Control System Simulator for Steam Boiler Parameters

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Abstract: - The paper presents the research results related to control of the steam boiler parameters: drum level, furnace pressure and steam pressure. It was developed the mathematical model of the water-steam system and furnace part of the boiler. Also, the paper presents the algorithm for real time detection of model parameter variations. In this context a correction method, validate through simulation was developed.

Key-Words: - steam boiler, steam pressure, furnace pressure.

1 Introduction

Related to the systemic point of view, the boiler is frame in the category of the MIMO system (more input more output).

To simplify the procedures for determination of the mathematical model will establish a block scheme for the boiler as shown in Fig.1, specifying channels

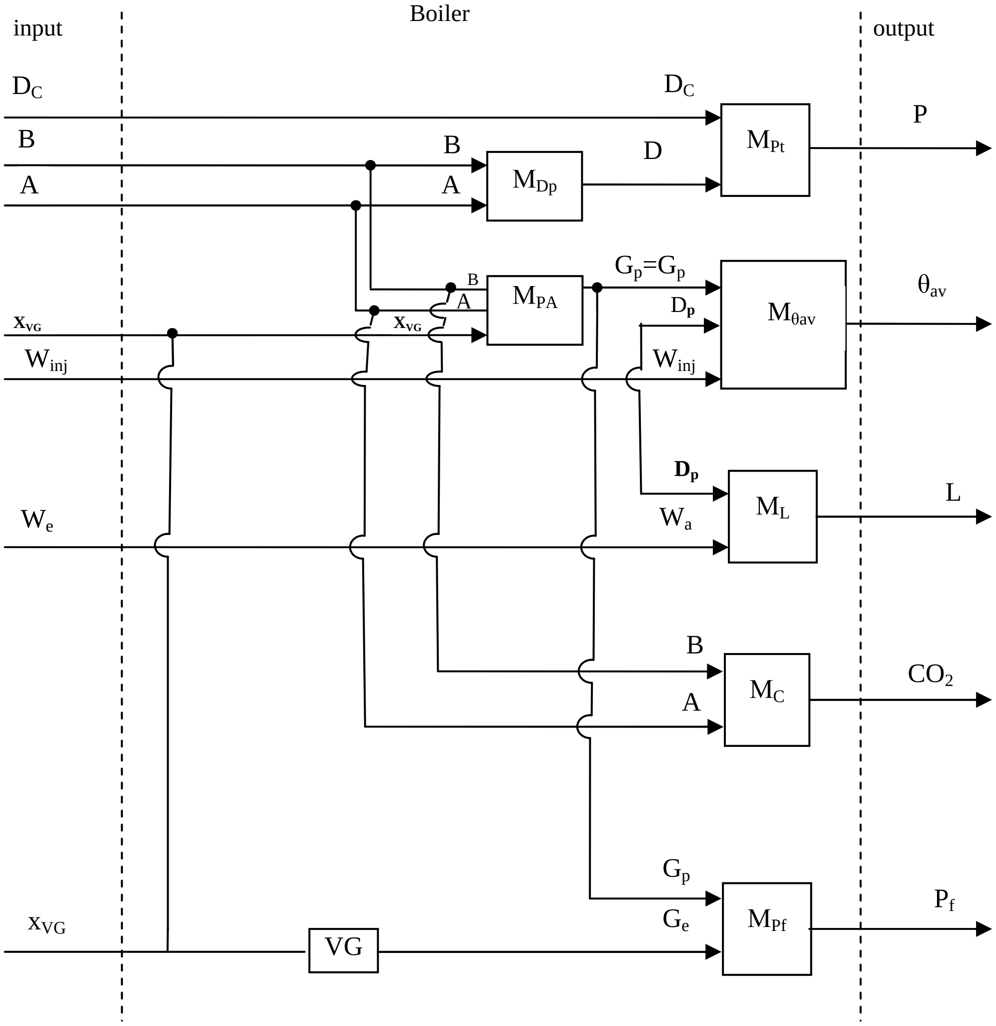

Fig. 1. The input-output variable for boiler

of input-output.

On the left side are passed the input variables (variable which can be command directly with the usual actuators), and in the right the measurable output variables under which it will develop the control structures with typical feedback.

B – the fuel flow
A – air
Ge – the evacuated gas
X_{VG} - the command of the gas ventilator
Winj – the injection flow
L – the water level in the drum
P_f – the furnace pressure
VG – the gas ventilator

It is important to choose the adequate input-output pair, which to assure an efficient control for the output variables through the input variable, with maxim effect and without main perturbation for the other output variables [2].

We will choose as the output variables that measurable variable how permit the obtaining a complete information on the state of the boiler in each moment of time (Fig. 1).

The dependence between input-output variables:

- The steam pressure *p* in the drum is a variable how depend on the boiler steam flow Dp and the turbine steam flow Dc.
- The furnace pressure depending on the resulted gas flow Gp and the evacuated gas flow Ge.
- The water level in the drum depending on the water flow, the boiler steam flow Dp and the turbine steam flow Dc.
- The fuel flow B is an independent variable, because it isn't affected by the other variable and it may be modified with the conveyor.
- The air flow, from the burning process, it must to has a value how corresponding with fuel flow B.
- The oxygen, oxide and carbon dioxide in the combustion gases depends on the air / fuel and therefore may be acting as the flow of air and fuel.
- The boiler steam flow Dp depends on the quantity of heat boiler developed in the furnace zone, meaning depends on the fuel flow and the air flow because the quantity of heat developed depends on both.
- The turbine steam flow Dc is, in relation to the boiler, a random variation of variable because the loading turbine depends on the conditions of operation of the energetically area.

We will choose the supply water flow for the control of the level drum, and the fuel flow for the control of the furnace pressure [3].

For the control of the steam pressure in the drum we will choose the heat transfer coefficient through radiation K_{re}, such as will be presents in chapter 2.

2 The automatic control structure of the steam boiler

Writing the balance thermal equation for burning process we obtain the next equation:

$$\begin{aligned}\frac{d(m_g H_{gf})}{dt} &= A \cdot C_{pA} \cdot T_A + K_{comb} \cdot B \cdot H_{cn} - \\ &- G_e \cdot C_{pg} \cdot T_g - K_{\mathrm{Re}}(T_m^4 - T_s^4)\end{aligned} \tag{1}$$

We make the next assumption [4]:

-The burning gases are treated like a perfect gas.

-The calorific power of fuel it is consider equal with the net heat and deviation from the ideal burning is represented by the burning coefficient K_{comb}.

-The heat exchange to furnace zone (convection, conduction and radiation) and the water from pipes, at the saturation temperature T_s, is equivalent with a direct heat exchange through radiation. T_m is the middle temperature of burning gases.

From the low of perfect gases we can approximate:

$$m_g H_{gf} = \frac{VC_{vg} P_f}{R} \tag{2}$$

where:

V- the volume used from the gases in the furnace zone;
C_{vg}- the specific heat of gases at constant volume;
R- the perfect gases constant;
P_f- the furnace pressure.

Writing the equation (1) depends by the furnace pressure P_f with T_g and T_m calculated, result:

$$\begin{aligned}\frac{VC_{vg}}{R}\frac{dP_f}{dt} &= AC_{pA}T_A + K_{comb}BH_{CN} - \\ &- G_e C_{pg} T_g - K_{\mathrm{Re}}(T_m^4 - T_s^4)\end{aligned} \tag{3}$$

We consider that in the drum exist two phases (steam and liquid in equilibrium) and the measured liquid level don't give as an exact information about the existent liquid quantity from the drum and we must to introduce the supplementary correction about water flow at the input of the drum.

The balance material equation for water from the drum is:

$$\frac{dm_e}{dt} = W_e - D_c - D_s \tag{4}$$

where:

m_e- the effective liquid mass from the drum;
D_c- the turbine steam flow from the drum;
D_s- the water outflow (through the broken pipes).

$$\frac{dm_e}{dt} = (\rho_{ls} - \rho_{vs})\frac{dV_e}{dt} + \begin{bmatrix} [V_e + V_{tv} + V_V(1-\alpha)]\dfrac{d\rho_{ls}}{dp}\dfrac{dp}{dt} \\ + (V_{lm} - V_l + V_V\alpha)\cdot\dfrac{d\rho_{vs}}{dp}\dfrac{dp}{dt} - \\ -V_V\dfrac{d\alpha}{dt}(\rho_{ls} - \rho_{vs}) \end{bmatrix} \quad (5)$$

where:
V_l- the liquid volume used in the drum;
V_{tv}- the descending pipes volume;
V_{lm}- the liquid volume measured with a transducer level;
V_e- the volume used from steam in the liquid space;
V_V- the volume used from steam in the drum;
α - the fraction used from steam in V_v;
ρ_{ls}, ρ_{vs}- the density at saturation for steam and liquid
p- the steam pressure in the drum.
The balance thermal for the water and steam from the drum and the boiler pipes:

$$\left\{\begin{aligned} & M_m C_m \frac{dT_s}{dp} + M_1\frac{dH_{ls}}{dp} + M_v\frac{dH_{vs}}{dp} - (V_{lm} + V_v + V_{tv}) + \\ & + (H_{vs} - H_{ls})\cdot[V_l + V_{tv} + V_v(1-\alpha)]\frac{d\rho_{ls}}{dp} + \\ & + (V_{lm} - V_l + V_v\alpha)\frac{d\rho_{vs}}{dp} \end{aligned}\right\}\frac{dp}{dt} =$$

$$= -W_l(H_{vs} - H_l) - D_p(H_{vs} - H_{ls}) + (1+\beta)* \quad (6)$$

$$*(H_{vs} - H_{ls})(W_l - D_c - D_p) + K_{\mathrm{Re}}(T_m^4 - T_s^4)$$

where:
M_m– the metal mass of the drum and pipes;
C_m – the specific heat of the metal;
M_l – the total liquid mass from drum and pipes;
M_v – the total steam mass from drum;
H_{vs}, H_{ls} – the steam and liquid content heat at saturation;
β -the steam fraction who condense in the drum;

We can express the measured liquid level depending on the liquid volume measured V_{lm}.

$$\begin{aligned} & V_{lm} = \frac{\gamma \cdot l \cdot R^2}{2} - \frac{1}{2}(R - L)R\sin\frac{\gamma}{2} \\ & \cos\frac{\gamma}{2} = 1 - \frac{L}{R}; \\ & V_v = \pi \cdot R^2 \cdot l - V_{lm} \end{aligned} \quad (7)$$

In the equation (1) to (6) we don't know exactly and will be modify on the time of functioning of the boiler the next variables:
-the necessary water flow W_e, controlled by the measured level;
-the heat transfer coefficient through radiation K_{re};
- the burning coefficient K_{comb}.
The structures of the program who witch realize the simulation is presented in the Fig. 2 .
We compare the measured values from the real process: the level in the drum, the water flow W_e, the pressure in the drum P_T and the relative pressure in furnace, with the measured values from the model of the boiler [1].
This results permit as to estimate the correction which be done in the model of the boiler to assure the tuning parameters correction's of the controllers.

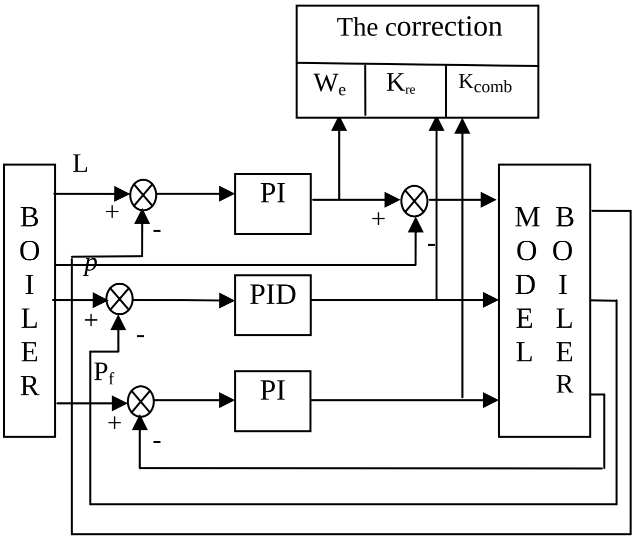

Fig. 2 The simulated model of the boiler

2.1. The design of the automatic control structure of the drum pressure

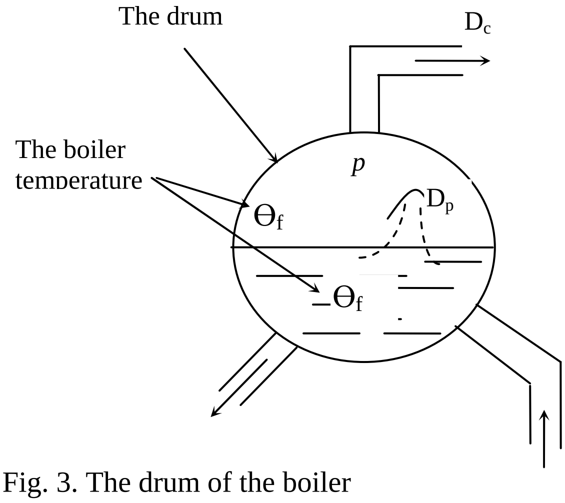

Fig. 3. The drum of the boiler

2.1.1.The mathematical model of the drum pressure

The variation speed of the steam pressure in the drum is proportional with the difference between the boiler steam flow and the turbine steam flow and inverse proportional with the thermal accumulation capacity of the boiler.

So, we can write the equation:

$$\frac{dp}{dt} = \frac{D_P - D_C}{C_a} \qquad (8)$$

where C_a is the thermal accumulation capacity.

The numerical value of the coefficient C_a depending on the next variable:

- The steam flow supplied in the boiler in stationary regime;
- The metal mass of the vaporization system;
- The rotation $m \in (0{,}1 \div 0{,}8)$

$$m = \frac{w_a}{D_{\max}} \qquad (9)$$

where w_a is water quantity from the boiler and $D_{\max}$ is the maximum steam flow.

Conform to this specification, result:

$$C_a(D_0)\frac{dp(t)}{dt} = D_P(t) - D_C(t)$$

$p(t)=p_0+\Delta p(t)$

$D_p(t)=D_{P0}+\Delta D_P(t)$

$D_C(t)=D_{C0}+\Delta D_P(t)$

For stationary regime:

$$D_{P0} = D_{C0} = D_0 \qquad (10)$$

For dynamic regime:

$$C_a(D_0)\frac{d\Delta p}{dt} = \Delta D_P - \Delta D_C \qquad (11)$$

After integration we obtain:

$$\Delta p\ (t) = \Delta p\ (t_0) + \frac{1}{C_a(D_0)}\int_{t0}^{t}\left[\Delta D_P(\tau) - \Delta D_C(\tau)\right]d\tau \qquad (12)$$

$$\Delta p\ (t) = \Delta p_1(t) + \Delta p_2(t) \qquad (13)$$

$$\Delta p(t) = \frac{K_{\Delta P}}{sT_{\Delta P}}\Delta D_P(s) - \frac{K_{\Delta P}}{sT_{\Delta P}}\Delta D_C(s) \qquad (14)$$

where:

$$K_{\Delta P} = \frac{p_N}{D_{\max}},\ T_{\Delta P} = \frac{C_{a0}\,p_N}{D_{\max}},\ C_{a0} = C_a(D_0)$$

According to equation (14) result the bock scheme from Fig. 4:

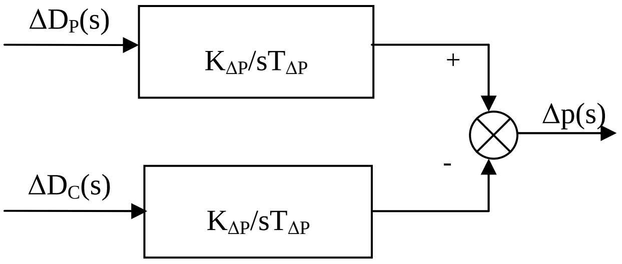

Fig. 4. The block scheme for the control of *p*

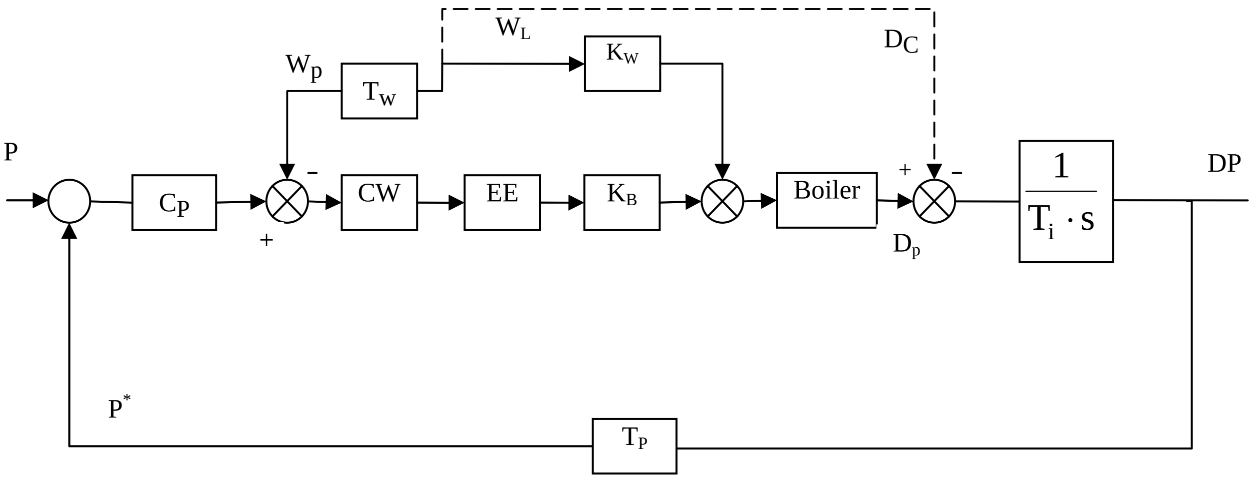

Fig. 5. The block scheme for the automatic control circuit of the drum pressure

2.2. The design of the automatic control structure of the furnace pressure

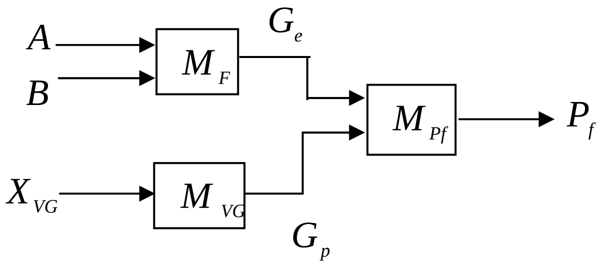

Fig. 6. The block scheme for the automatic control circuit of the drum pressure

2.2.1. The mathematical model of the furnace zone relative to the balance material

The oxidation chemical process of the fossil fuel (carbon, hydrogen and sulf) consist in the next relations:

$$C + O_2 = CO_2$$

$$Q_1 = 8140 Kcal/kg$$

$$C^{'} = \frac{C}{12 \cdot 100} 16{,}8 \cdot 10^{-3}$$

$$2C + O_2 = 2CO$$

$$Q_2 = 2473 Kcal/kg$$

$$H^{'} = \frac{H}{2 \cdot 100} = 9{,}5 \cdot 10^{-3}$$

$$2H + O_2 = 2H_2O$$

$$O^{'} = \frac{O}{32 \cdot 100} = 3{,}5 \cdot 10^{-3}$$

$$S + O_2 = SO_2$$

$$S^{'} = \frac{S}{32 \cdot 100} = 0{,}25 \cdot 10^{-3}$$

$$N^{'} = \frac{N}{28 \cdot 100} = 0{,}14 \cdot 10^{-3}$$

The theoretical oxygen quantity:

$$O_t = C^{'} + \frac{H^{'}}{2} + S^{'} - O^{'} = 0{,}0183\ moli/gram$$

The necesar theoretical air:

$$\alpha_T = \frac{O_t}{0{,}21} = 0{,}087$$

The amount of excess air to be introduced:

$$\alpha = a \cdot \alpha_t = 2{,}5\ m^3/kg$$

a=1,3 is the coefficient of excess air.
The total quantity of gas resulting from the combustion complete a gram of fuel is g_p.

$$g_p = 22{,}4 \cdot \left(mco_2 + mh_2o + mn_2 + mo_2 + mso_2\right)$$

$$G_P = g_p \cdot B$$

$$G_P = k_1 \cdot B + k_2 \cdot A$$

$$A = \alpha \cdot B$$

$$k_1 = 22{,}4 \cdot \left(C + H + W + N + O + S\right) + 5 \cdot Z_{inj}$$

$$k_1 = 1{,}33;\ k_2 = 0{,}838$$

$$B = 50{,}83 kg/s;\ A = 127{,}007;\ G_P = 174{,}008$$

The furnace zone may be treated as a gas container at constant volume and having behavior such with a perfect gas [5].

$$P_f \cdot V_f = m \cdot R \cdot T_f$$

The material balance equation for the mixture of gas volume will be:

$$\frac{dm}{dt} = G_p - G_e$$

where G_e represents the evacuate gas flow.

$$\frac{V_f}{R \cdot T} \cdot \frac{dP_f}{dt} = G_p - G_e$$

The evacuate gas flow G_e depends on the furnace pressure and the fluidic resistance appearing on the channel of the evacuate gas and the position adjustment flap of the gas ventilator.

$$\frac{V_f}{R\cdot T}\cdot\frac{d\Delta P_f}{dt}=\Delta G_p-\Delta G_e$$

$$G_e=k_3\cdot P_f+k_4$$

$$T_2=\frac{V_f}{R\cdot T_f\cdot k_3}=1{,}05s$$

2.2.2 The mathematical model of the furnace zone in terms of heat balance

The thermal balance equation for gas:

$$\rho\cdot V_f\cdot C_f\cdot\frac{dT_f}{dt}=P_{ci}\cdot B_2+\rho_{ai}\cdot C_{ai}\cdot T_{ai}\cdot A-$$
$$-P_f\cdot C_f\cdot G_p-k_r\left(\left(\frac{T_f}{100}\right)^4-\left(\frac{T_a}{100}\right)^4\right)$$

$B_2=k_5\cdot B_1$ the fuel flow of entrance and burned

$$k_5=0{,}965$$

The water-steam balance equation:

$$\left(C_{ab}\cdot X_{ab}\cdot\rho_{ab}+C_{ab}\left(1-X_{ab}\right)\cdot k_{rap}\right)\cdot V\cdot\frac{dT_a}{dt}=$$
$$=k_r\cdot S\cdot\left(\left(\frac{T_f}{100}\right)^4-\left(\frac{T_a}{100}\right)^4\right)+C_{api}\cdot T_{api}\cdot F_{ai}-$$
$$-\left(C_{ap}\cdot X_{ab}+C_{ab}\cdot\left(1-X_{ab}\right)\right)\cdot T_a\cdot F_a$$

T_f the gas temperature at output of the furnace zone

P_{ci} - the inferior calorifical power of the fuel

C_{ai}, T_{ai}, A - the specific heat, the temperature, the entrance air fuel

k_r - the heat transfer coeficient trough radiation

S – the surface of the shield

T_a - the composition temperature from superheater

C_{ab} - the specific heat of steam from superheater

C_{ap} - the specific heat of water from superheater

C_{api}, T_{api}, F_{ai} - the specific heat, the temperature and the water flow at the entrance

V – The interior volume of the superheater

X_{ab} - the steam concentrantion from composition

Trough linearization, in stationary regime, we obtain the next equation:

$$T_3\cdot\frac{d\Delta T_f}{dt}=k_6\cdot\Delta B_2+k_7\cdot\Delta T_{ai}+k_8\cdot\Delta A-\Delta\cdot T_f-$$
$$-k_9\cdot\Delta G_e+k_{10}\cdot\Delta T_{at}$$
$$T_4\cdot\frac{d\Delta T_a}{dt}=k_{11}\cdot\Delta T_f+k_{12}\cdot\Delta T_{api}-\Delta T_{at}-\Delta\cdot T_f-$$
$$-k_{13}\cdot\Delta F_{at}$$

The equation balance of flow:

$$\Delta F_a=\Delta F_{ai}$$

The coefficients T and k in stationary regime are determined by the following amounts:

$P_{ci}=1652Kcal/Kg$

$B_2=0{,}965x86{,}112$

$\rho_{ai}=0{,}672Kg/m^3$

$C_{ai}=1094{,}6J/KgK$

$T_{ai}=603K$

$A=140{,}4m^3/s$

$P_f=0{,}404Kg/m^3$

$T_f=1373K$

$C_f=3146{,}6J/KgK$

$G_P=189{,}2m^3/s$

$k_r=8{,}64$

$S=2384m^2$

$T_a=589{,}6K$

$T_{api}=562{,}4K$

$X_{ab}=0{,}82$

$C_{api}=2136{,}2J/KgK$

$F_{api}=164{,}1Kg/s$

$C_{ab}=4986{,}6J/KgK$

$C_P=3142{,}5K/KgK$

The control scheme for furnace pressure is presented in Fig. 7

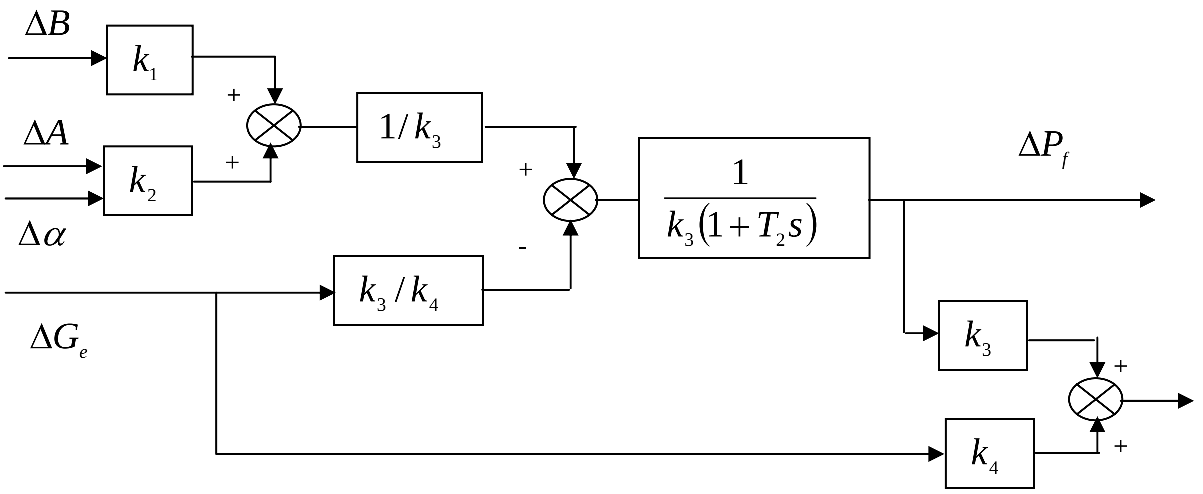

Fig. 7. The control scheme for furnace pressure

2.3. The design of the automatic control structure of the water level in the drum

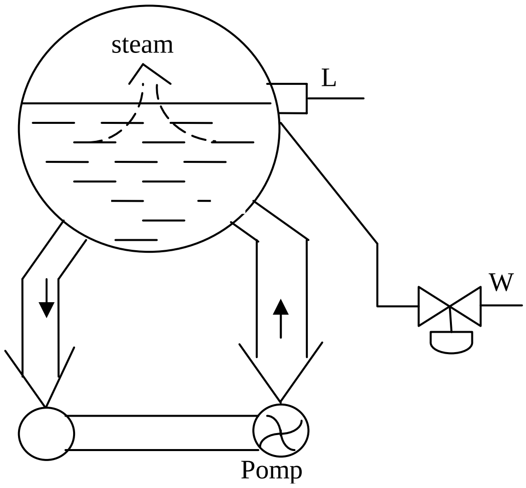

Fig. 8. The drum of the boiler

W_e- the command variable for control of the water level in drum (at boilers with drum) or control vaporization zone at boilers without drum

$D_p = W_e$, so L= constant,D_p is not dictated by W_e

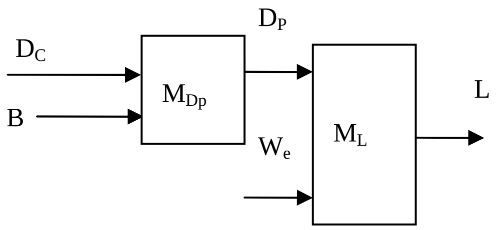

Fig. 9. The block scheme for the water level in the drum

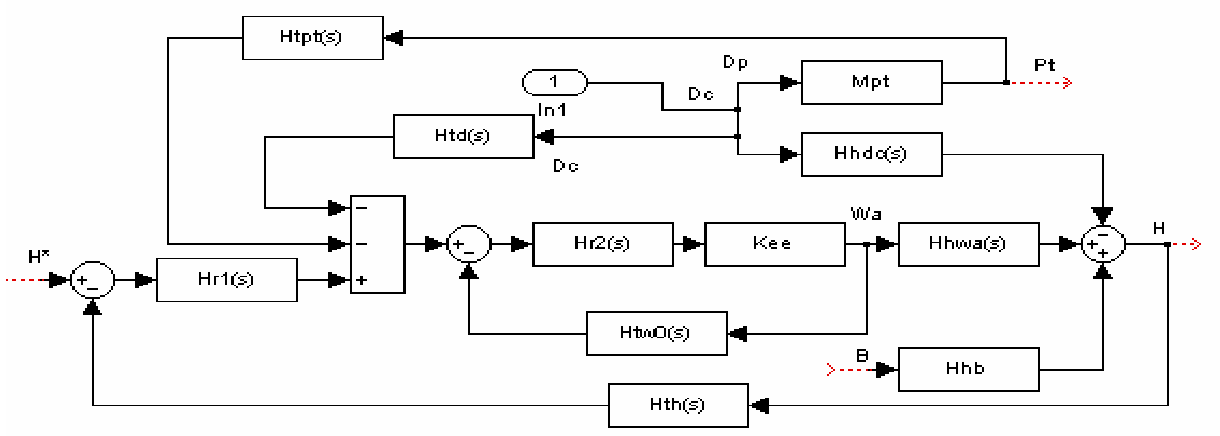

Fig. 10. The block scheme for control of the water level

2.4. Adjusting the fuel volume

No matter we talk about a natural circulation boiler or about a forced crossing one, generally *the task adjustment loop* follows to maintain constant the steam pressure at the boiler's output, modifying the fuel quantity and the air for burning volume.

For the boilers which work on *fuel oil*, we use a *cascade loop control*, which contains a main task regulator (*PID* type) and a fuel regulator (*PI type*) in following loop.

The stability of the loop may be increased by introducing in the adjustment the steam volume signal as a perturbation. It is observed that in this case, the quantity of coal is represented by the sum of revolutions of the redler belts.

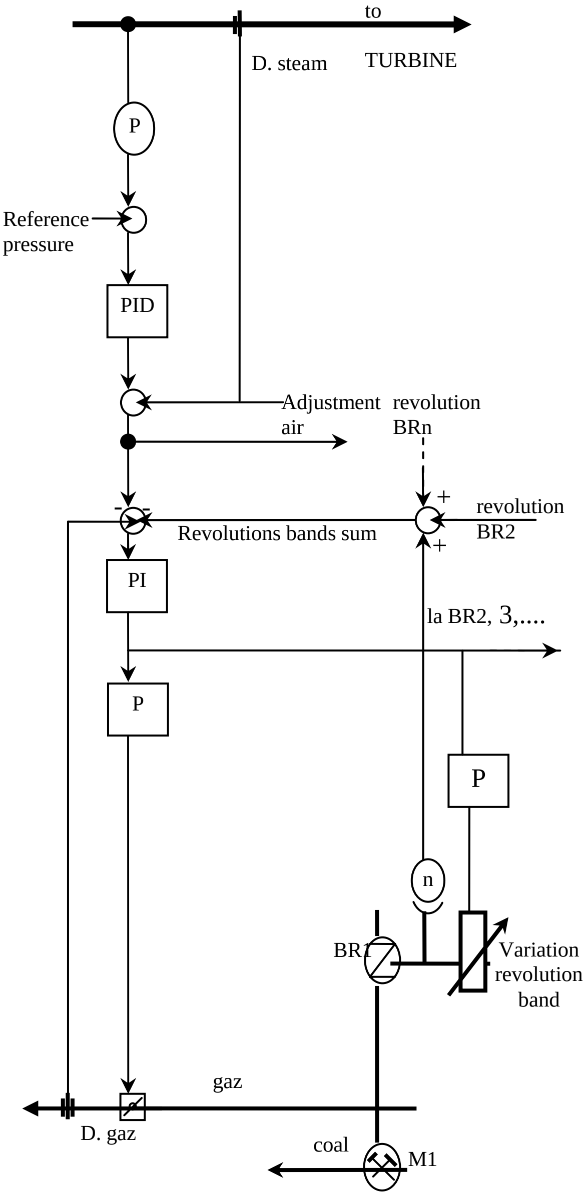

Fig.11. The control loop in cascade from boiler with gases and coal

The execution elements are revolution variators of the belts (which may be frequency converters or mechanical variators for revolution) and the shutter for the gas volume adjuster.

These are commanded through some proportional regulators. The main task regulator (*PID steam pressure regulator*) and the volume of steam took over from the turbine establish a reference value for the fuel quantity (gas + coal), which is then compared to the sum of gas and coal volumes, and the obtained signal is introduced in the fuel regulator which will determine increase or decrease of the fire power of the boiler (Fig.11).

2.4.1. The mathematical model of the automated process

The following equations are deduced from the material evaluation and thermo evaluation:

- the transfer function for the transporting belt:

$$H_{BT} = e^{-\tau_b s} = \frac{B_M}{B_B}, \; \tau_b = \frac{l_B}{v_B}$$

- the equation of the coal mass:

$$m_B(t) = \frac{V_M \cdot C_B}{g_2} \cdot B_2(t)$$

Applying the Laplace transformation, it results through simple transformations the transfer function of the coal mill:

$$H_M = \frac{1}{T_M s + 1} = \frac{B(s)}{B_M(s)}$$

3 The experimental results

The experimental results are obtained by simulation under MATLAB Simulink.

The air flow A, from the burning process, it must to has a value how corresponding with fuel flow B: $A=k \cdot B$, $k=2,5$.

If we modify the coefficient k, using the control structure from Fig. 2 we can determinate the correction which be done in the model of the boiler to assure the tuning parameters correction's of the controllers.

In Fig. 13 and Fig. 14 we have the correction's values K_{re}, K_{comb} for k=2,6, respective for k=2,4.

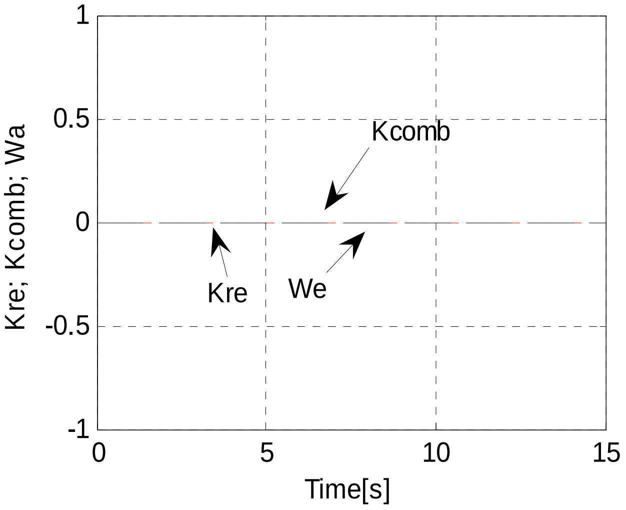

Fig. 12. The corrections at A=2,5·B

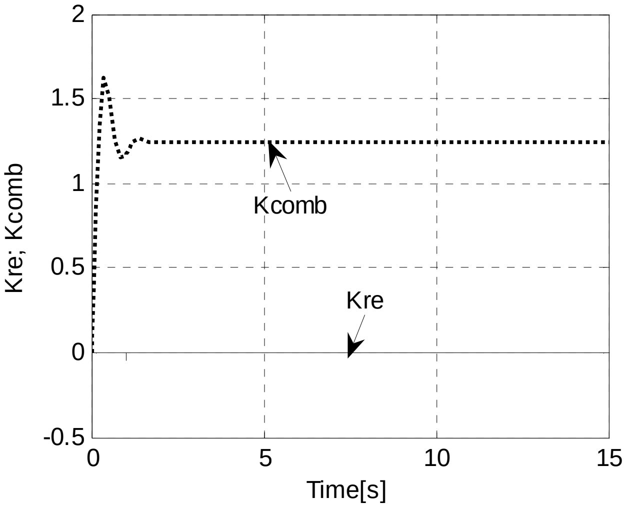

Fig. 13. The corrections at A=2,6·B

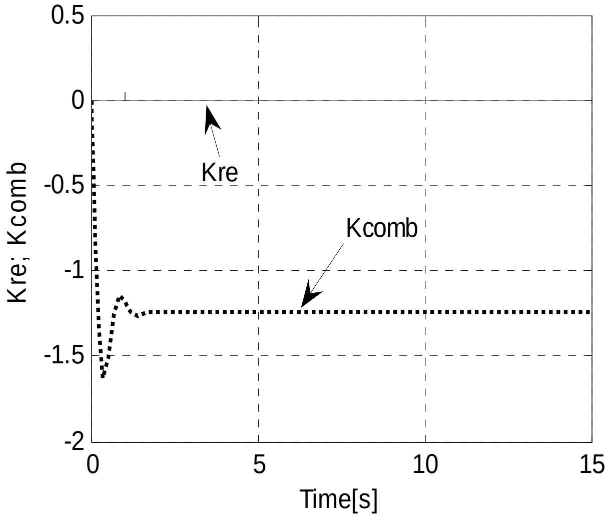

Fig. 14. The corrections at A=2,4·B

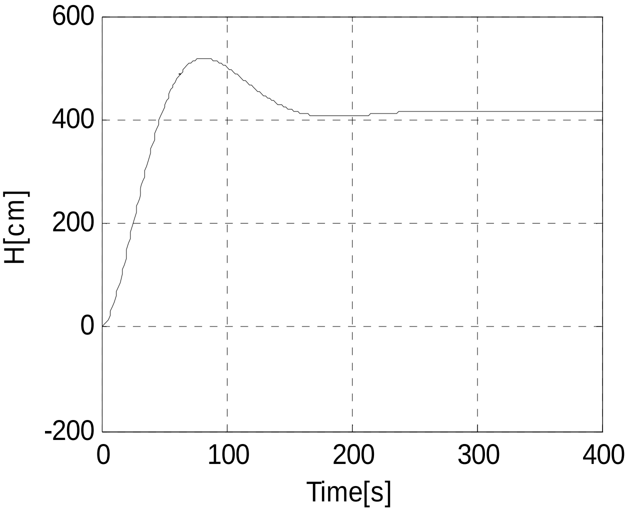

Fig. 15. The water level in the drum

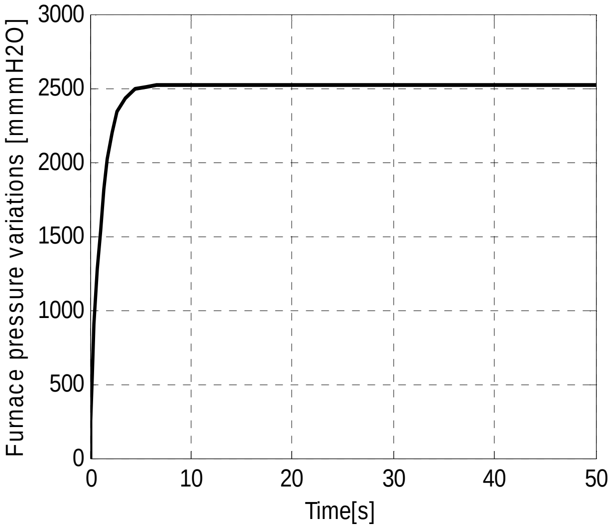

Fig. 16. The furnace pressure variations

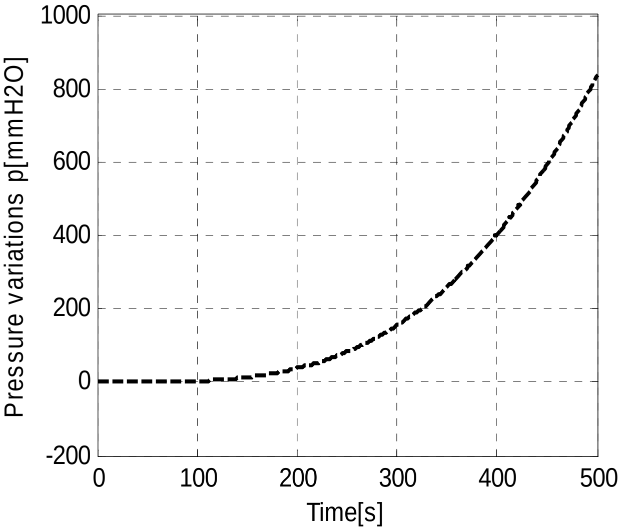

Fig. 17. The steam pressure variations in the drum

In Fig. 15, Fig. 16 and Fig.17 is represent the level in the drum, the furnace pressure variations and respective the steam pressure variation in the drum.

4 Conclusion

We have realized the simulated model of the boiler and the control structure for the boiler.

This structure of simulation permit as to estimate the correction which be done in the model of the boiler to assure the tuning parameters correction's of the controllers.

We intend to realize a program, which can be offer to users the dedicated software for fault detection and the solution for the value corrections which be done in the model of the boiler.

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