Cost Function Formulation and Realization Methods for Optimum Control of Fluidized Bed Combustors

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Abstract:

The Fluidized Bed Combustion (FBC) technology differs basically from other combustor types, one example is the double role of air flow: combustion and fluidization. Because of such differences, the well proven classical combustion control methods can not be used effectively for FBCs. In this paper, the task of combustion control will be formulated by means of a cost function. A general form of this function will be proposed, the exponential terms of which define sufficiently the optimal operating point within the two-dimensional space spanned by the two air flows. The parameters of these terms should be set according to the actual local circumstances such as supplier prescriptions and financial ambiance. Several ways of realization can be outlined for finding the minimum of the cost function, two of which will be discussed in detail. These structures were programmed and tested, throughout which tests, a verified programmed model of an industrial CFBC unit was used. The test runs of both control strategies pointed out their proper operations.

Keywords: FBC, combustion control, optimum control, cost function, model-based solution

1. INTRODUCTION

The importance of the fluidized bed technology is enormous today, and a permanent increase can be observed not only in the number of installed units worldwide, but also in the number of new application areas where this technology seems to be very advantageous. Fluidized Bed Combustors (FBCs) are used successfully for the thermal utilization of biofuels and waste (wood chips, saw dust, waste from paper industry) as well as for fossil fuels e.g. coals with high ash contents and lignites.

The fuels are burned as single fuel or as fuel mixture in a FBC. The fluidized bed consists mainly of bed material (fuel ash and silica sand) and only a few percentages of the fuel itself. The fluidization is performed with the combustion air. Due to the fluidization with combustion air, a strong coupling between the on-going combustion chemistry and the flow characteristics is given. The fluidized bed has to be operated between the minimum fluidization velocity and the terminal fluidization velocity. If the velocity is high, an increased entrainment of fine particles will arise. This leads to operating conditions which have to be optimized for given particle size distributions. If ashes are generated which melt at low temperatures, agglomerates may be formed that may lead to a complete defluidization of the fluidized bed combustor.

Because of these and some other reasons, basic behaviors and characteristics of the fluidized bed combustion technique differ definitely from those of other, traditional combustion techniques. That's why the well proven classical combustion control methods can not be used effectively for FBCs. For solving this problem, a new approach for FBC optimum control was developed and will be presented in this paper It is based on an adequate form for cost function outlined in the next chapter, while subsequent chapters will introduce some possible ways of its realization.

Throughout the latest development of modern control theory and practice, it became an evidence that control performance can be significantly improved based on in-depth knowledge of the process to be controlled. This means – on the one hand – required technological cognition of the person designing the controller, but also – on the other hand – high level process information applied by the control algorithm itself. An excellent tool for this is a programmed mathematical model of the system. This is the case of the actual development, since a dynamical model of a 300 MW_{th} CFBC unit is available. Its details were published elsewhere (Szentannai, 2011), only some results of the steady-state and dynamic verifications will be shown here (Fig. 1 and 2).

2. COST FUNCTION

The basic goal of combustion control is always identical, regardless of the actual combustion technique or control strategy, namely, setting the air flow rate so that optimal combustion conditions can be assured among the actual fuel feed, fuel composition and other circumstances. Despite of this strong similarity, significant differences appear between FBCs and other combustion technologies, since in case of the Fluidized Bed Combustion,

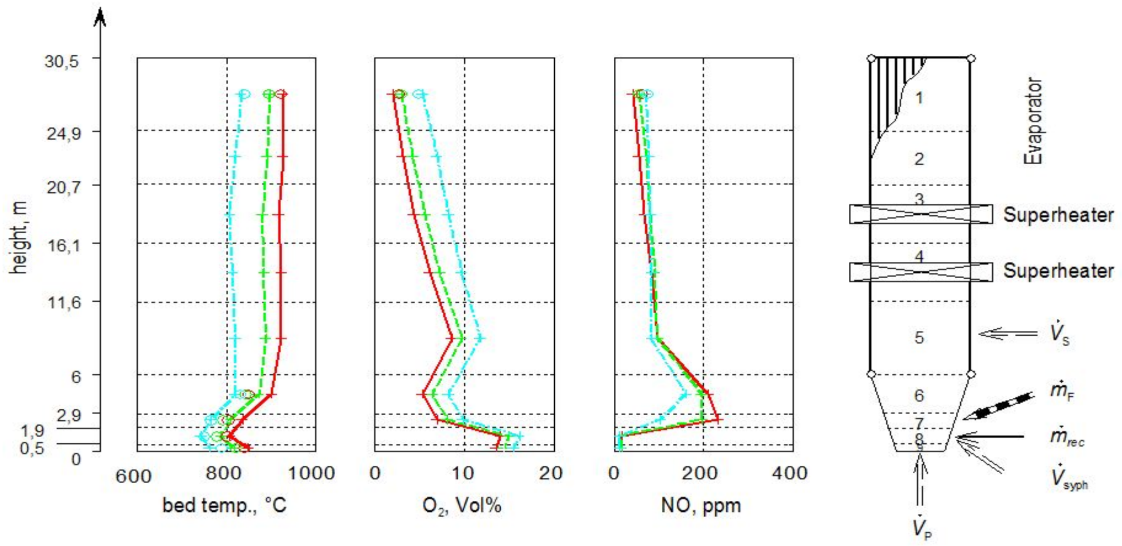

Fig. 1. Results of the steady-state verification of the mathematical model of a 300 MW_{th} CFBC unit. This model was used as a tool for the optimum control development. The one-dymensional lumped cell model structure was used to describe the basic effects of spacial inhomogenities resulted by the structure elements of the riser outlined on the right. Line types: continuous: t=5min; dashed: t=110min; dashdotted: t=175min. Markers: +: simulated; O: measured

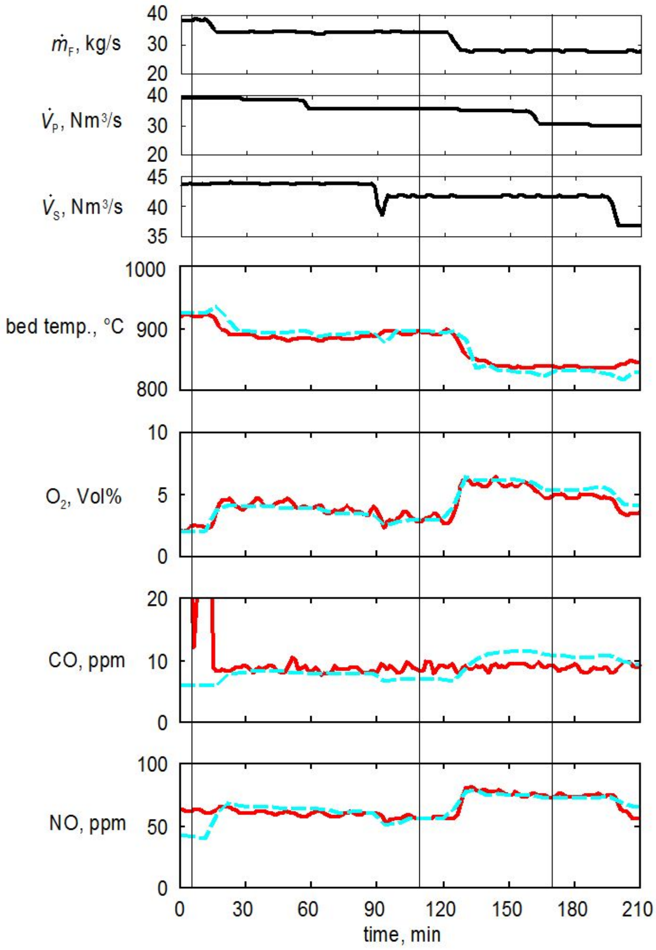

Fig. 2. Results of the dynamical verification of the model used as a tool for optimum control development. Identical input time series (upper three diagrams) were applied to both the programmed mathematical model and the industrial facility (dashed and continuous lines, respectively).

- the combustion air must assure not only optimal combustion, but also appropriate fluidization;
- the combustion air must be set with respect to the actual fuel inventory, not to the actual fuel feed rate;
- air distribution between primary and secondary air is a supplementary task of high importance.

The proposed approach in setting up the control strategy follows the traditional way of formulating a cost function (also called: target function) to be minimized, but the significant differences listed above will be considered as well. While traditional combustion control has one control variable only (the air flow), the new one is two-dimensional, since the optimal flow rates of both primary and secondary air must be controlled. While traditional combustion control considers a few losses only (basically: incomplete combustion loss because of too low air flow and heat loss by exhaust gas because of too high air flow), the new one must consider also some other significant influences. The list of aspects we propose to build in into the new cost function is the following:

- Satisfactory fluidization must be assured in the lower section of the combustion chamber (below the secondary air inlet).
- Satisfactory fluidization must be assured in the upper section of the combustion chamber (above the secondary air inlet).
- The characteristic bed temperature must not be too high.
- Total CO emission must not be too high (or: it must not exceed its threshold).
- Total NO emission must not be too high (or: it must not exceed its threshold).

This list of terms was found to be sufficient in practical cases. Limiting the bed temperature also from below was found to be unnecessary for example, because other terms of the list assure that this deviation can not happen. As a mathematical representation of this set of terms, exponential functions are proposed because of their easy handling both numerically and analytically, and also because of their abilities for being parametrized so that different limiting shapes can be realized from a nearly linear manner up to a practically sharp threshold. According to this, the proposed form of the cost function, which is to be minimized by the combustion control is the following:

$$\begin{aligned} K = & \exp(a_1 \cdot \dot{V}_P + b_1) \\ & + \exp(a_2 \cdot (\dot{V}_P + \dot{V}_S) + b_2) \\ & + \exp(a_3 \cdot \vartheta + b_3) \\ & + \exp(a_4 \cdot C_{CO} \cdot (\dot{V}_P + \dot{V}_S) + b_4) \\ & + \exp(a_5 \cdot C_{NO} \cdot (\dot{V}_P + \dot{V}_S) + b_5) \quad . \end{aligned} \tag{1}$$

Its parameters a_1 to a_5 and b_1 to b_5 should be set according to the actual local needs dictated by the technology (temperature, fluidization, e.g.), economical circumstances (prices of losses, e.g.) and authority prescriptions (emission limits, e.g.). Input variables in (1) are in strong relationships with the criteria described in the bulleted list above: $\dot{V}_P(\mathrm{m^3/s})$ is the primary air flow rate, $\dot{V}_S(\mathrm{m^3/s})$ the secondary air flow rate, $\vartheta\ (\mathrm{K})$ stands for the characteristic bed temperature,while C_{CO} and C_{NO} (mol/m^3) are the concentrations of CO and NO in the flue gas, respectively. The proposed control concept allows other cost functions as well, of course.

The control task formulated above (to minimize the cost function *K*) should be realized by an appropriately designed controller. Furthermore, we believe that better control performance can be reached on the basis of better knowledge of the process to be controlled. While in case of the traditional PID controller the whole information about the process is represented by only three numbers, advanced control theories use more detailed models. It is advisable in the actual case to benefit the existence of a validated mathematical model, of course, however, the control task is not the most general one. The minimum of a calculated variable should be found in this case, not a given set-point of the controlled variable should be followed, as generally. Different approaches can be followed while designing a controller configuration to solve the model-based optimum control problem outlined above, some of them are listed here:

- Off-line optimum seeking algorithms can be run on the programmed model and cost function while simulating a high variety of operating conditions. The found optimal settings can than be loaded to in a real time (on-line) controller.
- An on-line optimum seeking algorithm can be realized in the real time controller.
- The above closed loop optimum seeking controller can be supported by initial guesses coming from either the off-line optimum search (first bullet above) or learned previous results of the on-line search (second bullet).
- Further model-based on-line optimum seeking procedures can be developed based on the results of the advanced control theory.

The first and second approaches will be discussed in the next two sections in detail. The latest one can be considered as a basis for further enhancements by means of versatile tools supplied by the advanced control theory.

3. OFF-LINE OPEN-LOOP REALIZATION

The simplest way of realization of combustion control of FBCs based on the cost function proposed here is rather close to the way generally used. In this approach, feed-forward elements will be applied to set the optimal values for both primary and secondary air flows corresponding to the actual thermal load as shown on Fig. 3.

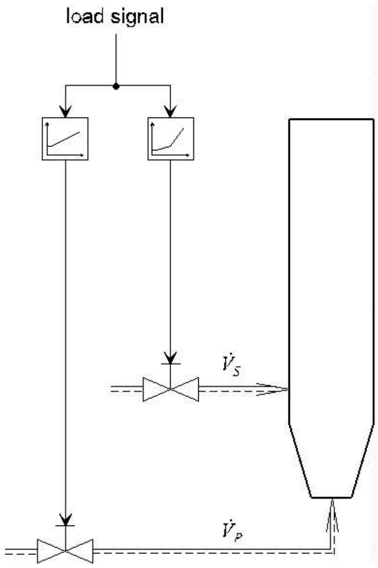

Fig. 3. Structure of the off-line open-loop realization of the control concept based on the proposed cost function.

The main point is here, of course, the way of determining the exact data within the feed-forward blocks in the upper part of Fig. 3. In the actual case, when a verified mathematical model exists, and it can be connected to the programmed

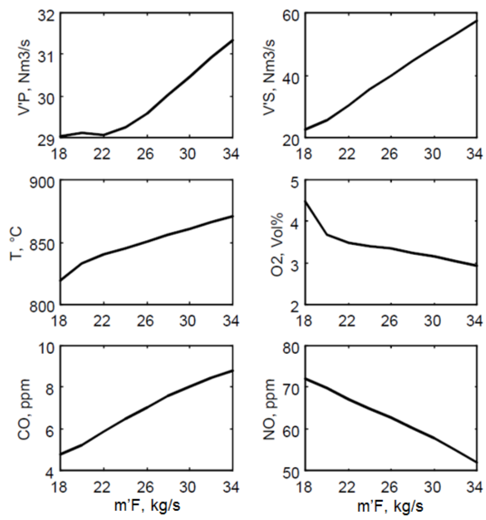

Fig. 4. Results of the optimum-seeking procedures carried out on the verified CFBC model coupled with the cost function (1). The upper two diagrams should be set as the feed-forward elements of the open-loop controllers.

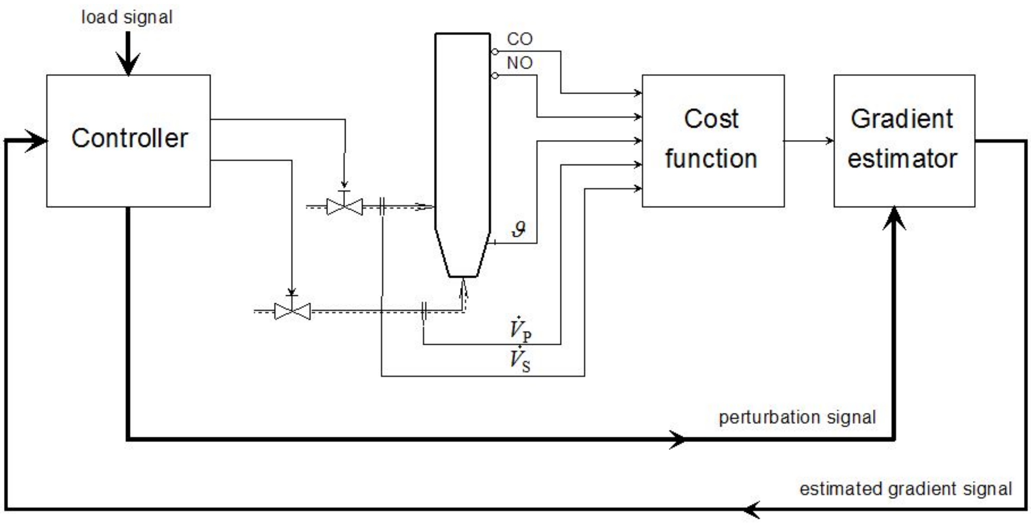

Fig. 5. The proposed structure of the on-line closed-loop realization of the optimum control strategy developed for Fluidized Bed Combustors.

realization of the cost function (1), standard optimum-seeking procedures can be run, which will deliver the optimal controller outputs as functions of thermal load. (Of course, these optimum-seeking procedures can not be run directly on the real process on-line, because of their needs for fast function evaluations in several neighboring steady-state operating points.) The results of these off-line, model-based optimum seeking procedures are shown on Fig. 4, which includes not only the functions to be built in into the feed-forward controllers (upper two diagrams), but also some output values corresponding to the optimal solutions found (the four diagrams below).

A good way of checking the reliability of the procedure (together with that of the model) is to compare its results with those used in the practice. Unfortunately, such control diagrams are rarely published by the suppliers, however, in some early publications their shapes can be found at least (see, e.g.: Bunzemeier, 1992 and Edelmann, 1992). Based on these and some further published data referring to the optimal values in the last four diagrams in Fig. 4, it can be stated that the functions got this way are rather similar to those found by means of experimental procedures. The basic difference is the exact formulation and fast execution of the procedure proposed in this paper.

4. ON-LINE CLOSED-LOOP REALIZATION

The idea of the second way of realization discussed in this paper is simple: it traces back the optimum control task to an ordinary control task. According to this, the gradient of the actual value of the cost function K should be controlled to zero (Fig. 5.).

All process variables of the fluidized bed combustor involved in the cost function will be continuously measured, of course. Their actual values will be forwarded to the block that calculates the actual scalar value of the cost function K, the minimum of which should be found and set by the remaining elements of the control structure. Its gradient should be estimated in the next block. The space of search is two-dimensional spanned by the manipulated variables $\dot{V}_{\mathrm{P}}$ and $\dot{V}_{\mathrm{S}}$, but in practice it often seems to be better handleable to use another space defined by the coordinate transformation $\dot{V}_{\mathrm{A}}=\dot{V}_{\mathrm{P}}+\dot{V}_{\mathrm{S}}$, $r=\dot{V}_{\mathrm{P}}/\dot{V}_{\mathrm{A}}$, where $\dot{V}_{\mathrm{A}}$ is total air and r primary air ratio.

In the gradient estimator, a known identification method will be used first. A two-dimensional, discrete-time ARX model will be identified on-line, which standard method delivers the model parameters in the following form:

$$A(q)\cdot\Delta y(t)=B_1(q)\cdot\Delta u_1(t)+B_2(q)\cdot\Delta u_2(t)+e(t)\,, \qquad (2)$$

where q is the time shift operator, $y(t)$ is the process output (which is the K value in the actual case), and Δu_1 and Δu_2 are the process inputs ($\dot{V}_{\mathrm{P}}$ and $\dot{V}_{\mathrm{S}}$ in the actual case). This procedure needs to know also the perturbation signal, which will be defined and added to the inputs by the controller block. The results of the identification procedure are in this case the coefficients of the polynomials $A(q)$, $B_1(q)$, and $B_2(q)$. The final output of this block (the gradient estimates) can be calculated according to

$$\frac{\partial K}{\partial \dot{V}_{\mathrm{A}}}=\left.\frac{B_1(q)}{A(q)}\right|_{q=1} \quad , \quad \frac{\partial K}{\partial r}=\left.\frac{B_2(q)}{A(q)}\right|_{q=1} \qquad (3, 4)$$

The controller block in the proposed control structure (Fig. 5) can be any traditional controller. The set-point is zero, and the process variable to be controlled is the estimated gradient delivered by the block described above. In the actual implementation of the scheme, a rather simple, conservative control law was built in: the (two-dimensional) controller step is always proportional to the negative gradient (Csébfalvi, 2009) received. A flat sawtooth signal of very low amplitude compared to the effective outputs added to a random binary signal (of low amplitude as well) was chosen as perturbation signal needed for the ARX identification. It is generated within the control block, it is added to the calculated control output, and it is forwarded extra to the ARX identifier located in the gradient estimator block. The load signal of the block is introduced to the controller block for further developments only, as an additional information for learning the optimum values once found.

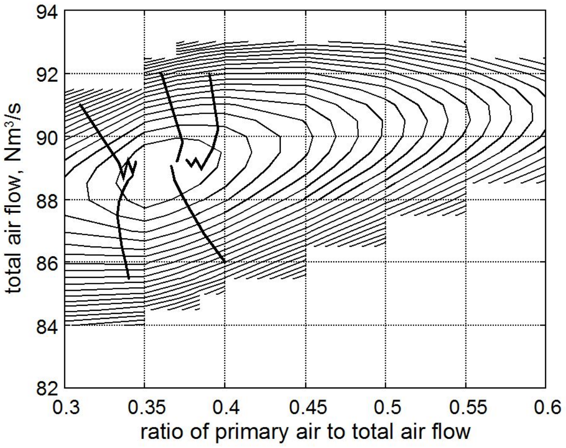

Fig. 6. Trajectories of the Extremum Control from different starting points.

The control strategy was realized in the simulation environment Matlab-Simulink©. The model referred to in the Introduction section (Szentannai, 2011) was used throughout the simulations tests, and also for plotting the surface of the cost function over the space. (The surface of this function is not visible for the on-line controller, of course.) Fig. 6 shows the paths of some simulated searches started from different initial guesses far from the optimum. The results are satisfactory, the controller succeeded in shifting the fluidized bed combustion system close to its optimum in all cases.

4. NEXT STEPS

Based on the results reached by simulation, also experimental tests are foreseen. An excellent basis for them is the pilot-scale CFBC facility of BME, Department of Energy Engineering. This unit is characterized by its 5000 mm riser height, 158 mm riser internal diameter, 3-staged air supply, and about 80 kW thermal capacity in case of 11 MJ/kg brown coal. This facility is equipped with dozens of measuring points allowing detailed monitoring the internal processes.

The entire facility was completely recently refurbished to turn it into a high level, reliable, and easy-to-operate experimental basis for several researches in the areas of fluidized bed combustion and gasification. Besides several technological refurbishments, a completely new Digital Control System was put into operation, which will allow the tests of several control methods requiring even high and fast computing capacities.

Based on this recently refurbished test facility, both control methods outlined in this paper are planned to be tested in the near future. Moreover, upcoming research and development works of the Department will contribute to the improvement of the control strategies of fluidized bed combustors. Within these frames, many further advanced control algorithms will be implemented and tested, together with the development and real tests of some new control techniques (Szentannai, 2010).

5. CONCLUSIONS

Basic behaviors and characteristics of the Fluidized Bed Combustion technique differ definitely from those of other, traditional combustion techniques. In spite of this, most known control strategies use the traditional approach also in this case. A new approach for FBC optimum control was presented in this paper. An adequate form for cost function was proposed first, the parameters of which can be flexibly selected according to the requirements of the actual plant. Several ways of application can be outlined, two of which were discussed in detail. In the first one the optimum seeking procedure will be performed on a mathematical model off-line, while in the other, on-line solution the same, verified model (which was published elsewhere) of a 300 MW_{th} FBC unit will be applied.

Future work will focus on the experimental tests of these and further advanced control strategies for FBCs. For this, the 80 kW pilot-scale FBC facility of BME, Department of Energy Engineering will be used, because this unit was recently completely refurbished, including the introduction of a top quality and capacity Digital Control System.

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