ABSTRACT

A method and system for decision making and control (DMC) of combustion process of pulverizing fuel-air mixture in large multiburner furnace is proposed. Due to the lack of necessary information inference measurements are created on the basis on the first principle CFD model of the combustion process and a sequential image processing. Decision making procedure is based on Case Based Reasoning and Rule Based Reasoning which contains some elements of knowledge, acquired via a long time operator experience and off-line simulations on the CFD – model. Combination of off-line and on-line procedures is accepted in to two stage algorithm of DMC which improves the efficiency and safety of combustion process.

Keywords: Case Based Reasoning (CBR), combustion process, control, decision making, inference measurement, Rule Based Reasoning (RBR).

INTRODUCTION

The combustion process (CP) is still important for a great number of plants in chemical, metallurgical and power industries. Despite of the large volume of long standing investigations, the control of the CP, especially in a big size combustion chamber with a multiburner systems, continues to be at least in part the problem of operator skill. The main reason is a lack of relevant information for main characteristics of the turbulent flame. To cope with this obstacle into the last decade a lot of methods for flame measurement appear – laser, fiber-optical, video-camera, spectroscopical, colour-based [1]. This methods have a promising potential, but nowadays they are with limited commercial success because are costly, unreliable and with problematic maintenance in hard industrial conditions [1, 2].

In parallel a very extensive development of inference methods for measurement, monitoring, decision making and control, can be observed [3-5]. They are considered as an alternative or compliment solution in reengineering initiative [6]. In the present paper a new approach is presented for decision making for improvement of combustion process based on softsensing and inference control [3, 5, 7]. A novel hybrid system is proposed based on mathematical modeling, image processing and incorporating some intelligent techniques containing knowledge elements – Case Based Reasoning (CBR) and Rule Based Reasoning (RBR) [8 - 11].

As a case study, a typical plant is chosen for decision making and control of combustion process of pulverized fuel-air mixture with direct feeding. The technological and economical considerations are combined with the \( NO_x \) minimization in flue gases.
STEAM BOILER PROPERTIES

A typical scheme of a steam drum-type boiler plant with mill-fans based pulverization system is shown in Fig. 1. The combustion process is carried out in furnace 1, where through a system of main (12) and auxiliary (13) burners a mixture of pulverized coal, air (primary and secondary) and flue gases is fed. The pulverization system comprises a mill-fan (8), electro-drive (9), inertial separator (10) and dust concentrator (11). The raw coal from the bunker 3 through the feeder 4 is directed toward the drying shaft 5, where it is mixed with flue gases intaked from the top of the furnace via the duct 2. The furnace crossection (Fig 1b) shows the placement of 8 mill-fans (A-H) with tangential organization of the combustion via central vortex.

The direct firing pulverizing system is a source for a lot of difficulties [1, 2, 4, 6]:

- The flame stability depends on the combination of many factors: mill-fans load, their technical condition, fuel/air flow ratio;
- Big number of disturbances such as changeable heating value of the coal, nonregular work of the raw coal feeder, strongly variable temperature of the drying
flue gases;

- Risk of fire in the air-fuel mixture;
- Problems with overloading and underloading of the mill fans;
- Relatively short operational life of the mill-fans (less than 2000 h);
- The conventional measurements in pulverizing system are very poor. A large number of key variables are unmeasurable: fineness of the dust, flow rate of the air-fuel mixture, degree of the separator recirculation, flow rate of the additional cold air and hot air, moisture of the pulverized coal.

The number of control variables, only the throughput capacity of the fuel and secondary air, is very limited.

The pulverization system plays the main role in organization and maintaining the combustion process. Existing conventional monitoring and control systems are not able to cope with the listed above circumstance in order to ensure the flame stability, safety and effectiveness of the combustion process.

**PROBLEM STATEMENT**

The objective of the considered problem is to propose a relevant procedure for Decision Making (DM) and control of dust-air mixture combustion process into a multiburner furnace in order to satisfy the next multicriteria requirements:

$$J = \langle J_1, J_2, J_3, J_4, J_5 \rangle > extr$$

where $J_i$ are partial criteria as follows:

- $J_1$ - Efficiency of the combustion process maximization getting up by:
  - Fuel/air ratio optimization,
  - Radiation/Convection heat balancing,
  - Fowling minimization;
- $J_2$ - $NO_x$ concentration in flue gases restriction;
- $J_3$ - Minimization the risk of abnormal conditions owing to:
  - Slagging,
  - Flame unstability (e.g. Lost Of Ignition - LOI),
  - Local overheating of constructive elements (e.g. arousing the water tube ruptures),
  - Overloading or underloading of mill-fans,
- $J_4$ - Minimization of off/on and over switching of MF;
- $J_5$ - Minimization of Kindle Oil Burner (KDB) switches on/off.

The problem can be solved via combination of quantitative approaches (formal methods, CBR, RBR) and qualitative ones (operator expertise).

**MATHEMATICAL MODELING OF THE COMBUSTION PROCESS**

In this work a first principal $k - \varepsilon$ model of the combustion process is accepted. Following [12], the CFD model could be presented in the next generalized form:

$$\frac{\partial (\rho u_i \varphi)}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \Gamma_\varphi \frac{\partial \varphi}{\partial x_i} \right) + S_\varphi + S_{p\varphi}$$

where $x_i$ is a direction of Cartesian coordinate system and $(i = 1,2,3)$ for 3D space, $u_i$ are the velocity components in $x_i$ direction; $\varphi$ is a generalized variable, which represents all main components of the thermodynamical state of the system – velocity, $k - \varepsilon$ characteristics, fraction contents, entalphy (temperature) and masses; $\Gamma_\varphi$ is a generalized transfer index, corresponding to each particular acceptation of $\varphi$, $S_\varphi$ and $S_{p\varphi}$ are generalized sources terms for a gas and particle phases. More detailed description of this CFD model can be found in [12].

The next values for each discrete element of the mesh are determined: the trajectories of the dust particles; the heat received from dust particles combustion; temperature of the gas and coal particles; density of gas-fuel mixture; sequential velocities of the gas and dust correction in dependence on the temperature and density in the mesh.

The input conditions for the model are: power unit load $N_{\text{MW}}$; total throughput capacity of the coal $B_t$, t h$^{-1}$; working lower heating value of the coal $Q_{l}^{m}$, kJ kg$^{-1}$; concentration of oxygen in flue gases $O_2$, %; efficiency of the boiler $\eta_b$, %; Temperature of the cold air $\theta_{ca}$, °C; temperature of the hot secondary air $\theta_{sa}$, °C; temperature of the flue gases at the end of furnace $\theta_{gt}$, °C; working moisture of the coal $W_{w}$, %; working mass of the ash in coal $A_w$, %; theoretical volume of air for combustion $V_0$, m$^3$ kg$^{-1}$; portion of regularly
blowed air $g$, 

In order to adopt the model parameters, the relevant constructive data are used for combustion chamber, burners, mill-fans, inertial separators, etc.

Model tuning is carried out via iterative correction of model parameters (Fig. 2), using data from number of direct measurements, arranged in the following vectors:

$Y_1 = (N, B_1, B_2, V_{ac}, \theta_{ac}, V_{ah}, \theta_{ah}, O_2)$

$Y_2 = \left( Q_L, \eta_B, W^w, A^v, g \right)$

$Y_3 = \left( \omega_v, \omega_g, V_0 \right)$

$Z_1 = \left( \theta_{af}, \theta_{gs}, \theta_{gh}, D_{sh}, H_f \right)$

$$Z_1^M = \left( \theta_{gs}, \theta_{gh}, \theta_{af} \right)$$

The data for the temperature of intake drying gases $\theta_{gs}$ must be filtered because of significant measurements errors due to fouling, slagging, aerodynamic shadows. This can be seen from the experimental data given in Table 1.

**INPUT DATA PROVIDING**

Three types of input data for considered above first principle CFD model to compute the temperature, velocity and concentration fields of combustion process, are used:

From direct measurements: $\theta_{af}, \theta_{gs}, O_2, \theta_{ac},$

<table>
<thead>
<tr>
<th>Experiment No</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>772</td>
<td>875</td>
<td>929</td>
<td>876</td>
<td>851</td>
<td>-</td>
<td>916</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>915</td>
<td>-</td>
<td>930</td>
<td>936</td>
<td>814</td>
<td>-</td>
<td>931</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>-</td>
<td>953</td>
<td>923</td>
<td>871</td>
<td>872</td>
<td>877</td>
<td>-</td>
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<tr>
<td>4</td>
<td>-</td>
<td>-</td>
<td>932</td>
<td>921</td>
<td>857</td>
<td>876</td>
<td>877</td>
<td>-</td>
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<tr>
<td>5</td>
<td>975</td>
<td>918</td>
<td>-</td>
<td>909</td>
<td>-</td>
<td>928</td>
<td>-</td>
<td>930</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>854</td>
<td>-</td>
<td>932</td>
<td>868</td>
<td>809</td>
<td>-</td>
<td>932</td>
</tr>
<tr>
<td>7</td>
<td>841</td>
<td>871</td>
<td>-</td>
<td>824</td>
<td>662</td>
<td>-</td>
<td>734</td>
<td>840</td>
</tr>
<tr>
<td>8</td>
<td>794</td>
<td>885</td>
<td>-</td>
<td>845</td>
<td>634</td>
<td>-</td>
<td>738</td>
<td>861</td>
</tr>
<tr>
<td>9</td>
<td>792</td>
<td>-</td>
<td>-</td>
<td>793</td>
<td>549</td>
<td>-</td>
<td>693</td>
<td>803</td>
</tr>
<tr>
<td>10</td>
<td>978</td>
<td>906</td>
<td>886</td>
<td>812</td>
<td>1009</td>
<td>-</td>
<td>920</td>
<td>-</td>
</tr>
</tbody>
</table>
From indirect measurements - $\alpha_f, \alpha_B, V_MF$

From inference measurements:

a. Based on information from direct and indirect measurements: $\eta_B, Q_L^w, W_w, A_w, A^d$;

b. Based on established design models [13]: $V_\theta, \theta_g, \theta_{gf}$.

Here some of the inference measured values are considered, which contain new authors results.

Efficiency of the boiler can be found using two different ways [4,13]:

1. Direct balance method

$$\eta Q_L^w = \frac{A}{B}, \quad A = \sum D_j \Delta i_j$$

where $D_j$ - output steam flow rates, $\Delta i_j$ - corresponding enthalpies differences.

2. Indirect (inverse) balance method

$$\eta_{IN} = 1 - \sum_{i=2}^{6} q_i$$

where $q_i$ ($i = 2,6$) are respectively the relative heat losses with: waste gases, incomplete combustion, unburned carbon to surrounding, and with physical heat of slag.

The heat balance can be presented additionally in the next form:

$$\eta Q_L^w = \frac{qN}{B} = \frac{q}{F}, \quad \text{where} \quad F = \frac{B}{N}$$

where $N$ is the current electrical power load, $q$ - function, which was derived using experimental data. It is presented in Fig. 3.

According to eq. (4) and eq. (6) we have two relationships for the working lower heating value of fuel $W_w^L$. As the right sides of the eqs. (4) and (6) are known, and $\eta_{IN}$ is defined from eq. (5), $Q_L^w$ can be derived using the equation:

$$\hat{Q}_L^w(k) = \beta Q_{Ld}(k) + (1 - \beta)\hat{Q}_{Ld}^w(k)$$

where $\beta$ is weighting coefficient.

The relationship between the coal moisture $W_w$ and the ash content $A_w$ have been found in the form

$$W_w^L + A_w = 94,2 - 0,0139\hat{Q}_L^w$$

The values of $V_\theta, \theta_g, \theta_{gf}$, which are of critical importance for the developed model parameters tuning, are derived following the recommendations in [13].

**SIMULATION RESULTS**

The established methods for combustion chamber design [e.g. 13] are based on using averaged values of temperatures in each crosssection of the furnace. This design patterns do not give any data for the spatial displacement of the flame, no thermograms in zones of interests or hydrodynamic characteristics of the combustion process. As it was discussed above, the problem of local information of flow, temperature and concentration fields are very important for avoiding unadmissible situations via proper control of the combustion process.

Realistic scenarios have been accepted to cover the representative operational situations with enough density. In order to obtain more detailed maps of the main characteristics of the combustion process a lot of simulation results using this different working structures, load, technical conditions and values of input variables have been received. As an illustration some of them are shown in Figs. 4-7. They are in accordance with Fig. 4, showing the horizontal and vertical cross-sections.

Some conclusions can be made from the analysis of the simulation results:

- The temperature and concentration fields are strongly nonregular, nonhomogeneous and with a lot of local peculiarities.
- The velocity field is more regular, but the corresponding maps are less informative than the temperature
Fig. 4. A scheme of horizontal (a) and vertical (b) cross-sections.

Fig. 5. Cross-section of the furnace at the burner level.

Fig. 6. Cross-section of the furnace at the top of the combustion chamber.

Fig. 7. Vertical cross-section distribution of the flame.
distribution.

- Nonregularities of the temperature field exist both in radial and axial direction.
- The concentration fields are closely correlated with the temperature field.

All simulation results show that the digital model is very complex and can not be directly used for decision making and control.

The calculation time for each scenario is too long in comparison with the combustion time of a separate particle (3 - 4 s). Thus only after some kind of approximation of the obtained 3D fields they can be acceptable for on-line implementation.

Image processing should be applied for appropriate features selection.

**PROCEDURES PROVIDING COMPONENTS FOR DECISION MAKING AND CONTROL**

**Feature selection**

Nowadays the image processing [1, 2] allows the problem of feature selection from sophisticated images to be solved successfully. In our study it is addressed in three most important cross-sections:

**Horizontal cross-sections at the burner’s level**

The next features are selected in order to form the attributes for CBR:

- Deriving the center of combustion vortex from velocity distribution (Fig. 5a),
- Determination the degree of cross-section filing by flame using the isoterms (Fig. 5b),
- Average temperature at the burner level,
- Estimation of the local burner stream flame length for each working burner.

b. Horizontal cross-sections at the top of the furnace

- Deriving the center of the vortex,
- Defining the zones with highest temperatures lean against the water tube walls,
- Determination the local average gas temperatures into the inputs of intake drying shafts,
- Average temperature of the flame at this level,
- Finding the zones with the maximal temperatures,
- Extraction the isotherms with temperature \( > 1000^\circ \text{C} \).

b. Vertical cross-sections at the axis with the highest temperature in the top of the furnace

- Defining the place of the maximum temperature in axial direction,
- Estimation of the equivalent diameter of the fireball.

**Case base for CBR formation**

CBR is promising approach for reasoning on the base of analogy [8 - 10]. In this study the cases are presented in established \“problem (P) solution (S)\” form:

\[
C = \langle P, S \rangle
\]  

Here \( P \) is accepted to be considered as a \“situation\” in a form

\[
P = \langle I, F, T \rangle
\]  

where \( I \) is the vector of input information, \( F \) is the vector of the selected features from the image processing, \( T \) is the vector of given thresholds as requirements. Each of vectors \( I, F, T \) contains number of relevant attributes.

\( S \) is solution for MF control actions and is presented as follow:

\[
S = \langle B, V_{ac}, V_{ah}, V_{at}, T_s \rangle
\]  

where \( B, V_{ac}, V_{ah} \) are the vectors of the throughput capacity of the fuel, flow rate of the cold and hot air, respectively. \( V_{at} \) is the total combustion air flow rate, \( T_s \) is the vector of the thresholds.

As in this study a two stage procedure for DMC is proposed, two corresponding case bases have been formed - simplified \( C_{ss} (P_s, S_s) \) and full \( C_{ff} (P_f, S_f) \).

**Rule base for RBR formation**

On the base on a long time of operational experience, existing technical instructions, and supplier’s requirements a set of particular \( RB_j \) have been derived. A small part of them is presented in Tables 2, 3 and 4.

**Decision making approach**

The basic acceptance in DM approach in this study are:

- CBR is used in two different variants - simplified and full;
- CB is used to create CBR local regressions corresponding to the \( KNN_j \) area of interest [8],
- Simplified procedure at the first stage of DM
allows a faster retrieval. It is concentrated mainly on the most important aspect of the combustion process — availability ($J_3$).

- At the second stage of DM, partial criteria $J_3, J_4, J_5$ can be accepted as constraints,
- To faster the calculations for an optimal distribution of the coal $B_i$ and cold air $V_{aci}$ between $MF_i$ the changes of control variables are carried out by actions over the opposite pairs of burners.

**Software tools**

The established tools for CBR, myCBR and jColibry, have been used in accordance with the earlier accepted adaptation and modification [9, 11].

### A SYSTEM FOR DECISION MAKING AND CONTROL (DMC) OF COMBUSTION PROCESS

An iterative two level system for DMC is proposed (Fig. 8). At the first level $L_1$ (left side of the scheme) the preliminary recommendations are deduced for:

- a. Current structure of the pulverizing system (number and indexing of the proposed for running mill-fans (MFs), state of the Kindl Oil burners (KOB);

### Table 2. Regime checking.

<table>
<thead>
<tr>
<th>Rule No</th>
<th>IF</th>
<th>THEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IF $V_{fg} &lt; 1850.10^3 \text{ m}^3\text{h}^{-1}$ THEN there still exists reserve in exhausters</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>IF $\alpha_f \geq \alpha_f^{min}(N,Q_{w}^n)$ THEN there exists reserve in combustion air</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>IF $100^\circ C \leq \theta_{ai} \leq 180^\circ C$ (i=1,8) THEN there isn’t danger of fair in burner tract</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>IF $5th^{-1} \leq B_{MF_i} &lt; 55th^{-1}$ (i=1,8) THEN there exists grinding capacity in each mill-fan</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>IF $10mm H_2O &lt; H_f &lt; 2mm H_2O$ THEN the vacuum into the furnace is admissible</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3. Checking the slagging conditions.

<table>
<thead>
<tr>
<th>Rule No</th>
<th>IF</th>
<th>THEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IF $\rho = \frac{r}{r_{max}} \leq 0.15$ THEN the flame deviation is OK</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>IF $\Delta0_{sui} &lt; 30^\circ C$ THEN the radial asymmetry is OK</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>IF $\theta_{max}^{sui} &lt; 950^\circ C$ THEN the temperature in intake shaft is OK</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>IF $\theta_{ai} &lt; 1100^\circ C$ THEN the temperature of the flue gases at the end of furnace is OK</td>
<td></td>
</tr>
</tbody>
</table>

### Table 4. Certain rules for decision making for separated Mill-Fan.

<table>
<thead>
<tr>
<th>Rule No</th>
<th>IF</th>
<th>THEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_1$</td>
<td>$\rho &lt; 0.05$</td>
<td>No flame position correction</td>
</tr>
<tr>
<td>$R_2$</td>
<td>$0.05 &lt; \rho \leq 0.15$</td>
<td>Flame position is corrected only via $MF_i$ loading with coal $(\Delta B_i \neq 0)$</td>
</tr>
<tr>
<td>$R_3$</td>
<td>$0.15 &lt; \rho \leq 0.3$</td>
<td>Flame position is corrected with both loading $(\Delta B \neq 0)$ and flowrate of cold air $\Delta V_{aci} \neq 0$ of corresponding pair Mill-Fan</td>
</tr>
<tr>
<td>$R_4$</td>
<td>$\rho &gt; 0.3$ with variations</td>
<td>Switching over another pair Mill-Fans</td>
</tr>
<tr>
<td>$R_5$</td>
<td>$\rho &gt; 0.3$ constantly</td>
<td>Switching on new Mill-Fan</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>$R_i$</td>
<td>Vibration amplitude of MF is $a \geq 0.5 \text{ mm}$</td>
<td>Switching over new Mill-Fan</td>
</tr>
</tbody>
</table>
Fig. 8. A system for decision making and control (DMC).
b. Distribution of coal $B_i$ and cold air $V_{aci}$ for each $i$ - indexed MF. To define these recommendations the subsistem $L_1$ uses an information from direct, indirect and inference measurements. After retrieval of$k$-nearest neighbours ($KNN_{11}$) and adaptation according $R^k$ cycle for CBR [8 - 10], a primary optimal ($B_i V_{aci}$), distribution is carried out. Because the initial retrieved case is changed, an iterative procedure is started via $KNN_{12}$ retrieval. When the requirements for level $L_1$ are covered, these recommendations are sent via logical block $LB_{21}$ toward the functional level $L_2$ (right side of Fig. 8). As the case base $CB_1$ addressed to the level $L_2$ contains more attributes in comparison with $CB_2$, a new retrieval $KNN_2$ is fulfilled. A comparison of both values $C_{12}^*$ and $C_{21}^*$ directs the procedure to be executed in $MF_i$, or to continue the improvement of the preliminary recommendation given from the first level $L_1$.

The proposed decision making and control system (DMC) is situation based. It adapts the pulverizing system toward the new conditions. In a relatively simple way the proposed system can maintains the thermal fireball in the center of the combustion chamber and will improve the efficiency of the whole combustion process accordingly the accepted multicriteria $J(1)$ as well.

**CONCLUSIONS**

A new method is proposed for a real time decision making and control of flame position and combustion process improvement. Inference measurements are developed to add the lack values on the base of the conventional measurements. A hybrid system for decision making and control, based on first principle model of the combustion process, image processing, and building blocks containing knowledge elements - Case Based Reasoning and Rule Base Reasoning is considered. Experimental data from a multiburner combustion process are used to tune mathematical model and to acquire relevant production rules. The proposed hybrid system contains promising potential to assist the operators with different level of expertise to adjust the combustion process.

**REFERENCES**


