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MATHEMATICAL MODEL OF THE PULVERISING PLANT AS A MASS ACCUMULATOR WITH ASSOCIATED DYNAMICS OF BOTH IMPELLER AND COAL DRYING PROCESS

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Abstract. *In this paper, based on the real, acceptable assumptions, first nonlinear and then linearized mathematical model of the pulverising plant, are developed, which include, for the first time, the dynamics of the coal drying process having significant influence on the overall dynamic behaviour of the considered plant. The obtained model can be used efficiently for the analysis as well as for the synthesis of control for this complex energy process.*

1. INTRODUCTION

The analysis and the design of the modern automatic control systems at the present degree of the science and the technology as well as the necessity of fulfilling very severe demands for the quality of the dynamic behaviour of the system on the whole demand a knowledge of their sufficiently accurate mathematical models.

The dynamic behavior of the pulverising plants is of the fundamental importance to a function of the steam generation plant on the whole. The knowledge of the pulveriser dynamics can make the control of the steam generation plant easier to a great extent as well as it can eliminate a certain problems that can arise during their common function.

The dynamic behaviour of the coal pulverisers was a subject of significant interest to a huge number of the scientists and the engineers. A series of the models suitable for a certain purposes and the practical use have been developed. The basic characteristic of

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those models was stated in the fact that all of them were modeled as a mass accumulators only. The impeller dynamics and the great inertial capability of the pulveriser were neglected as a rule due to the fact that a lot of variables that form active and passive moments and forces haven't been known or couldn't have been found correctly. It is perfectly clear that a certain number of these variables have stochastic character making this complex problemacy even more complex. The subject of this study is an attempt to add to the dynamics of pulveriser as a mass accumulator the associated dynamics of its impeller as well as the drying process, so the energy and mass flows united in that way can complete a notion of the real dynamic behaviour of the pulveriser.

2. DESCRIPTION OF PROCESS TAKING PLACE IN THE COAL PULVERISING PLANT

For the preparation of the powdered coal a different kinds of the pulverisers are used which basicaly differ on the mechanism of pulverisation. Due to the fact that the pulverisers are rotating machines, the type of pulverisation is determined by rotative speed of their impellers. For that reason the pulverisers are classified by their rotative speed into slow speed pulverisers, medium speed pulverisers and high speed pulverisers.

For the high speed pulverisers it is characteristic that the pulverising process takes place mostly by impact. In aim to prepare the powdered coal for the industrial and energy steam generators in our country the fan mills are used most often. They are most convenient for the pulverisation of the domestic brown-lignite coals and lignite, which consist most of the domestic coal supplies of the solid fuels.

The construction of the fan mill is shown in Fig. 1. The coal is brought in the pulveriser through the inlet throat (1) together with the combustion products recirculated from the furnace. During its passage through the impeller (2), the coal is pulverised by impact with massive impact blades (3) placed in a similar way as blades of the radial fans. During the pulverising process a sudden release of transport fluid occurs due to the intensive drying taking place simultaneously with the pulverising process. The aeromixture is brought out from the pulveriser through control flaps in the inertial separator where, due to inertial force during the deflection of the flow the coarse, insufficiently pulverized particles separate. These particles return through the funnel (7) to the pulveriser inlet and pulverise again to achieve satisfactory grain structure of the powdered coal.

Together with the coarse particles from the separator returns a considerable quantity of the cooled drying products causing the increased energy consumption for the pulverisation. During the pulverising process the breakage of the coal pieces occurs at their weakest points, so for that reason the ground coal particles are more rigid and affect wear of the pulveriser.

For a credible mathematical modeling it is necessary to adopt a control boundary. From description of the construction it is obvious that a certain quantities of the coal and gases return to the process, but these return flows will not be taken into account. In practice, the drying process starts as soon as the coal and drying medium come into contact, but later accepted assumptions will locate precisely place where the drying occurs depending on the required mathematical model. It is necessary to emphasize that there are a certain quantities of the cool air and harmful gases in the process. Neither of these won't be taken into account.

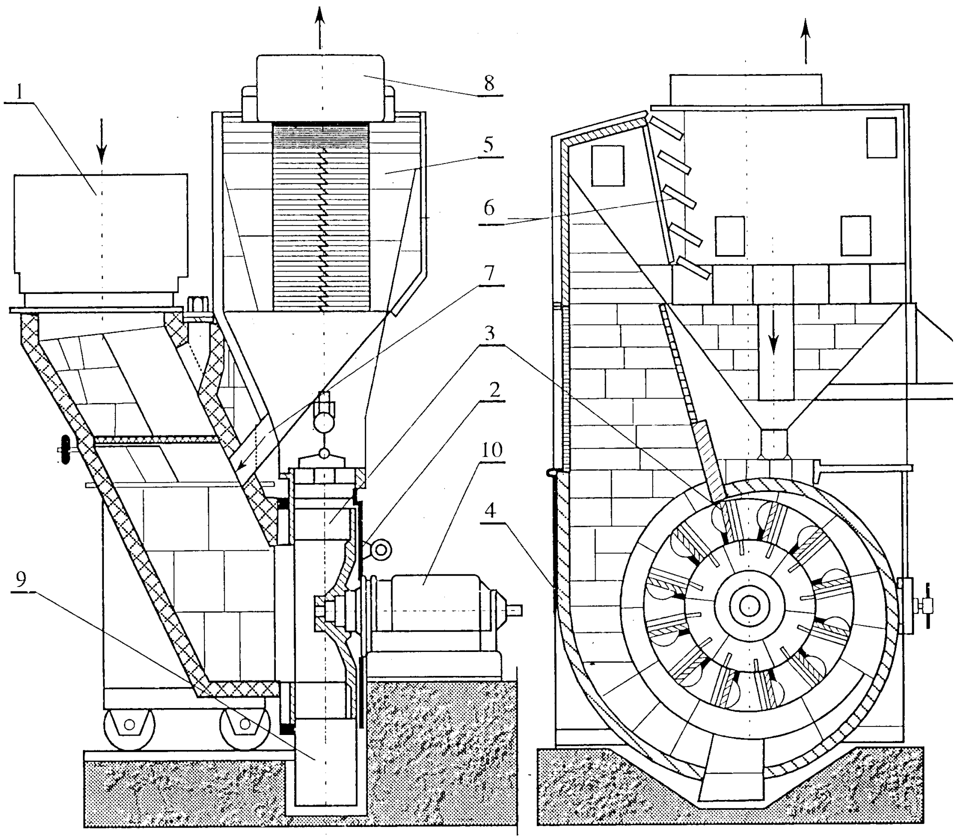

Fig. 1. 1. Coal and gases inlet; 2. Impeller; 3. Impact blades; 4. Pulveriser casing; 5. Pulveriser separator; 6. Control flaps; 7. Return duct for the coarse ground particles; 8. Aeromixture outlet; 9. Channel for collection of the iron particles; 10. Double-row bearing

From above stated it follows that only the processes taking place in the pulveriser, more precisely in the casing of the pulveriser impeller, will be relevant. It practicaly means that both the coal entering the pulveriser and the coal remaining in the separator will be taken into account as inlet coal flow G_{Bi}, and all gaseous products will be considered as gas mass flow G_g.

3. Mathematical model of coal pulverising plant as a mass accumulator with associated dynamics of impeller

This problemacy has been discussed in detail in the study of Debeljković et al. (1997). In addition, a brief preview of obtained results will be given, in aim to understand and conceive completely the basic contributions of this study presented in addition.

3.1 Adoption of Process Model

Mathematical modeling of this process will be executed for its model characterized by the following assumptions.

A1: The coal drying process occurs and finishes before the coal is brought in the pulveriser.

A2: Quantity of the gaseous combustion products is negligible small compared to quantity of the coal contained inside of the pulveriser during the pulverisation.

A3: The coal is ideal and isotropic material.

A4: Moment of inertia of the impeller is constant.

Discussion and justification of the presented assumptions can be found in the studies of Debeljković (1987) and Begović (1996).

In Fig. 2a is given a schematic diagram of a pulveriser, and in Fig. 2b is given its block diagram.

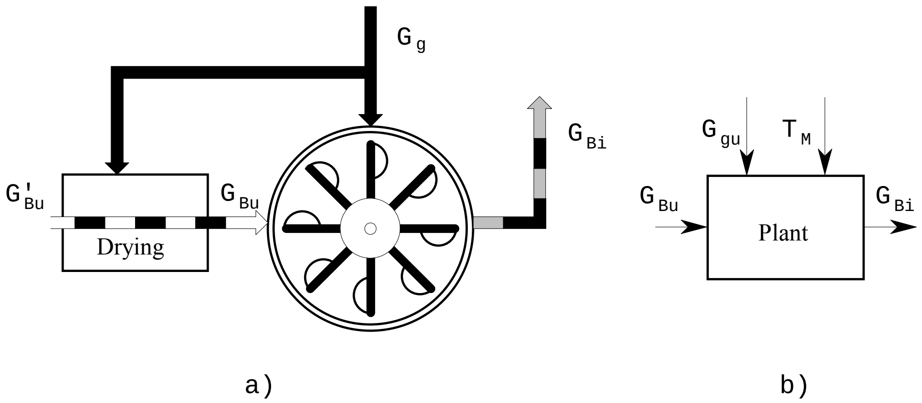

Fig. 2.

3.2 Mathematical Model of Process

The basic balance equations describing the dynamical behaviour of the pulveriser are:

*The mass balance equation for the coal:**

$$\frac{dm_B(t)}{dt} = G_{Bi}(t) - K_{SB}G_{Bo}(t). \tag{1}$$

The mass balance equation for the gaseous combustion products:

$$\frac{dm_v(t)}{dt} = G_{gi}(t) - K_{Sv}G_{go}(t). \tag{2}$$

The kinetic energy conservation equation for the pulveriser impeller:

$$\frac{dE_k}{dt} = \frac{1}{2}\cdot\frac{d\,/J\omega^2(t)/}{dt} = \frac{\pi^2}{90}n(t)\frac{dn(t)}{dt} = N_a(t) - N_p(t). \tag{3}$$

The detailed derivation of the appropriate mathematical model is given in the study of Debeljković et al. (1997) and it have resulted in the following system of the differential

* The list of used symbols is given in Appendix A

equations:

$$T_M \frac{dx_{o1}(t)}{dt} + x_{o1}(t) = u_1(t) + T_M \frac{dz_1(t)}{dt}, \tag{4}$$

$$T_R \frac{dx_{o2}(t)}{dt} + x_{o2}(t) + K_M x_{o1}(t) = u_2(t), \tag{5}$$

where:

$$\begin{gathered} x_{o1}(t) = \overline{\Delta G_{Bo}}(t), \quad x_{o2}(t) = \overline{\Delta n}(t), \quad z_1(t) = \overline{\Delta G_{vi}}(t), \\ u_1(t) = \overline{\Delta G_{Bi}}(t), \quad u_2(t) = \overline{\Delta U}(t). \end{gathered} \tag{6}$$

and $\overline{\Delta}(.)$ denotes relative variations of the relevant variables.

A block diagram corresponding to the linearized mathematical model of this process is shown in Fig. 3. and it does not include the pure time lag due to the presence of the conveyer for the coal which is placed at its inlet.

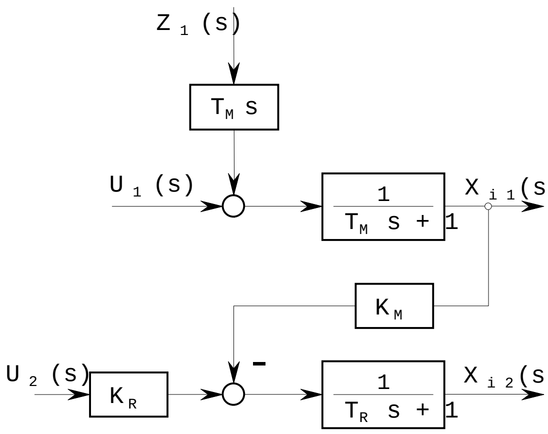

Fig. 3.

4. MATHEMATICAL MODEL OF PULVERISING PLANT AS A MASS ACCUMULATOR WITH ASSOCIATED DYNAMICS OF BOTH IMPELLER AND COAL DRYING PROCESS

Before presentation of the appropriate mathematical model, it is necessary to describe above mentioned technological operation i.e. the drying process.

The drying can be classified into mechanical-heat diffusive operations and it is a process of removing moisture from a material. In essence, the drying represents a process of heat and mass exchange between a material which is dried and a drying medium. In case of fan mills, a fluid used for drying sonsists of combustion products recirculated from the furnace, air heated in the air heater, recirculated cool combustion products, harmful air and moisture evaporated from the coal. All of them constitute the drying medium, and in the equations they are considered as a gas mass flow G_g.

Kinds of molecular bonds between moisture and material, structure and composition of dried material determine a character of changes occuring during the drying. Driving forces of this diffusive process break above mentioned bonds and the moisture is released from the material. As a rule it can't be eliminated completely, so in description of the drying process we consider only the elimination of the surface and sorption moisture, while the process of removing crystallization moisture is considered separately. So the drying process is considered as both the transfer of the moisture from the surface of wet material (the coal in this case) to the drying medium and the transport of the moisture inside the material itself, where for the analysis are relevant capillary phenomena, diffusive speed and some other effects in the material itself which won't be considered here.

In Fig. 4.a is given a schematic diagram of a plant and in Fig. 4b is its block diagram.

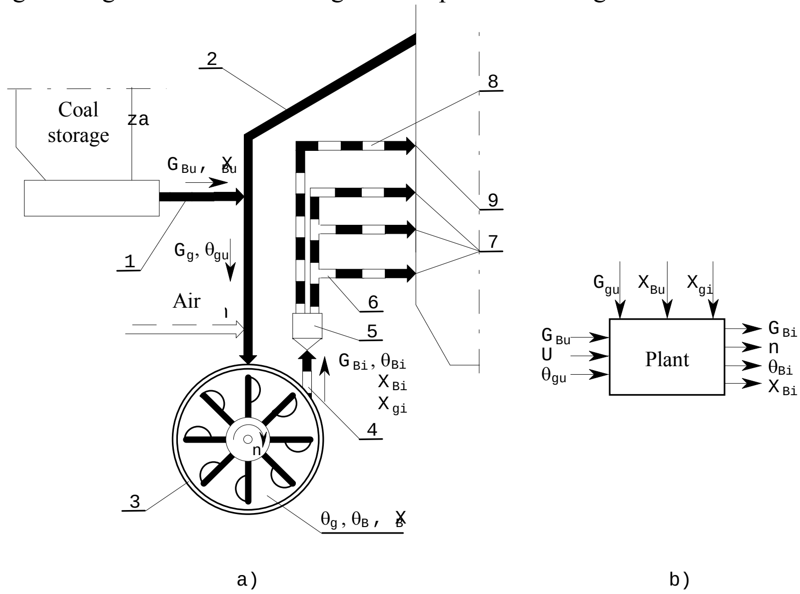

Fig. 4. 1. Coal supply; 2. Duct for gases recirculation; 3. Coal pulveriser; 4. Aeromixture duct; 5. Aeromixture separator; 6. Duct for primary flow of aeromixture; 7. Main burners; 8. Duct for secondary flow of aeromixture; 9. Burner for exhaust gas

A good knowledge about the process itself is a precondition for mathematical description of the drying process dynamics. Due to extreme complexity of the process, it must be idealized, but in such way that physiognomy of the process wouldn't be changed. Real process is characterized by the distribution of both moisture and temperautre fields in the material as well as in the drying medium. Special complexity results from the fact that motion of the material is rather chaotic and stochastic, so real motion of the material is not known practicaly. With existing phenomena of dried material nonhomogeneity, time lag and nonstationarity, it is clear that mathematical description of the drying process associated with the impeller dynamics and the mass motion includes a high degree of complexity.

4.1 Adoption of Process Model

Compared to above accepted simplifications for derivation of the model of this, now more complex process, following assumptions must be adopted.

A5: The drying process takes place in the casing of the pulveriser impeller.

A6: Due to good mixing of the material in the impeller both the moisture content and temperature fields are considered to be homogenous.

A7: Heat transferred from the impact blades to the material is negligible.

A8: Heat accumulated in the wall of the pulveriser impeller is negligible.

A9: Radiative exchanged heat, if any, is negligible.

A10: Heat brought in the process by evaporated moisture is negligible.

A11: Heat capacities and convective heat transfer coefficient are constant.

A12: Enthalpies of the drying agents can be expressed as a functions of appropriate temperatures.

A13: With sufficient accuracy it can be adopted that $\theta_{go} \approx \theta_g$, as well as $\theta_{go} \approx \theta_{Bo}$, $\theta_B \approx \theta_{Bo}$.

A14: With sufficient accuracy it can be adopted that $X_B \approx X_{Bo}$.

4.2 Mathematical Model of Process

The basic balance equations which characterize the drying process in the pulverising plant, according to Buzurović (1997), are:

Energy balance equation for the drying agent

heat accumulated in medium	=	heat of medium at inlet	–	heat of medium at outlet	–	heat transferred to coal by convection

$$m_g \frac{di_g(t)}{dt} = G_{gi}(t) i_{gi}(t) - G_{go}(t) i_{go}(t) - \alpha a \rho_g V_M [\theta_{gi}(t) - \theta_B(t)] \quad (7)$$

i.e. after use of the accepted assumptions:

$$C_{pg} \rho_g V_M \frac{d\theta_{Bo}(t)}{dt} = C_{pg} G_{gi}(t) \theta_{gi}(t) - C_{pg} K_{SV}^{-1} G_{gi}(t) \theta_{Bo}(t) - \alpha a \rho_g V_M [\theta_{gi}(t) - \theta_{Bo}(t)]. \quad (8)$$

Mass balance equation for the moisture contained in the coal

quantity of moisture accumulated in coal	=	quantity of moisture in coal at inlet	–	quantity of moisture in coal at outlet	–	quantity of moisture transferred to drying medium

$$m_B \frac{dX_B(t)}{dt} = G_{Bi}(t) X_{Bi}(t) - G_{Bo}(t) X_{Bo}(t) - G_{go}(t) X_{go}(t) \quad (9)$$

i.e. after use of the accepted assumpitons:

$$K_{SV} K_M V_M \frac{G_{Bo}(t)}{G_{Bi}(t)} \cdot \frac{dX_B(t)}{dt} = G_{Bi}(t) X_{Bi}(t) - G_{Bo}(t) XB_o(t) - K_{SV}^{-1} G_{gi}(t) X_{go}(t) \quad (10)$$

Adopting relative perturbations in the relevant values a following choice is made:

$$x_{o3}(t)=\overline{\Delta\theta}_{Bo}(t),\quad x_{o4}(t)=\overline{\Delta X}_{Bo}(t),\quad u_{3}(t)=\overline{\Delta\theta}_{gi}(t),$$
$$z_{2}(t)=\overline{\Delta X}_{Bi}(t),\quad z_{3}(t)=\overline{\Delta X}_{go}(t) \tag{11}$$

so it is possible to obtain a system of differential equations which presents nonlinear mathematical model of the coal pulverising plant including dynamics of the motion of the material, the impeller dynamics and the drying process:

$$\frac{dx_{o1}}{dt}=\frac{u_{1}(1+z_{1})}{T_{M}}+\frac{1+x_{01}}{1+z_{1}}\cdot\frac{dz_{1}}{dt}-\frac{x_{01}}{T_{M}(1+z_{1})}, \tag{12}$$

$$\frac{dx_{o2}}{dt}=\frac{\Omega_{1}U_{N}}{n_{N}}u_{2}-\Omega 2x_{o2}-\Omega_{3}n_{N}{}^{2}[(1+x_{o2})^{3}-1]-\Omega_{4}G_{BoN}[(1+x_{o1})(1+x_{o2})-1], \tag{13}$$

$$\frac{dx_{o3}}{dt}=\frac{1}{C_{pg}\rho_{g}V_{M}\theta_{BoN}}\{C_{pg}G_{goN}\theta_{giN}[(1+u_{3})(1+z_{1})-1]-C_{pg}K_{SV}{}^{-1}G_{giN}\theta_{BoN}[(1+z_{3})(1+x_{o3})-1]$$
$$-\alpha a\rho_{g}V_{M}\theta_{BoN}(\frac{\theta_{giN}}{\theta_{BoN}}u_{3}-x_{o3})\}, \tag{14}$$

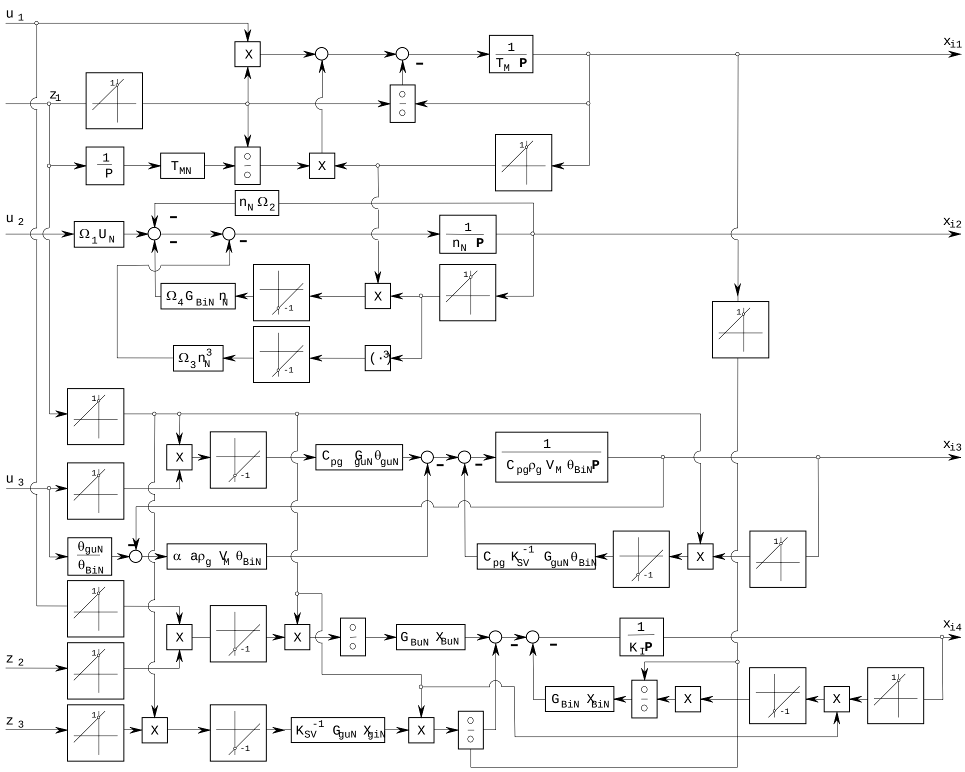

Fig. 5.

$$\frac{dx_{o4}}{dt}=\frac{1}{K_1}\cdot\frac{1+z_1}{1+x_{o1}}\{G_{BiN}X_{BiN}[(1+u_1)(1+z_2)-1]-G_{BoN}X_{BoN}[(1+x_{o1})(1+x_{o4})-1]$$
$$-K_{SV}{}^{-1}G_{giN}X_{goN}\cdot[(1+z_1)(1+z_3)-1]\}. \quad (15)$$

All time constants and the other constants can be calculated on the base of the geometrical-constructive and the working parameters of the pulverising plant given in summary in Appendix B and Buzurović (1997).

In Fig. 5. is given a block diagram which corresponds to the nonlinear mathematical model of the pulverising plant.

Under assumption that all condition for the linearization are fulfilled, the obtained model reduces to:

$$T_M\frac{dx_{o1}(t)}{dt}+x_{o1}(t)=u_1(t)+T_M\frac{dz_1(t)}{dt}, \quad (16)$$

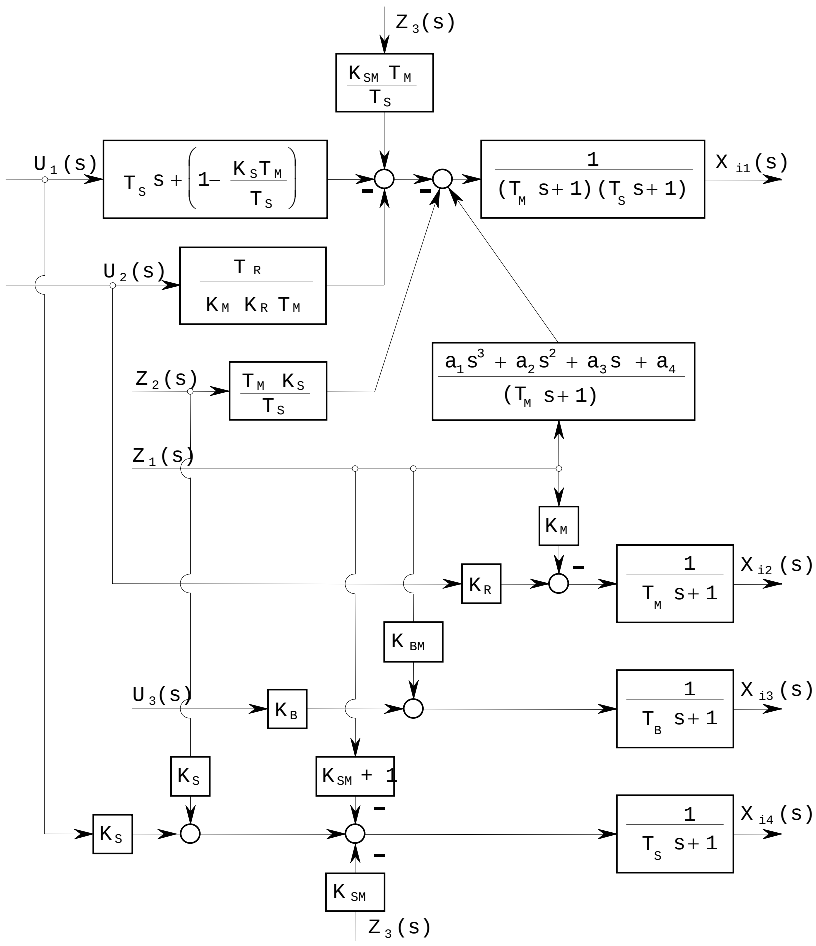

Fig. 6.

$$T_g \frac{dx_{o2}(t)}{dt} + x_{o2}(t) + K_M x_{o1}(t) = K_g u_2(t), \tag{17}$$

$$T_B \frac{dx_{o3}(t)}{dt} + x_{o3}(t) = K_B u_3(t) + K_{BM} z_1(t), \tag{18}$$

$$T_S \frac{dx_{o4}(t)}{dt} + x_{o4}(t) + x_{o1}(t) = K_S u_1(t) - K_{SM} z_1(t) + K_S z_2(t) - K_{SM} z_3(t). \tag{19}$$

with appropriate block diagram shown in Fig. 6.

5. CONCLUSION

The coal pulverising plant is a very complex object for automatic control, because multiple exchange of energy occurs in it due to the nature of process that leads to the complex mathematical models describing its dynamical behaviour. In this study a model of such kind is derived based on basic laws of mass conservation, energy conservation and law of conservation of momentum for the transient states of the process.

6. APPENDIXES

APPENDIX A - THE LIST OF USED SYMBOLS

Basic symbols

A	Cross-section	p	Pressure
a	Specific area	R	Gas constant, residue on the sieve
B	Milling capacity	r	Heat of evaporation
b	Width of the impeller	s	Complex operator
c	Specific heat capacity, constant	T	Time constant
D	Drying fluid flow	t	Time
d	Diameter	U	Voltage
E	Energy	u	Manipulated variable
G	Mass flow	V	Volume
H	Head	w	Speed of the impeller
i	Specific enthalpy	x	State variable, absolute moisture content
J	Moment of inertia	x_o	Output variable of the object
j	Current index	x_i	Input variable of the object
K	Constant	z	Disturbance variable
k	Index, constant of the ground material internal structure	α	Convective heat transfer coefficient
		β	Mass transfer coefficient
K_{SB}	Coal drying coefficient	θ	Temperature
K_{SV}	Drying coefficient	μ_1	Friction coefficient of the ground material
m	Mass	ρ	Density
N	Power	Ω	Coefficient
n	Rotative speed	ω	Angular speed
P	Symbol for differentation with respect to time	$\bar{\Delta}(.)$	Relative variation

Lower indexes

c	Duct	M	Pulveriser	R	Impeller	i	Input
B	Coal	m	Ground material	s	Tranquilization, drying	V	Air
g	Gas, gaseous combustion products	N	Nominal working regime	sr	Mean value	W	Moisture
o	Output	n	Rotative speed	tr	Friction		
K	Kinetic	p	Pressure	U	Voltage		

APPENDIX B - THE WORKING AND CONSTRUCTIVE CHARACTERISTICS OF THE COAL PULVERISING PLANT

The Working and Constructive Characteristics of the Process							
Meaning	Symbol	Dimension	Value	Meaning	Symbol	Dimension	Value
Nominal coal mass in the pulveriser	m_{BN}	kg	400	Temperature of the drying fluid at the pulveriser impeller inlet	θ_g	K	830
Nominal output flow of the coal	G_{BoN}	kg/s	16.667	Temperature of the aeromixture	θ_2	K	473
Constant of the ground material internal structure	K		0.78	Head constant	ψ		0.525
Coefficient of the ground material	K_m		3200	Density of the transport fluid at the pulveriser impeller inlet	ρ'	kg/m^3	1.25
Hardgrove index	K_H		46	Density of the transport fluid at the pulveriser impeller outlet	ρ''	kg/m^3	1.20
Residue on sieve with 90μm openings	R_{90}	%	55	Return coeffi-cient of the ground material	C_r		3
Maximum milling capacity	B_{max}	kg/s	19.89	Width of impact blades	b	m	1.007
Volume of the pulveriser	V_M	m^3	10.245	Coefficient of the friction of the ground material on the impeller blades	μ_1		0.5
Pulveriser coefficient	K_M	kg/m^3	0.1	Moment of inertia of the impeller	J	kgm^2	50 000
Stress coefficient	K_u	AVs	0.9	Nominal rotative speed of the pulveriser impeller	n_N	1/s	8
Rotative speed coefficient	K_n	Nms	0.6	Nominal voltage of the drive electric motor	U_N	V	6 000
Residue on sieve with 5 mm openings	R_{5000}	%	28	Drying coefficient	K_{sv}		0.8
External diame-ter of the impeller	d_1	m	3.6	Specific heat capacity of the drying medium	C_{pg}	kJ/(kgK)	1.2561
Internal diameter of the impeller	d_2	m	2.7	Convective heat transfer coefficient	α	kJ/(m^{2}sK)	0.1163
Coefficient of the fuel structure and the pulverising process	K_1		0.005	Specific area of the coal	a	m^2/kg	10
Wear coefficient of the impact blades	K_2		0.9	Nominal coal moisture content at the pulveriser impeller inlet	x_{BiN}	kg of moisture/ kg of dry	0.474
Coefficient of the coal moisture content	K_3		0.9781	Nominal coal moisture content at the pulveriser impeller outlet	x_{BoN}	kg of moisture/ kg of dry	0.0968
Coefficient of the coal moisture content	K_4		1.2949	Nominal fluid moisture content at the pulveriser impeller outlet	x_{goN}	kg of moisture/ kg of dry	0.1
Volumetric flow of the drying fluid at the maximum pulveriser capacity	D_{max}	m^3/s	40.786	Dried coal concentration in the aeromixture	μ	kg/kg	0.34

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MATEMATIČKI MODEL PULVERIZACIONOG POSTROJENJA KAO AKUMULATORA MASE SA DINAMIKOM VENTILATORSKOG MLINA I PROCESA SUŠENJA UGLJA

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U datom radu polazeći od realnih prihvatljivih pretpostavki, razvijeni su prvo nelinearni a onda i linearni matematički modeli pulverizacionog postrojenja, koji uključuju, po prvi put, dinamiku procesa sušenja uglja koja ima značajan uticaj na ukupno dinamičko ponašanje celokupnog postrojenja. Dobijeni model može se uspešno iskoristiti u analizi kao i u sintezi upravljanja ovim složenim energijskim procesom.