Some consideration about the superheaters modelling of steam generators

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Abstract — The paper presents, in the first part, the importance of the steam generator in the operation of power plants, especially, the importance of the superheaters, the heat exchange surface on the route of the combustion gases, with all physical phenomena produced, which lead to the shaping of the physical model. The paper proposes the development of a mathematical model in absolute units and the simulation the operation of the steam superheater of the steam generator. The theoretical model proposed is implemented in Matlab-Simulink for simulations in dynamic regime.

Keywords — mathematical model, simulation, superheater

I. INTRODUCTION

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. Simulation can be defined as a method used for studying the behavior of a real system or phenomenon. Thermal power plant simulations can be for operator training, operator guide or as a design aid. A training simulator need to be able to simulate very wide phenomena, all in real time, where as for design aid simulation range is much smaller and real time capability is not needed, in the case of operator guide real time and on-line capabilities is required.

The most important component of the conventional power generation plant for fuel optimization studies is the steam generator. The control of the steam generator to archive optimum performance is a difficult problem that has been studied during the last years. The steam generator is a heat exchanger that converts water into steam pressure and temperature required, by the heat produced by the combustion of fossil fuels. The production of steam or hot water in the boiler is achieved by two successive energy conversion or chemical burn and transfer of heat. Chemical energy of the fuel is converted into heat in the combustion process, resulting combustion gas with high temperature that transfers heat water or steam through pipes generator metal surfaces. The steam generator is continuously fed with water and debit continuous hot water or steam. The heating and water vapours takes place practically at constant pressure, neglecting frictional losses inside. The evolving gases from the steam boiler are steam boiler combustion air and gases resulting from combustion, their rates are directly proportional to the amount of fuel burned, [2].

It is well known that in the steam generator, the supplied suffers a succession of phases in various, and with diverse design heat exchangers with an adequate diameter in order to obtain an acceptable heat transfer coefficient and low pressure losses with restrictions regarding the metal temperature. The transformations are: liquid heating in economizer, vaporization in the evaporator under superheating in the superheater, and reheat in the intermediary superheater. It’s worth mentioning that this delimitation it’s not always that obvious, especially between the economizer and evaporator, or the evaporator and the superheater. Between these heat exchange surfaces there are input-output collectors.

In order to outline the analyzed physical processes Fig.1 presents the configuration of the superheater system of a high power steam generator.

As it is shown in Fig. 1, the superheater I is situated between the two flue gasses passes. From the collector 6, behind the II gasses pass, the steam flows through the pipes of the first, I, pass and reaches the output collector. From the collector’s extremities the steam climbs through two $324 \times 25$ pipes, that intersect each other and enters the collector 7 at the input of the superheater II as in Fig. 1. The II superheater is upper part of the furnace in the first gasses road. From the input collector, 7, the sustaining pipes are descending of the first gasses road where the pipes of the II superheater start. After these pipes the steam reach the output collector 8. By the intricate latera connection pipes, the steam reaches the input collector of the superheater III, 9. In the superheater III the steam travels against the flue gasses, over the convection superheater I and over the superheater IV, [7].

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The superheater IV continues directly after the superheater III pipes without an intermediary collector. The steam passes through the pipes of the superheater IV against the flue gases and reaches the output collector, 10. All these informations create the basis of the heat exchange surface mathematical model for our mathematical modeling.

II. THE PHYSICAL AND MATHEMATICAL MODEL OF THE SUPERHEATER

The paper proposes the development of a mathematical model in absolute units and the simulation of a convective heat exchange surface operation for the steam generator in steady and dynamic regime. The theoretical model proposed is implemented in Matlab-Simulink obtained simulations in dynamic regime.

In the dynamical modeling and the steam generator control there are three one-dimensional categories of models for:
- the analysis of the fuel burning stability at partial loads - for the exact calculation of the combustion process; it necessitates an exact calculation of the combustion dynamic considering also the kinetic reactions;
- the dynamical analysis of the fuel - gasses pass - to design pressure control systems;
- forecasting the spatial distribution of the water-steam properties - models for pressure, temperature, level, and dynamical load variation control.

The modeling and simulation of heat exchangers it's a difficult task for any simulation software and especially for the ones dedicated to steam generators mainly for the following general concepts, [6]:
- segmentation - dividing the heat exchangers in more sections based on the complexity of the physical reality.
- decoupling - separate equations solvers for fluids, gasses, steam-water considering the heat accumulation in the metallic wall.
- biphasic mixture - important for the generator's dynamics because the boilers surface constitutes an important part of this one, a major issue for the interaction of the two phases.
- thermal transfer - influences the predominant metallic wall temperature profile - a main difficulty for the simulation process.

Based on the block scheme and taking into account the energy mass conservation we have tried to obtain a simplified model of the boiler that simulates its behaviour in dynamic regime.

For the elaboration of the model we have considered the following hypothesis: the pressure influence over the water supply enthalpy is negligible; equivalent the distributed furnace burners with one concentrated burner; calculating the exit gasses temperature leaving the furnace with the usual methods based on their enthalpy of the air and of the feed water; the determination of the experimental coefficients for pressure loss calculation for the analyzed unit; estimating the enthalpy from the steam water tables based on the measured parameters.

As it was presented, the superheater constitutes a heat surface where the steam is superheated until the nominal temperature. It is a step processes due to the modification in large limits of the specific volume.

The physical model for the superheater is presented in Fig.2.
kJ/kg°C; \( f_t \) is the friction coefficient, L, d, A and V are the geometrical dimensions, m, m², m³.

The physical processes that describe the superheater operation are the heat transfer by convection and radiation from the gasses to the pipes and the monophase convection from pipes to the steam; the heat accumulation in pipes and monophase flow through the pipes.

In the development of the mathematical model a series of hypothesis were adopted such as:
- only steam enters the superheater, the variables of the model are in respect the physical principles,
- the model with concentrated parameters has only time derivatives;
- gravitational and acceleration losses are irrelevant.

The mathematical model proposed in absolute units, is based on mathematical equations specific to heat exchange and some existing models that were suitable - the equations of mass and energy conservation, heat transfer and heat accumulation - applied to the two fluids - combustion gases and steam, [3].

The simulation was developed in Matlab-Simulink with a 1% error of the calculated values by comparison with tables data obtained for a time smaller than the rated time (0.2...0.5 s), of the system in real time.

The conservation equation for the primary superheater is reduced to:
\[
p_{2ab} = p_{1ab} - \beta D_{1ab}^2 \tag{1}
\]

Convection heat transfer equation from the flue gasses to the superheater pipes is:
\[
Q_{gt} = \alpha_{gt}S(T_g - T_t) \tag{2}
\]

with \( \alpha_{gt} \) the convective heat transfer coefficient from the flue gasses to the superheater pipes, W/mK; \( T_g, T_t \) are the average flue gases temperature and of the pipes respectively, K.

Predominantly radiant heat transfer equation from the flue gasses to the superheater pipes is:
\[
Q_{gg} = \alpha_{gg}S(T_g - T_t) \tag{3}
\]

where \( \alpha_{gg} \) is the global radiation heat exchange coefficient from the flue gasses to the superheater pipes, kW/K⁴.

Predominantly convection heat transfer equation from the superheater pipes to the steam:
\[
Q_{so} = \alpha_{so}S(T_s - T_s) \tag{4}
\]

where \( \alpha_{so} \) the heat transfer coefficient from the superheater pipes to the steam, W/mK.

Heat transfer equation, mainly by radiation, from the superheater to the steam is:
\[
Q_{rs} = \alpha_{rs}(T_r - T_s) \tag{5}
\]

where \( \alpha_{rs} \) is the global heat transfer coefficient by radiation from the superheater to the steam, kW/K⁴.

Mass conservation equation for the steam is:
\[
\frac{d}{d\tau}(V_{ab}\rho_{ab}) = D_{1ab} - D_{2ab} \tag{6}
\]

with \( V_{ab} \) the steam volume, m³ and \( \rho_{ab} \) the average steam density, kg/m³.

Conservation equation for the flue gasses is:
\[
\frac{d}{d\tau}(V_g\rho_g) = D_g - D_2g \tag{7}
\]

where \( V_g \) is the gasses volume, m³; \( \rho_g \) flue gasses average density, kg/m³.

Superheater heat accumulation equation:
\[
M_{so}c_s \frac{d}{d\tau}(t_s) = Q_{gs} - Q_{sa} \tag{8}
\]

Energy conservation equation tacking also into consideration the mass conservation for the steam:
\[
V_{ab}\rho_{ab} \frac{d}{d\tau}(h_{ab}) = Q_{sa} + D_{1ab}h_{1ab} - D_{2ab}h_{2ab} \tag{9}
\]

Energy conservation equation tacking also into consideration the mass conservation for the flue gasses:
\[
V_g\rho_g \frac{d}{d\tau}(h_g) = D_g h_g - D_2g h_{2g} - Q_{gs} \tag{10}
\]

For the main superheater we have considered the outside variables such as: \( D_{2ab}, t_{1ab}, t_{1g} \) and \( D_{mc} \).

The unknown variables specific to the main superheater are \( D_{1ab}, p_{2ab}, t_{2ab}, t_{2g}, Q_{gs}, Q_{la}, t_i \) and \( t_g \).

### III. THE SIMULATION OF THE SUPERHEATER

The mathematical model of the steam superheater is part of the steam generator model. So, beside the unknown heat surface variables in the scheme also appear input variables from the previous simulation blocks and from the furnace simulation block.

The proposed analytical methodology covers the following general requirements:
- modeling technology specific to the heat exchange surface of the steam generator – in this case the superheater; simulation schemes operating between 50 and 100%;
- the entry data for each model are considered known, while the related data are calculated by the model (flow, pressure, temperature);
- the outputs for each model are: flow rate, pressure, temperature, and enthalpy.

As stated in the presentation of the mathematical model equations, of heat transfer models, used in relative units, the data from the literature were replaced by equations of the convection heat transfer. Both convective heat transfer coefficients, of combustion gases to the metal and the metal to the steam, are determined using the criteria equations given in the literature, depending of the thermophysical properties of the fluid and the and the flow characteristics:
\[
\alpha_{gt} = 0.2 \cdot \frac{\lambda}{d_g} \left( \frac{w}{v} \cdot \frac{d_g}{2} \right)^{0.65} \cdot Pr^{0.33} \cdot C_z \cdot C_y \tag{11}
\]

The simulation scheme for the steam superheater integrates the calculation subsystems, including MATLAB functions, for cinematic viscosity, thermal conductivity and specific heat for the steam and the flue gasses, all this being determined by the pressure and temperature of the fluid attained.

A part of these variables are determined based on the output variables for the furnace block scheme, and respectively.
the fuels composition, its humidity and of the burning products SO$_2$, CO$_2$ volumes and water vapours, [5].

For example, the flue gases specific heat is determined as a function of the components specific heats determined by the implementation of the MATLAB functions as in Fig. 3, respectively Fig. 4, [3].

![Fig. 3. MATLAB function for the calculation of the specific heat](image1)

![Fig. 4. Specific heat calculation diagram](image2)

Also, Fig. 5 and Fig. 6 presents the MATLAB functions that were created for Prandtl number and friction coefficient.

![Fig. 5. Specific heat calculation diagram](image3)

![Fig. 6. Specific heat calculation diagram](image4)

For both the convective heat transfer coefficients were created the calculation block diagrams. Fig. 7. presents the diagram of calculation for the convective heat exchange coefficient from the combustion gases to the metal of the pipes.

In Fig. 8 is presented the steam superheater calculation diagram and the calculation block scheme in Fig. 9.

![Fig. 7. Diagram calculation of the convective heat exchange coefficient](image5)

![Fig. 8. Steam superheater calculation diagram](image6)

![Fig. 9. Block diagram with external variable](image7)
On the superheater block scheme we have analyzed the influence of the dynamic regimes over the input steam flow, the pressure of the input flow, $p_0$, and its temperature, $t_0$, considering 10% step variations. In the Fig. 10 - 12 we have presented the dynamic behavior of the superheater for the step variation of these parameters.

![Graph Image]

**Fig. 10. Vaporization temperature influence**

![Graph Image]

**Fig. 11. Input superheater steam pressure influence**

- a. over the steam pressure;
- b. Over the steam temperature;
- c. over the input steam flow

**Fig. 12. The demanded steam influence over**

- a. the live steam temperature
- b. the steam flow at the input

The live steam temperature has the slowest variation. The calculated values of the parameters are close to the reference values (used for calculations) and the values from the boiler’s observation sheets with an average error of 1.2%.

### IV. Conclusion

The mathematical model it’s part of the larger generator model, being the basis for its operation simulation. It has the major advantage of eliminating the recalculation of the parameters for each step of the algorithm – in relative units model, as in previous works – the entire coefficients set being determined and included in the model as a function of the parameters from the previous operation regimes.

The linear tendencies around the stabilized operation point are removed. The nonlinear characteristics are included in the model. It manages to find the operation points on the nonlinear characteristics and refreshes the parameters’ values.

The model allows the determination of the heat exchange coefficients and of the heat exchange surfaces in real time, the results of the calculations respecting the recommended limits from previous works.

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### References


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