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Intelligent Multi-Soft Sensing for Flame Position of Steam Boilers

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Abstract: *A new inference control system for the flame position in the combustion chamber of a power plant system boiler is presented. The system is based on enhanced multi-softsensing at three operational levels – basic level, providing estimates of all necessary technological variables; a separate Mill Fan* (*MF*) *level, and a total Dust Preparation System* (*DPS*) *level. The control system involves a subsystem for the stabilization of the position of the common MF ventilation rate momentum in a given threshold area in a burner horizon, which is supervised by an inference correction based on softsensed 2D flame position in the output section of the combustion chamber. A hybrid approach is accepted in softsensing, using fusion of the first principle models, statistical models, neural networks and fuzzy logic based models. Real experimental results are presented from TPP.*

Keywords: *Combustion chamber control, flame inference, mill fan, power plant.*

1. Introduction

In Bulgaria, about 40% of electricity is derived from power units burning low-calorific value coal. The inclusion of renewable energy sources, the problems with natural gas supplies and especially sharply changing composition of the fuel puts powerful energy blocks in highly undesirable varying modes of participation in primary, secondary and tertiary frequency control and power of the power system. Steam generators are of crucial importance for the economic and secure operation of the power units. Robustness and the quality of the combustion process are problematic for them. The main role here belongs to the Dust-Preparation System (DPS). A number of research sources [1, 3, 4, 8, 9] show that the DPS-control is a complex problem because there are frequently changing situations, because the object is with changing properties (due to the abrasion of the Mill-Fan (MF) blades) mainly due to the lack of direct measurements of the state of the combustion process and also to the lack of possibilities to influence it. The problem with the indirect measurements [2] during the last decade attracted substantial attention; it transformed into an independent scientific direction united under the term softsensing [6, 9-12]. Its rapid development is determined both by the growing needs of current information to assess the characteristics and conditions of management with the available hardware and software tools that are implemented [5, 6] and by the rapid development of computational intelligence [4, 5, 10]. Along with the separate use of the already well utilized intelligent techniques (neural networks, fuzzy logic, genetic algorithms) [6, 10], it appears that a significant improvement of the accuracy of the assessment and therefore of the management is achieved by the application of hybrid systems incorporating different types of models (analytic, data based) with intelligent techniques and knowledge items [4, 5, 7-9, 13].

The current paper examines the use of hierarchically structured softsensing for an important practical problem – monitoring and management of the flame burning in the combustion chamber of powerful energy steam generators.

2. Dust preparation system and the combustion process

Fig. 1 shows a simplified diagram of the dust preparation system.

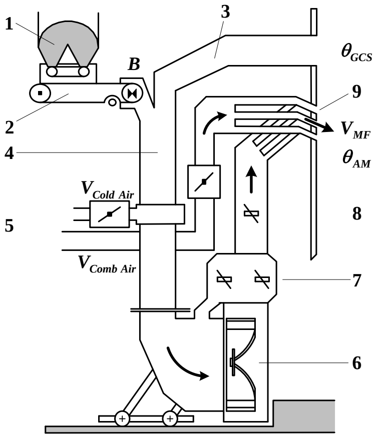


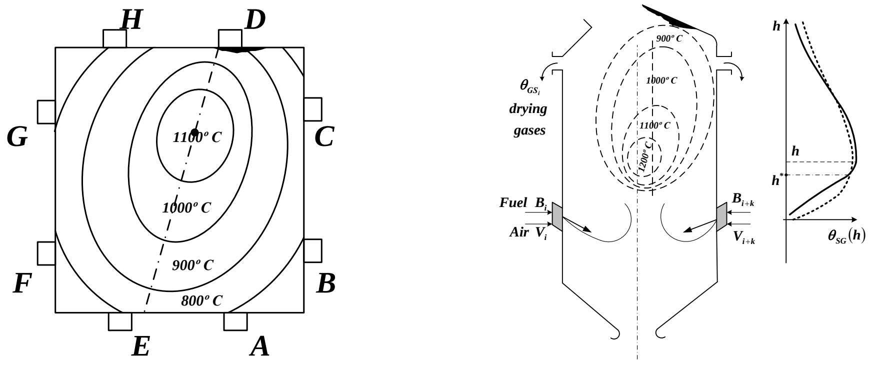
Fig. 1. Simplified scheme of the MF dust preparation system

From the bunker **1** the coal in the dispenser **2** is mixed with the recirculating drying gas sucked in by the end of the furnace along the gas collecting shaft **3**. The coal (with humidity up to 55%) is partially dried in the drying shaft **4** and after the addition of cold air **5** it is fed into the mill fan **6**, where it is crushed and grinded. The inertia separator **7** returns the coarse particles back into the MF and the resulting dust mixture is fed to the combustion chamber of the boiler **8** via the burners **9**. During the combustion of the coal dust a glowing flame is formed.

Fig. 2 shows two cross sections of the flame – horizontal, on the level of the gas collecting shafts (a) and vertical (b). The problem with the alignment of the flame is very substantial. In cases of radial displacements there is an increased risk of slagging the screens and also of the overheaters' sections, while in cases of unwanted vertical displacement of the flame (b) there are experienced adverse effects that severely impair efficiency of the steam generator [1, 3, 8]:

$$\theta_{\mathrm{SG}}(x, y, z_{\mathrm{GCS}}). \tag{1}$$

- There is an increase in the portion of the blown away underburned slack, because the residence time of the particles in the furnace is reduced.
- The usage of the shielded surfaces of the boiler is worsened.
- The ratio radiation/convective input heat changes.
- There is an increase in the temperature of the outlet gases from the boiler thus the efficiency is lowered.
- Combustion takes place in conditions with an increase of the amount of thermal Nitrogen Oxides (NO$_x$). This is related to fines under the existing provisions.



(a) (b)

Fig. 2. Position of the flame in the combustion chamber: horizontal (a) and vertical (b) sections

The combination of radial (a) and axial (b) displacements of the flame lead to improper filling of the furnace space, which reduces security and deteriorates the economy of the power unit "boiler – turbine".

3. Control problems with the burning flame

Flame control is a complex problem [1, 3], the existing practice in Bulgaria relates efficiency to the experience of the operator. In many emerging situations this is unacceptable, especially in a deregulated energy market, where competition is extremely high due to the limited demand for energy and the existing schemes of its redemption. The main reasons for the difficulties in determining and controlling the position of the torch are based on the following five conditions.

1. The lack of direct measurements of almost all important variables determining the processes in the dust preparation system. The only measurable parameters are the temperatures of the air, the drying gases and the dust-and-gas mixtures. The amount of fuel (B_i) to the separate MFs in some steam generators (e.g., “Bobov dol”) is measured accurately enough whilst in others (“Maritsa Iztok” 2) it is not. The measurements’ precision of the costs of air is insufficient. All other variables needed to control and to position the flame are not measured, the combustion process included.

2. In furnaces with tangential burners (Fig. 2a), the flame is formed by the collaboration of 5-7 mill fans. Each of them has a different milling, ventilation and drying performance. All other input and output quantities also vary widely. This is clearly seen in Table 1 based on data from special experiments. This causes significant variations in the configuration and the alignment of the flame.

3. Mill fans wear after 1500 to 2000 operative hours. The wear rate is different depending on the load, the ash content in the coal, the mineral composition of the ash, the material quality of the MF blades and many others This degradation with different speed directly affects the performance of each MF, and therefore the formation of the flame as well.

4. The variable composition of coal (Table 1) is a source of random changes in the position of the flame. They are particularly important in low-calorific burning lignite from the mine “Maritsa Iztok”.

Table 1. Indicators of the dust preparation system of a boiler in TPP “Bobov Dol”

Quantity	Designation	Mill fan					
		A	**D**	**E**	**F**	**G**	**H**
1. **Fuel**							
Moisture content, %	W^P	31.4	40.8	18.4	18.5	22.6	20
Ash, %	A^P	30.3	17.7	46.3	45.3	40.3	42.6
Calorific, kcal/kg	Q^P_D	2150	2340	2070	2080	2090	2135
2. **Temperatures**							
Gas collecting Shaft, ºC	θ_{GS}	835	952	920	910	950	920
Dust-air Mix, ºC	θ_{DM}	131	85	140	162	110	160
3. **Coal Dust**							
Moisture, kg per 1 kg	W_M	5.4	16	3	2.2	3	2.5
Grain size	R_{90}	40	49	44	50	43	51
PRoductivity in Dust, g/h	B^{PR}	19	22	22	30	34	36
4. **Output Speed**, m/s							
• Upper Channel	W^{UC}	21	16	22	27	21	18
• Middle Channel	W^{MC}	11	12	13	16	16	14
• Lower Channel	W^{LC}	18	18	4	19	12	15
5. **Ventilation Performance**, m^3/h	V_M	94.3	88.7	109.3	116.6	90.3	88.8

5. From the point of view of technological manageability of the MF system there exist the following difficulties:

- Management is cooperative with the need to coordinate 5-7 MFs to stabilize the thermal, speed and concentration fields.
- Each mill fan actually has only two regulating effects – the amount of fuel B_i and the cold air V_{CBi}, but no individual feedback to evaluate the effect of each of them.
- The stabilization of the flame can be performed under various combinations of control actions of the individual mill fans.

4. Formulation of the problem

This research has the following objectives:

1. Build a multilevel Softsensing System (SS) to provide input for adjusting the position of the flame in the combustion chamber by indirect indicators.
2. The multisensor system is a multipurpose one – evaluate immeasurable or difficult to measure variables and simulate the behavior of the dust preparation system.
3. Provide a system to control the position of the flame at indirect indicators derived on the basis of intelligent multisoftsensing.

5. Multilevel softsensing

The proposition concerns a three-level multisensor scheme shown summarized in Fig. 3, which includes primary SS_1, secondary SS_2 and tertiary SS_3 softsensing.

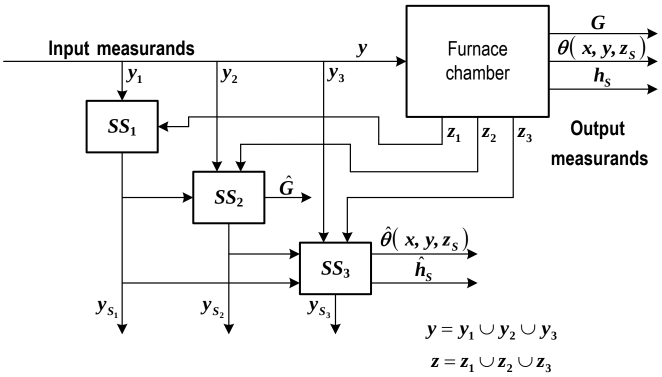


Fig. 3. Scheme of multilevel softsensing

a) Primary softsensing SS_1

The role of primary softsensing is based on direct measurements included in the DeCentralized management System (DCS), to form assessments of all necessary parameters for the secondary and tertiary sensing and management purposes. Elements are used that have already been developed in [1, 3, 7, 8, 9] and several new ones for primary softsensing:

SS_{11} – determine the right balance of the steam-generator efficiency η_{SG}^{R};
SS_{12} – determine the reverse balance of the steam-generator efficiency η_{SG}^{R};
SS_{13} – calculate the calorific value of coal Q_{D}^{R};
SS_{14} – determine the coefficient of excess air α_{EA};
SS_{15} – determine the amount of combustion air $V_{\mathrm{CombustAir}}$;
SS_{16} – calculate the amount of flue gases V_{FG};
SS_{17} – evaluate the moisture of coal W^{P};
SS_{18} – evaluate the gas temperature at the end of the furnace θ_{SG};
SS_{19} – evaluate the coefficient of air gaps K_{L}.

b) Secondary softsensing SS_2

The secondary softsensing in the present research is dedicated to assessing the ventilation performance of each mill fan using the hybrid model:

$$\widehat{V}_{\mathrm{MF}} = \beta_1 V_{\mathrm{MF}_i}^{\mathrm{MM}} + \beta_2 V_{\mathrm{MF}_i}^{\mathrm{FL}} + \beta_3 V_{\mathrm{MF}_i}^{\mathrm{NN}}, \quad \sum \beta_i = 1, \tag{2}$$

where:

$V_{\mathrm{MF}_i}^{\mathrm{MM}}$ is assessment for $V_{\mathrm{MF}i}$ on the basis of an analytical mathematical model (the generalized computational scheme of this model uses a big deal of the direct and indirect measurements of primary softsensing (Fig. 4);

$V_{\mathrm{MF}_i}^{\mathrm{FL}}$ is assessment for $V_{\mathrm{MF}i}$ based on a simplified fuzzy model with inputs $Q_{D_i}^{R}$, B_i and operative hours τ_i of MF_i until now (Fig. 5);

$V_{\mathrm{MF}_i}^{\mathrm{NN}}$ is assessment of $V_{\mathrm{MF}i}$ based on a neural network (Fig. 7).

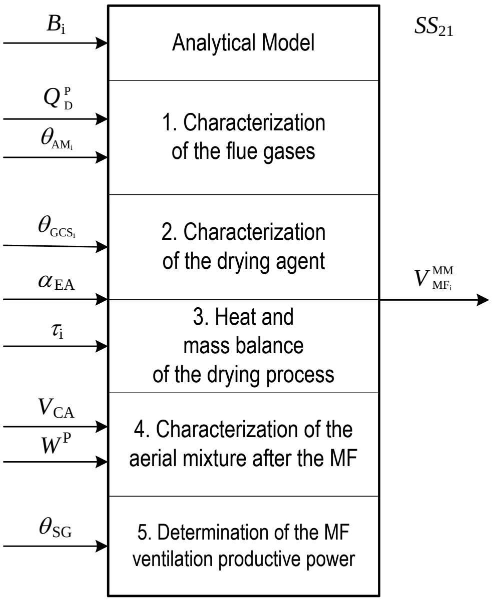


Fig. 4. Computational scheme of an analytical model to determine $V_{\mathrm{MF}_i}^{\mathrm{MM}}$

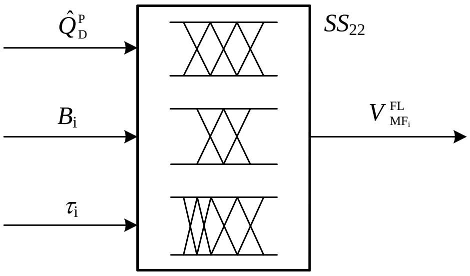
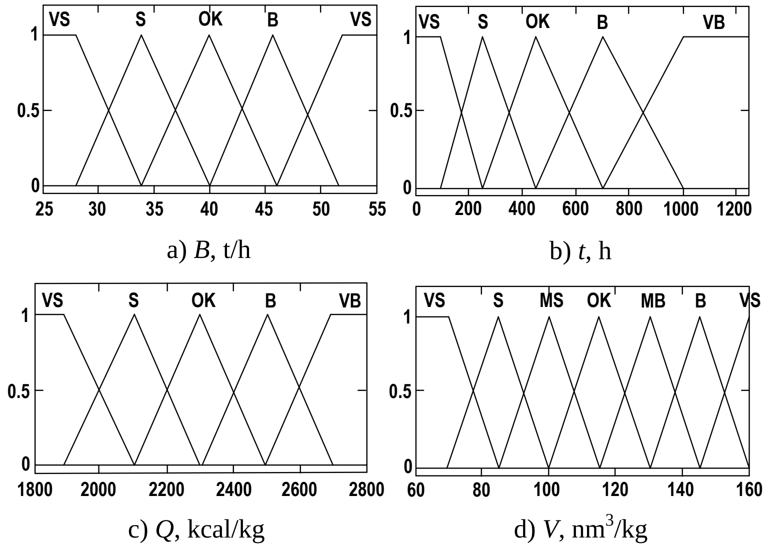


Fig. 5. Scheme of a fuzzy model to determine $V_{\mathrm{MF}_i}^{\mathrm{FL}}$



a) *B*, t/h b) *t*, h

c) *Q*, kcal/kg d) *V*, nm^3/kg

Fig. 6. Membership functions of the fuzzy model

Each of the input values is represented by a fuzzy set, with triangular membership functions defined by five linguistic variables: Very Big (VB); Big (B); normally – OK; Small (S); Very Small (VS). The output value – the ventilation performance – is transmitted with a fuzzy set represented by 7 linguistic variables (VB, B, Medium Big (MB), OK, Medium Small (MS), S, VS). Membership functions are shown in Fig. 6.

For three and five linguistic variables there are formed $5^3 = 125$ rules for fuzzy inference [5]. Fragment of this table of rules is shown in Table 2.

Table 2. Fuzzy inference rules (fragment)

Rule No	*B*	*τ*	*Q*	*V*
23	VS	VB	OK	MS
24	VS	VB	S	S
25	VS	VB	VS	S
26	MS	VS	VB	B
27	MS	VS	MB	B

Experimentally measured and assessed by the fuzzy model values of the ventilation performance are shown in Table 3.

Table 3. Measured and assessed ventilation performance

No	B	τ	Q	Vmeasured	V_{FUZZY}	Δ
—	t/h	H	kcal/kg	$\times 10^3 \mathrm{m}^3/\mathrm{h}$	$\times 10^3 \mathrm{m}^3/\mathrm{h}$	%
1	45.4	675	2500	97.6	89.9	7.9
2	49	675	2740	89.4	87.5	2.1
3	42.8	270	1930	118.4	108.2	8.6
4	49.4	270	1830	121.8	108.6	11
5	46.2	630	2400	86.0	90.7	5.3
6	52.9	630	2620	77.9	80,2	2.9
7	39.4	30	2250	145.3	145.0	0.2
8	51.6	30	1920	137.8	131.6	4.5
9	28.8	930	2320	96.7	101.4	4.8
10	39.8	1220	2130	73.4	72.18	1.8
11	45.3	840	2190	78.8	80.9	2.6
12	54.6	990	2220	78.6	71.2	9.5
13	50.7	285	2190	112.3	106.2	5.4
14	40.2	270	2110	110.7	115.4	4
15	52.6	270	2640	120.4	122.1	1.4
16	41.6	990	2800	80.3	85.9	6.9

It is evident that the error in some cases reaches 10%, which is insufficient. An attempt to improve the accuracy by increasing the number of input variables and/or reducing the number of linguistic variables proved futile. Neural Network (NN) training is shown in Fig. 8a) for a scheme with one hidden layer (Fig. 7). The optimal number of neurons in the hidden layer is 6 (Fig. 8b). The attempt to improve the accuracy by increasing the number of hidden layers was unsuccessful (Fig. 8c). It was therefore adopted a neuronal model of structure (6, 6, 1).

Coefficients β_i in the formula of the hybrid model to assess the ventilation performance $\widehat{V}_{\mathrm{MF}_i}$ are determined experimentally.

Secondary softsensing SS_2 includes (Fig. 9):

1. Determine the ventilation performance of each operational mill fan.
2. Calculate the momentum of the dust-and-gas jet of each mill fan.
3. Construct the momentum of the dust-and-gas jet of each mill fan.

In more detail this is illustrated in Fig. 10, where mill fans ***A***, ***D***, ***E***, ***F***, ***G***, ***H*** are operational.

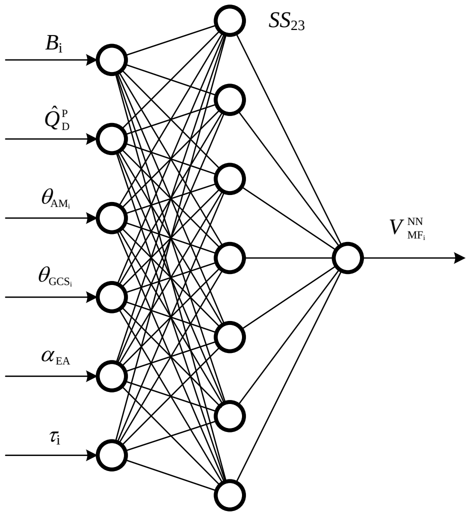
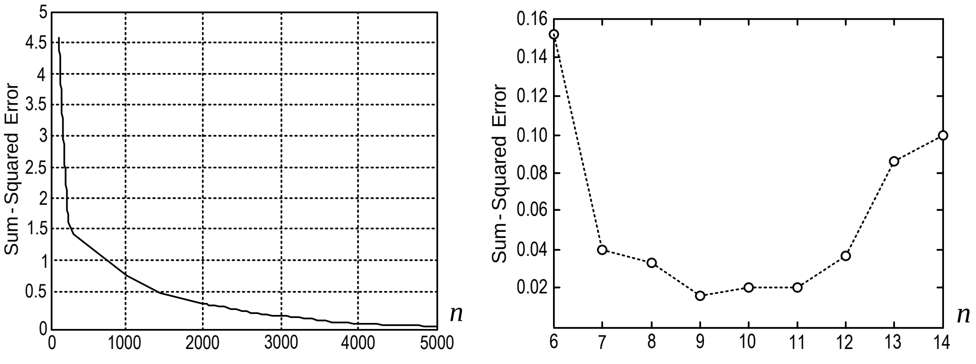
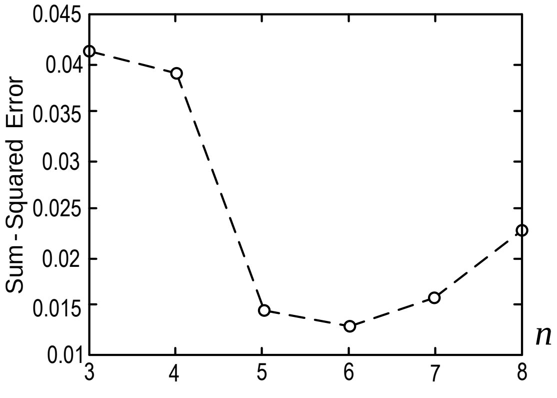


Fig. 7. Neural network to assess $V_{\mathrm{MF}_i}^{\mathrm{FL}}$



(a) (b)



(c)

Fig. 8. Optimization of the NN parameters: learning (a), single-layer NN (b) and two-layer NN (c)

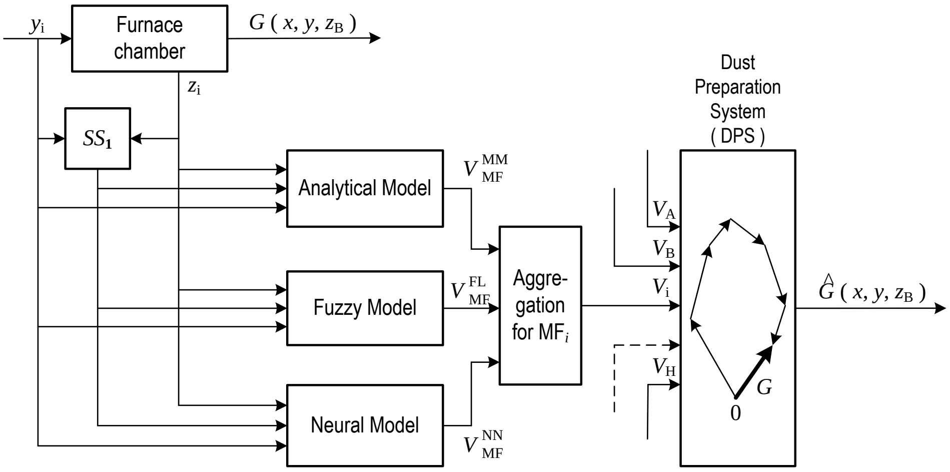
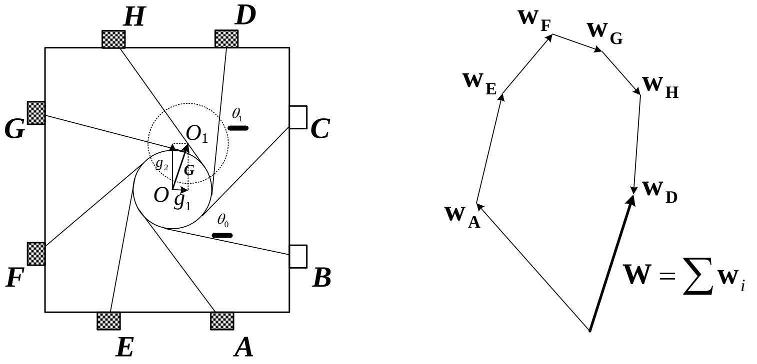


Fig. 9. Scheme of the stages to assess the total momentum of the dust preparation system



(a) (b)

Fig. 10. Evaluation of the displacement of the root of the flame

Vector ***G*** is an indirect estimate of the radial displacement of the root of the flame in the cross section of the burners $G(x, y, z_B)$ and it is used in the system for radial alignment of the flame as discussed below.

c) Tertiary softsensing SS_3

Tertiary softsensing has in this proceeding up the two components:

SS_{31} is 2D flame image on the level of gas collecting shafts $\theta(x, y, z_{GCS})$. The inputs are direct measurements of the temperature at the entries of gas collecting shafts θ_{GCS_i} for each mill fan as it is shown in Fig. 11.

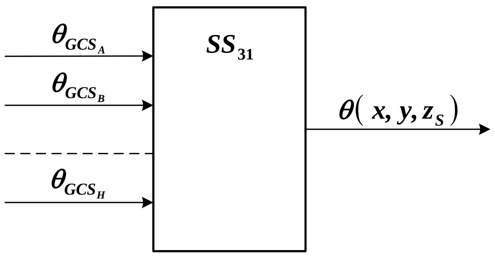


Fig. 11. Schematic diagram for evaluation of the temperature field at the end of the furnace

SS$_{32}$ is assessment of the value of the maximal-temperature of the flame h^* (Fig. 2) based on a statistical model for softsensing with inputs: fuel consumption B, Total Air (V_{TA}) and Cold Air (V_{CA}), the temperature at the end of the furnace θ_{SG}, the average temperature at the entry of gas collecting shafts $\bar{\theta}_{GCS}$, the coefficient of excess air for the furnace α_{EA} and the temperature in the first radiation section of the primary steam overheater θ'_{PS}.

Applied to the conditions in Bulgaria, tertiary softsensing should reduce spending by avoiding the introduction of some modern methods for measuring the position of the flame for a chosen horizon – mobile-cooled thermal camera, integrated optical sensors, laser systems, etc.

6. Control system for the position of the flame based on multisoftsensing

The system for controlling the position of the flame must overcome a large amount of modes and random disturbances characteristic of the power unit “boiler – turbine”. Some of them (stopping mill fans, enabling/disabling Incendiary Oil Burners (IOB), slagging) are of a discrete-event nature. Thus the use of conventional control systems for burning low-calorific lignite is ineffective [3, 8].

Using observers of the state is possible, most of all for boilers with liquid and gaseous fuel [4] and also for high-quality coal of comparatively constant composition [1].

Here we propose using a control system that stabilizes an indirect indicator of the position of the root of the flame G (Fig. 9, Fig. 10) and which imports corrections based on an software estimate of the 2D configuration of the thermal field of flue gases $\theta(x, y, z_S)$ (Fig. 2, Fig. 11).

The sequence of computational operations in this system based on multilevel softsensing (Fig. 3) is presented in Fig. 12.

The scheme includes unit for decision Making (DM) depending on the current situation P, and an unit for the optimal distribution of fuel and of the secondary air for the mill fans.

Fig. 13 shows the functional diagram of the proposed system for automatic control of the flame position. The information base comprises the systems for softsensing SS_1, SS_2 и SS_3.

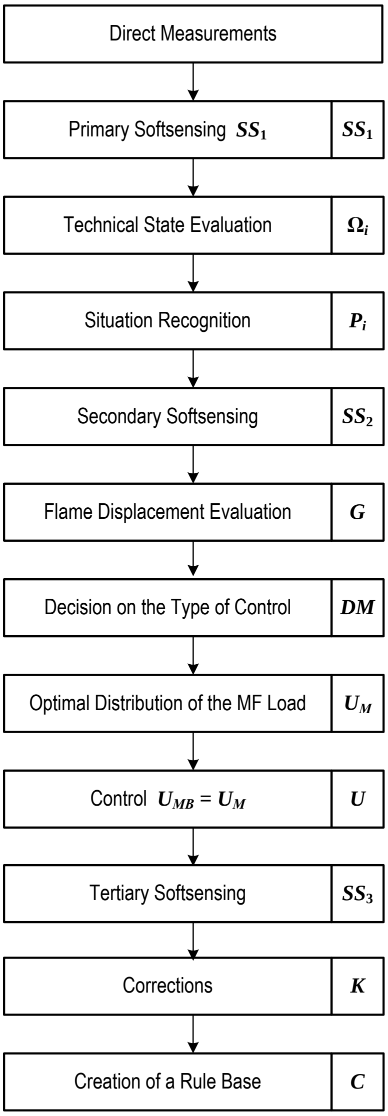


Fig. 12. Sequence of computational operations in the multisoftsensing scheme for flame control

The stabilization of the indirect indicator of the position of the flame ***G*** (Fig. 10) is the basis for decision making about the control mode: just fuel change, joint change of the fuel and the cold air, stopping or switching to another mill fan.

For this purpose there are empirical rules, gained from experience of the operating staff. Distribution of fuel and air between the MFs is an optimization problem to be solved on the basis of the selected control strategy. The solution is transferred to the execution unit which in our conditions is man-machine: a part of the functions are performed by conventional regulators and others (MF switching, enabling/disabling RMG) are implemented at the discretion of the operator. Tertiary softsensing SS_3 which provides monitoring of the position of the flame allows the implementation of necessary adjustments.

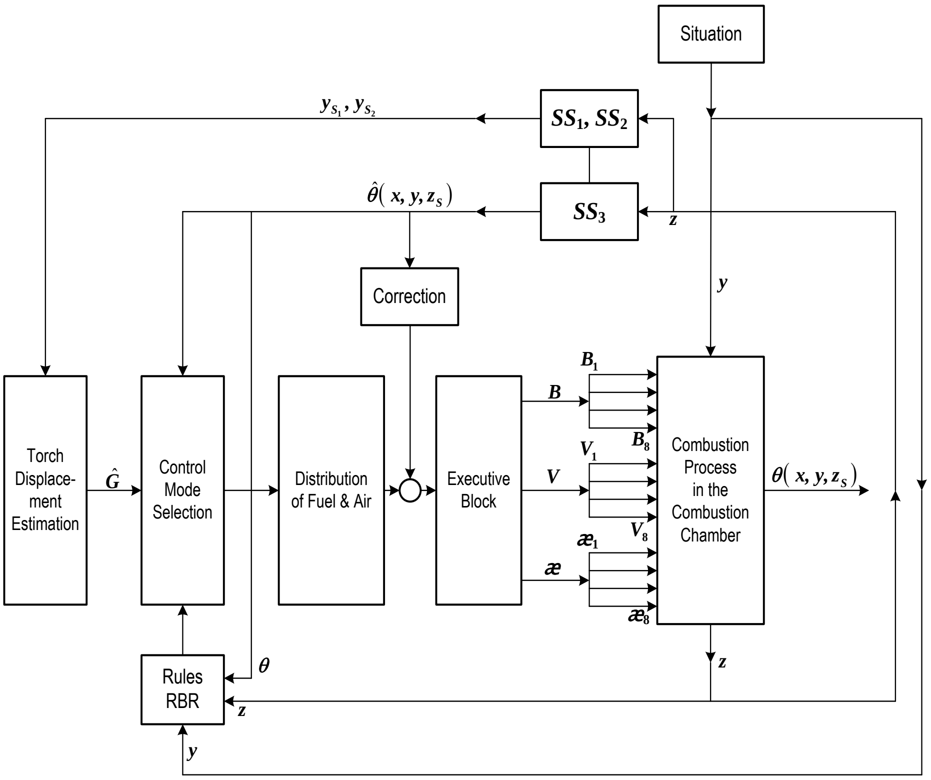


Fig. 13. Functional scheme to control the flame position

7. Experimental results

The basic modules of the developed system, presented in this paper, were software-implemented and they were included as an upgrade of an existing DCS in TPP.

Fig. 14 shows the depicting point of the normed position of the indirect indicator $G(x, y, z_B)$ testifying about a significant deviation of the flame root.

Fig. 15 shows in a real working system the temperature field in the furnace at the level of the gas collecting. It is determined by the pattern on Fig. 11. The obtained configuration confirms the appropriateness of using the indirect software assessment of the displacement of the flame root G in the control scheme.

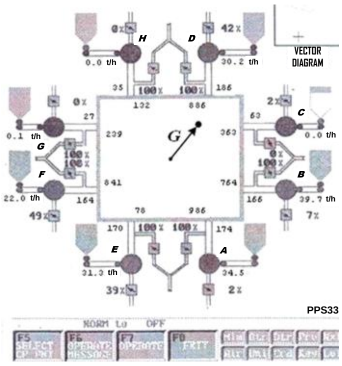


Fig. 14. Evaluation of the displacement of the flame root *G*

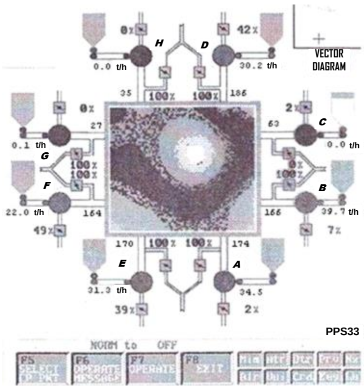


Fig. 15. Evaluation of the temperature field at the end of the furnace

8. Conclusion

An extension is proposed to software measurements and control via indirect measured values in the case of stabilizing the flame position in the furnace chamber of a powerful energy boiler. A new indirect assessed value is introduced – the resulting vector of momentum of simultaneously operable mill fans. Aggregating estimates of speeds of dust mixtures derived from the developed complete analytical mathematical model, a neural model and a fuzzy model leads to an on-line weighted value for the speed and the momentum at the output of each mill fan. Thus it is possible to obtain an assessment for the displacement of the flame at the level of the burners. A system is proposed to focus this indirect quantity in the center of the combustion chamber. This enables a simplification, speed-up and optimization of the cooperative management of all 6÷7 operating mill fans with no iterations related to the flame position in the actual furnace chamber at the level of gas collecting shafts which can lead to an increased risk of slagging and the deterioration of the boiler efficiency.

The obtained results can be successfully applied to real mill fan systems control design.

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