About Modeling and Simulation of Heat Exchange Convective Surfaces of the Steam Generator

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Abstract — *Among the priority issues that the modern society has to be solved, include also the energy and environmental issues. The notion of control (process control) has expanded in recent years, encompassing new areas such as automatic control of quality, the data processing with decisional purpose for one strategic leadership, ensuring uninterrupted of the system maintainability and thus, security and viability of the entire ensemble. In this context are part and the simplified simulation methods of the energetic installations from the power plants. The paper expose, in the first part, the importance of the steam generator in the operation of power plants, presents the energy processes complexity, emphasizing the importance of their management and automation to increase energy efficiency of each link in the chain. Then, taking as its starting point the real operational aspects, the mathematical modeling, the simulation and automatic control of steam generator, the paper proposes the development of a mathematical model in absolute units and the simulation the operation of a convective heat exchange surface of the steam generator in steady and dynamic regime.*

***Keywords* — *Mathematical model, modeling, power plant, simulation, steam generator*.**

I. INTRODUCTION

The paper presents a study for the application about the steam generators in terms of modeling and simulation of their operation in steady and dynamic regime in power plants. Treat modeling itself of steam generator: it is based on physical model of each heat exchange surfaces, simplifying assumptions adopted, equations for conservation of mass, energy and momentum and the heat transfer equations. Also is presented the model in relative units imposed by the literature - highlighting the entire set of mathematical equations the processes occurring in the installation, the coefficients given in the literature, and the disadvantages involved in its use. Then, as an alternative, is proposed the steam generator model in absolute units: processing of the basic equations, are highlighted development its advantages - eliminating the recalculation sequence of parameters at each step, eliminating the linearization around the stabilized operating point, nonlinear characteristics are included in the model, determining the coefficients of thermal heat exchange between agents and the exchange surfaces in real-time, and the disadvantages involved in its use. The theoretical model proposed, in absolute units, implemented in Matlab-Simulink, leads to the simulations of the operating in dynamic regime for all components of steam generator. The model provides information about the influence of each parameter - input and output (pressure, temperature, and flow for water supply, combustion gases) on monitored parameters, namely pressure and temperature live steam. The results from the simulation are compared with values measured for parameters in real operation. The aim was to provide information allowing analysis of the model of each heat exchange surfaces on the one hand and on the other hand time for calculation to be within the real time operation. The steam generator model can be completed with the modules of the turbine-generator group with their installations and internal services and of the electrical part of power plant. All these models of the stationary and dynamic regimes can be implemented in computer systems and leads to the creation of a system for the management and control in electrical and thermal energy supply.

II. THE IMPORTANCE OF STEAM GENERATORS IN POWER PLANT OPERATION

Considering the great technical and economic importance for energy, the dynamics of the specific processes of the most important energy aggregates - steam generator and steam turbine - has been the subject of numerous studies and research, starting with the dynamic analysis of a steam generator with natural circulation and continuing with the analysis of its optimal and suboptimal control, or of the plant assembly. The vast majority of models is designed specifically for control or proposes new techniques to solve. Therefore, global models are conveniently reduced to allow for dynamic analysis of the plant assembly with significant, generally accepted simplifications. For this purpose, the theory of linear control, which describes the state of the boiler using linear differential equations with constant coefficients, is sufficient, [2], [4].

Steam generators (boilers) are water vaporization systems that use the heat generated by the combustion of a fuel or an industrial process (heat recovery boilers). In boilers used in power plants, the steam from the vaporization process is overheated at a temperature higher than the saturation temperature of saturated steam to raise its enthalpy. It distinguishes two main circuits: water-steam and air-combustion gases. The steam-water circuit of the generator consists of pipe systems immersed in the flue gas ducts. From a functional point of view, the following heat transfer surfaces of this circuit are distinguished: Economizer - increases the temperature of the supply water to a value close to the saturation value, the heat transfer between the water and the flue gases is convective; Vaporizer - it ensures the passage of water from the liquid phase to the saturated steam, the heat transfer being carried out predominantly by radiation; The Primary Superheater - realizes the overheating of the saturated steam up to the temperature level desirable, heat transfer convective - radiation and Intermediate Heater - occurs in conventional steam boilers and provides an increase in steam temperature already released in the turbine high pressure body. The manner in which the heat transfer is effected on the one hand and the level of temperature required by the water-steam agent, on the other hand, requires the way in which these heat exchange surfaces are located inside the channels of combustion gases, [2], [4].

Inside the vaporizer tubes phase change takes place, the heat transfer coefficients have large values. In these circumstances it is necessary to place the heat exchange surfaces into the furnace where the outside of the tubes, the heat transfer coefficients are also large - achieving heat transfer by radiation is predominant. For the primary, intermediate superheater, and economizer case, the heat transfer coefficients can be obtained inside the pipes are slightly lower than for vaporizer, the three areas are located in the convective generator zone. High power boilers energy groups, 510 or 1035 t/h are Benson type boilers with Π-shaped building or tower. The boiler primarily presentation intended purpose of the study, namely the modeling of operating modes. Each power unit of 315MW is equipped with two steam boilers of 510 t/h identical type Benson, forced to pass single variable evaporation point, built in the form of Π.

III. CONVECTIVE HEAT EXCHANGE SURFACE PRESENTATION

In the dynamic modeling and control of steam generator are used mainly three types of one-dimensional models for the analysis of fuel combustion stability at low loads, the dynamic analysis of air-gas path and predetermining spatial distribution of water-vapor properties - models for studying the control pressure, temperature, level, dynamic load variation. The models are mathematically expressed by a set of equations from differential equations to partial differential equations; their nature is depending on the modeled process complexity and the purpose of their use. Modeling and simulation of heat exchangers is an essential problem of any simulation program and especially of steam generators, detailing the following general concepts, [11]: segmentation, disconnection, the biphasic mixture and thermal transfer. The location and complexity of the processes in steam boilers steam boilers had required that the process can be structured in technological modules.

Thus the economizer, a surface of the convective heat exchange, is mounted in the end of the heating surface of the steam generator, resulting in a saving of fuel corresponding to the heat recovery. Economizer heating surface is usually made from steel pipe or, more commonly, cast iron pipe with wings in the form of double coil, transversely spaced apart, forming economizer package supported by the support tube and connected to cylindrical collectors - inlet and outlet respectively. The economizer is placed on top of the convective circulation before the outlet gases to the air super heaters. Water passes through the economizer flue gas counter. The physical model of the economizer is shown in Fig. 1.

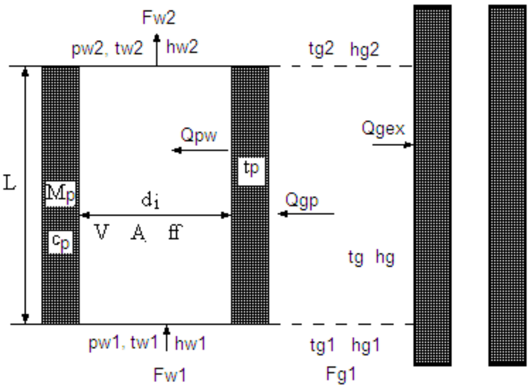

FIG.1. THE PHYSICAL MODEL OF THE ECONOMIZER

where: F_{w1}, F_{w2} are the mass flow of water input-output, kg/s; F_{g1}, F_{g2} are the mass flows of flue gas input-output, kg/s; Q_{gp} –

the heat transmitted from flue gas to pipes, W; Q_{pw} – the heat transmitted from sheet to water, W; t_{w1}, t_{w2} – the temperature of the water input-output, ^oC; t_{g1}, t_{g2} the temperature of the flue gas input-output, ^oC; t_g – temperature of the flue gases, ^oC; t_p – average temperature pipes, ^oC; p_{w1}, p_{w2} – the economizer inlet, respectively outlet water pressure, bar; h_{w1}, h_{w2}, h_{g1}, h_{g2} – the enthalpy of the water inlet-outlet or flue gas, kJ/kg^oC; M_p – the metal mass, kg; V – the total volume free, m^3; A- water flow area,m^2; f_f – friction coefficient; d_i – inside diameter of the pipe, m.

The physical processes describing the economizer operation are: single-phase flow through pipes; heat transfer from flue gases to pipes; heat accumulation in the pipe material; heat transfer from the economizer pipes to the heating water.

The simplifying hypotheses adopted in the mathematical model are, [11]: the economizer is without boiling; the variables of the model satisfy the physical principles; the economizer is considered to be made of a single package; the model is with concentrated parameters and contains only time, not spatial derivations; gravitational and acceleration losses are not important; heat transfer is predominantly by convection.

With the hypotheses presented, the mathematical model is described by the:

The impulse conservation equation is reducing to:

$$p_{w2} = p_{w1} - \beta F_{w1}^2 \tag{1}$$

The heat transfer equation, predominantly by convection, from the gases to the economizer pipes:

$$Q_{gp} = k_{gp} S \left(t_g - t_p \right) \tag{2}$$

with k_{gp} – the convective heat transfer coefficient from the gases to the economizer pipes, W/mK; S – the heat exchange surface, m^2; t_g – the average flue gases temperature, ^oC; t_p – the average temperature of the pipes, ^oC.

The heat transfer equation, predominantly by convection, from the economizer pipes to the water:

$$Q_{pw} = k_{pw} S \left(t_p - t_w \right) \tag{3}$$

with k_{pw} – the convective heat transfer coefficient from the economizer pipes to the water, W/mK; S – the heat exchange surface, m^2; t_s – the average water temperature, ^oC.

Convective heat transfer coefficients are determined using the criteria equations given in the literature:

$$k_{gp} = 0{,}2 \cdot \frac{\lambda}{d_e} \left(\frac{w \cdot d_e}{\nu} \right)^{0{,}65} \cdot \mathrm{Pr}^{0{,}33} \cdot C_z \cdot C_s \tag{4}$$

$$k_{pa} = 0{,}021 \cdot \frac{\lambda}{d_i} \left(\frac{w \cdot d_i}{\nu} \right)^{0{,}8} \cdot \mathrm{Pr}^{0{,}43} \cdot C_z \cdot C_s \tag{5}$$

Relationships in which thermodynamic properties are calculated in real time using MATLAB functions for the fluid achieved value by the pressure and temperature.

The mass conservation equation:

For the water

$$\frac{d}{d\tau} \left(V_w \rho_w \right) = F_{w1} - F_{w2} \tag{6}$$

and for the gases:

$$\frac{d}{d\tau}\left(V_g \rho_g\right) = F_{g1} - F_{g2} \tag{7}$$

The equation of heat accumulation in the economizer pipes:

$$M_p c_p \frac{d}{d\tau}\left(t_p\right) = Q_{gp} - Q_{pw} \tag{8}$$

The energy conservation equation, taking into account the mass conservation

For the water:

$$V_w \rho_w \frac{d}{d\tau}\left(h_w\right) = Q_{pw} + F_{w1} h_{w1} - F_{w2} h_{w2} \quad \Rightarrow \quad V_w \rho_w c_w \frac{d}{d\tau}\left(t_w\right) = k_{pw} S\left(t_p - t_w\right) + F_{w1} c_{w1} t_{w1} - F_{w2} c_{w2} t_{w2} \tag{9}$$

and for the gases:

$$V_g \rho_g \frac{d}{d\tau}\left(h_g\right) = F_{g1} h_{g1} - F_{g2} h_{g2} - Q_{gp} \quad \Rightarrow \quad V_g \rho_g c_g \frac{d}{d\tau}\left(t_g\right) = F_{g1} c_{g1} t_{g1} - F_{g2} c_{g2} t_{g2} - k_{gt} S\left(t_g - t_p\right) \tag{10}$$

The system of equations to determine unknown operational sizes, in relative units, is the same as the superheater, the corresponding coefficients being given by the literature, [8], [9].

In absolute units, the unknown sizes are the expression, [7]:

For the water pressure at the exit of the economizer:

$$p_{w2} = p_{w1} + \left\{ \frac{1}{10^5} \left[-\frac{9.86 \cdot g}{v_w} - F_w^2 \frac{1}{A} v_w \left(\frac{f_f \cdot L}{d_i} \right) \cdot 0.25 \right] \right\} \tag{11}$$

For the average water temperature:

$$t_w = \int \left[Q_{pw} + h_{w1} F_{w1} - h_{w2} F_{w2} \right] \frac{1}{V_w \rho_w c_{pw}} d\tau \tag{12}$$

For the water temperature at the exit of the economizer:

$$t_{w2} = 2t_w - t_{w1} \tag{13}$$

For the average gases temperature:

$$t_g = \int \left[h_{g1} F_{g1} - h_{g2} F_{g2} - Q_{gt} \right] \frac{1}{V_g \rho_g c_{pg}} d\tau \tag{14}$$

For the gases temperature at the exit of the economizer:

$$t_{g2} = 2t_g - t_{g1} \tag{15}$$

IV. SIMULATING OF THE ECONOMIZER

As stated in the presentation of mathematical model equations of heat transfer models used in relative units, data from the literature were replaced by equations of heat transmission by convection. For both the convective heat transfer coefficient of combustion gas in the pipes and water pipes were prepared from the calculation block diagrams, Fig. 2.

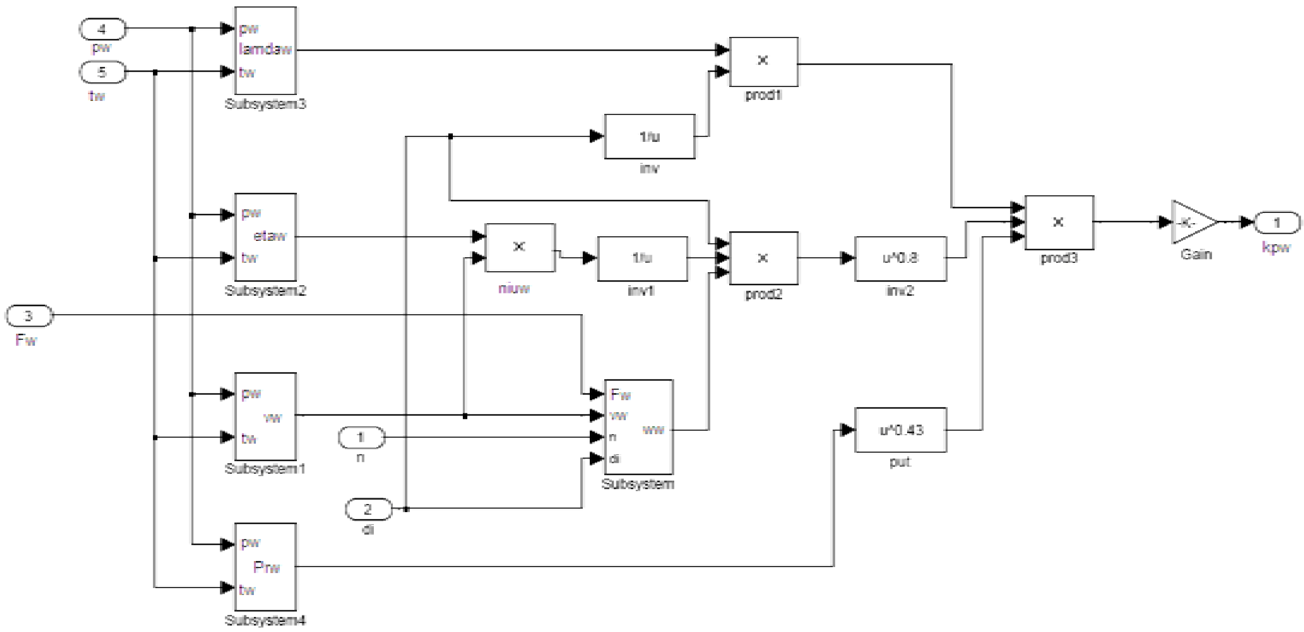

FIG.2. DIAGRAM CALCULATION OF THE CONVECTIVE HEAT EXCHANGE COEFFICIENT

MATLAB functions were created for Prandtl number, friction coefficient, thermal conductivity, kinematics viscosity and specific volume of water being determined by the pressure and temperature of the fluid attained, Fig 3.

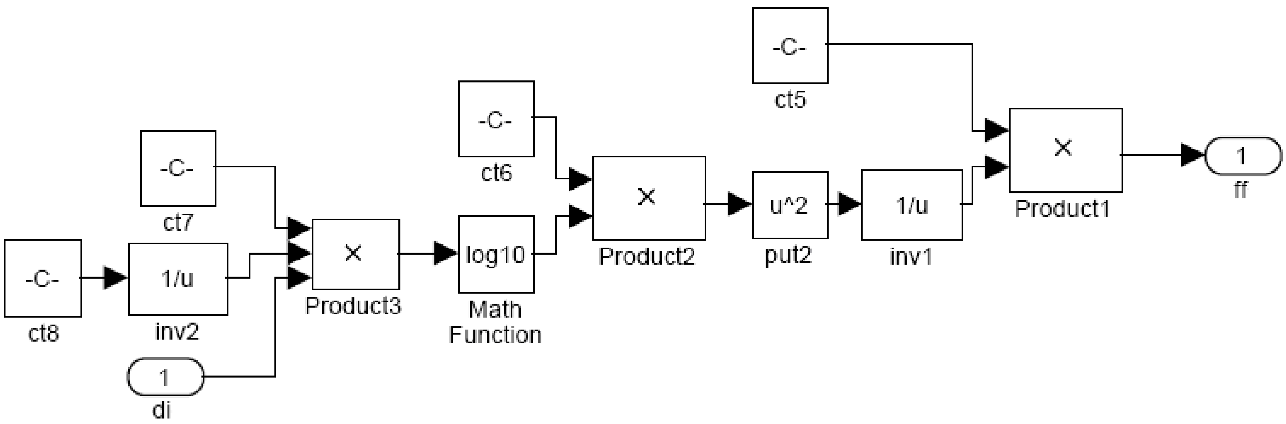

FIG.3. DIAGRAM CALCULATION OF THE FRICTION COEFFICIENT

From the point of view of the simulation of the operation of this heat exchange surface was analyzed at unitary variations of the input sizes on the outlet water pressure and the required water flow.

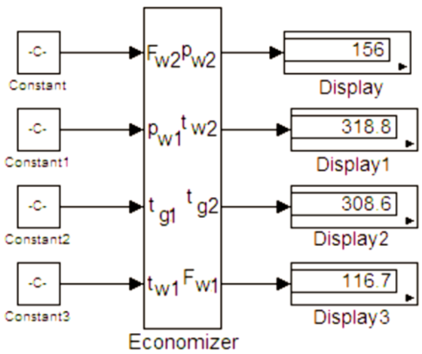

FIG.4. BLOCK DIAGRAM – SIMULATING OF THE ECONOMIZER OPERATION

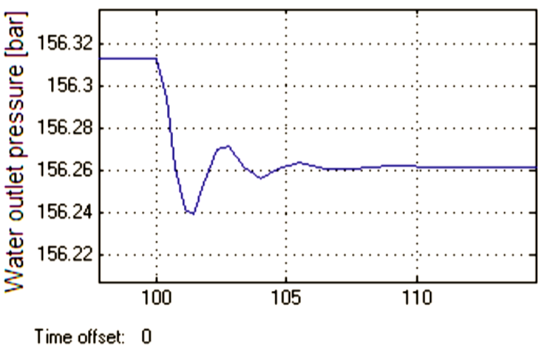

FIG.5. WATER PRESSURE VARIATION AT THE EXIT OF THE ECONOMIZER WITH THE ENTRANCE TEMPERATURE

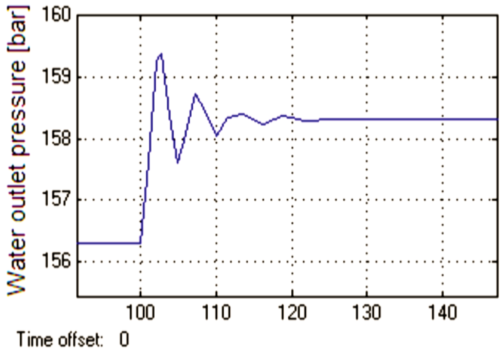

FIG.6. WATER PRESSURE VARIATION AT THE EXIT OF THE ECONOMIZER WITH THE ENTRANCE PRESSURE

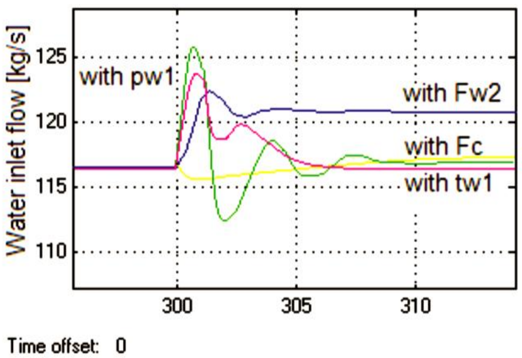

FIG.7. WATER FLOW VARIATION AT THE EXIT OF THE ECONOMISER

Analyzing the dynamic behavior of the steam generator economizer, step variations of the sizes - water temperature entering the economizer, economical input water pressure, combustion gas inlet temperature - it is found that the balance is achieved by damped oscillations. Output water pressure is greatly influenced by inlet pressure.

V. CONCLUSION

The model in absolute units is the basis for simulating the operation of the dynamic steam generator, [7]. He presents the major advantage of eliminating the sequence of recalculation of parameters at each step - in the models in relative units the whole set of coefficients is determined and entered into the model according to the parameters achieved in a previous reference regime; eliminates linearization around the stabilized operating point, nonlinear features being included in the model; it finds its own non-linear function points and updates parameter values; allows the determination of heat exchange coefficients between thermal agents and real-time exchange surfaces, their values obtained by computing within the limits recommended by the literature; removes the empirically determined coefficients, including the calculated exchange coefficients, from the heat exchanges exchanged between the thermal agents; it is characterized, with all its advantages presented above, as a slower model - relative to the one in relative units - due to the iterative calculation. The model in absolute units can be the basis for an intelligent system for simulation in real time operation of a steam generator. It is recommended to develop on other energy equipment. This supposes mathematical models in absolute units for the turbine and the electric generator, simulations of their static and dynamic regimes operation.

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