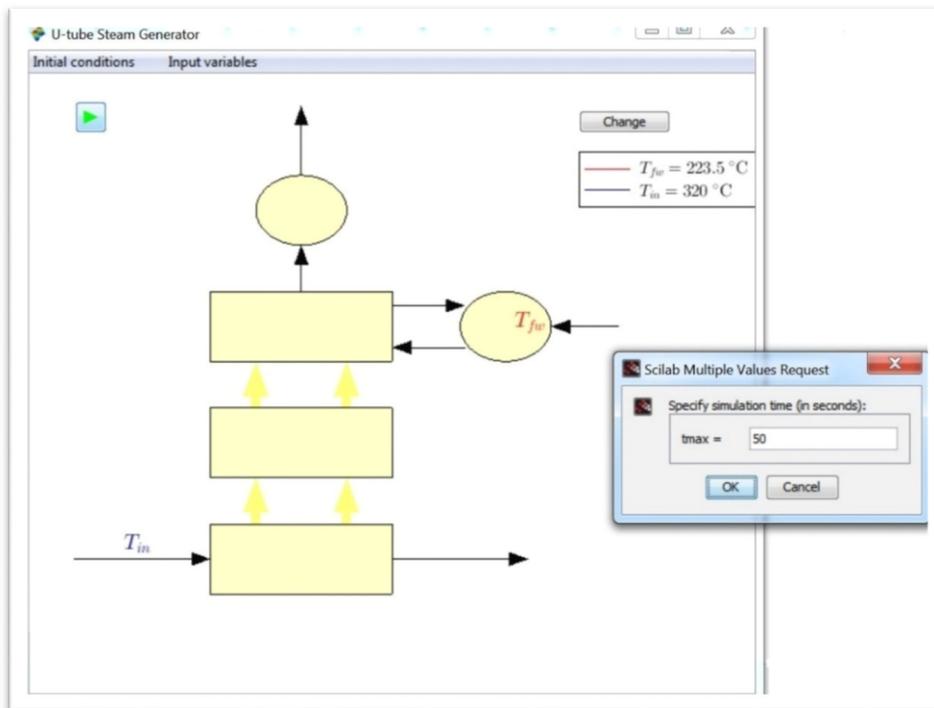


FIGURE 4. Input variables and specifying the simulation time.

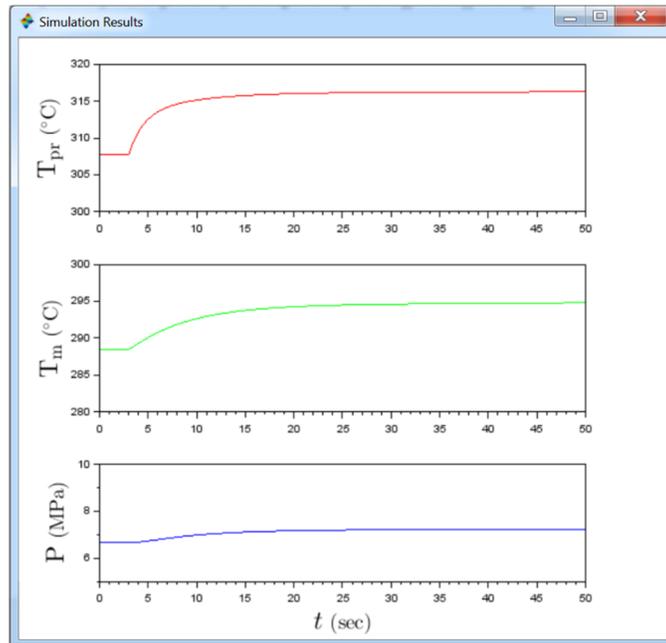


FIGURE 5. Simulation results. The control time was set to 3 sec. after which the temperature T_{in} was increased by 10°C. Correspondingly, the state variables given on the graph change their behavior after the 3rd second.

CONCLUSIONS

The TRIPLE S simulator can be classified as a combination between Basic Principle and Park-Task Simulators. It provides an overview of steam generator's behavior and a basic understanding of its operating mode. TRIPLE S can help trainees to understand fundamental physical processes, basic operation of complex systems as well as to modify and/or add equations to simulator's mathematical model.

We hope to motivate students in nuclear engineering by improving the quality of their education and making their learning process more interesting and interactive through the use of simulators.

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