Pulsation-based method for reduction of nitrogen oxides content in torch combustion products

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Abstract. Out of all ways to fuel burn the torch combustion systems is used most often. Even though the processes in the steam boiler are stochastic, the system can be controlled rather easily by changing the flowrate of the air pumped into it and – in case of balanced flue units – exhausters load. Advantages offered by torch-based combustion systems are offset by a disadvantage resulted in oxidation of nitrogen contained in the air. This paper provides rationale for an NOx content reduction method that employs pulsation mode of fuel combustion; it also describes combustion control and monitoring system employed for implementation of this method. Described methodology can be used not only for pulsation combustion studies but also for studies of torches formed by conventional burning systems. The outcome of the experimental study supports the assumption that it is possible to create conditions for NOx content reduction in flue gases by means of cycling the fuel supply on/off valve at the rate of 6 Hz.

1. Introduction

Fuel combustion processes have been thorough studied and are widely used in industry. Out of all ways to fuel burn the torch combustion method used most often. In this method, fuel and oxidizer (usually air) are supplied to the burner to be mixed and produce a burning torch on the burner outlet. The degree of air-fuel mixing directly affects the ratio of burned fuel to the total amount of fuel supplied to the burner and this degree depends on the burner design. The phenomenon of incomplete combustion of fuel supplied to the burner is called chemical underburning of fuel. Fuels conventionally used for combustion in torch include pulverized coal, fuel oil or gas.

The main purpose of the burner is to achieve high degree of air-fuel mixing in order to ensure maximum rate of fuel combustion as compared with fuel-bed or fluidized bed furnaces. This translates into higher temperatures in the torch core and high thermal stresses in the furnace. Since the combustion process comes to completion at a short zone (the torch length), combustion products produced by all burners further mix with each other forming a hot homogeneous mixture that comes into the heat-exchanging units of the plant. Even though the processes in the boiler are stochastic, the system can be controlled rather easily by changing the flowrate of the air pumped into it and – in case of balanced flue units – exhausters load. A typical automatic torch-combustion control system includes a negative feedback loop. It is worth noting that the load control is performed for the overall unit rather than individual burners, which makes the control system considerably simpler. The load on each burner changes in proportion to the total load.

Advantages offered by torch-based combustion systems are offset by a disadvantage resulted from the fact that a great amount of heat is released in a short path where combustion takes place and that
results in oxidation of nitrogen contained in the air. In effect, a number of environmentally noxious substances belonging to nitrogen oxide group (NOx) are released to the atmosphere.

This is why it is so important to reduce NOx content in combustion products generated in industrial and power-generation units. To solve this problem designers usually create heterogeneous lower-temperature zones where combustion process slows down [1]. However, this approach suffers from incomplete burning of fuel (i.e. chemical underburning) and the underburned fuel is carried out from the boiler along with combustion products, which does not help maintain clean environmental conditions near the heat plant. Therefore, for improvement of environmental safety of fuel combustion processes heat and power plants (HPP) call for fundamentally new control systems whose operation would be based not only on data on the overall combustion process outcome, but also on processes that take place in the combustion zone.

This paper provides rationale for an NOx content reduction method that employs pulsation mode of fuel combustion; it also describes combustion control and monitoring system employed for implementation of this method.

2. Rationale for the method for nox content reduction through the introduction of pulsation mode of fuel combustion

A critical parameter to take into account when burning fuels in power generation units, industrial furnaces, etc., is the excess air factor $\alpha$, which is the ratio between actual volume of air supplied to the furnace and the minimum amount of air necessary to completely burn the fuel fed to the furnace

$$\alpha = \frac{V^a}{V^0}, \quad (1)$$

where $V^a$ – actual volume of the air supplied to the furnace, $V^0$ – analytically found volume of air needed to completely burn the supplied fuel. This parameter affects both the combustion process and cost-efficiency of the unit. The volume of the needed air can be found from the content and flowrate of the air fed into the furnace. The actual volume of air fed to the furnace in practice is found from air flowrate per boiler, e.g. through the readings of orifice meters.

When using the torch method for fuel combustion efforts are made to ensure optimal value of $\alpha_{opt}$, that is calculated based on the overall fuel supply and air supply flowrates per boiler. In addition, the following basic technical and cost parameters should be taken into account: losses of heat carried away with residual gases $q_2$ and heat losses due to chemical underburning $q_3$. These parameters are used in the analysis of the power unit thermal balance. Since all flows are distributed nearly evenly between the burners, this assumed value of $\alpha$ is optimal for each burner.

The loss of heat carried out with residual gases $q_2$ takes place because enthalpy of the combustion products leaving the unit is greater than that of the air and fuel coming into the boiler, so that part of the produced heat is released into the atmosphere. This parameter depends on the volume of combustion products and, therefore, on the excess air factor $\alpha$. The greater factor $\alpha$ is, the more air is fed to the furnace and more combustion products are created. Supplying air in the volumes greater than minimum needed to burn the fuel causes some heat to be spent for heating the air that is not involved in the combustion process and releasing that heat into the atmosphere along with flue gases.

Chemical underburning takes place when the excess air factor falls below 1 since in that case there amount of air fed to the boiler is insufficient to completely burn the fuel. The loss due to underburning is the amount of heat $q_3$ is the amount of heat that would be generated at complete oxidation of the chemical underburning products.

To cope with this, the optimal $\alpha$ is thought to have a value that excludes chemical underburning and, at the same time, minimizes heat losses caused by carryover with residual gases. This value is calculated in the course of boiler design and then it needs to be adjusted at the start-up testing phase because it depends on fuel type and content, furnace or combustion chamber geometry, the unit operating loads range, etc. As a rule, modern gas-fired steam boilers of high capacity are designed to operate at the excess air factor of $\alpha = 1.05 + 1.1$. When using solid fossil fuels the factor is assumed to
be $\alpha \approx 1.2$ in order to allow for more complex mixing and ignition processes resulting in poorer interaction between the air and fuel particles.

As noted above, proper operation of torch systems causes extensive formation of nitrogen oxides that can be broken down into fuel, prompt and thermal NOx due to different nature of their formation. Fuel oxides are made of nitrogen contained in the fuel and they usually emerge when burning solid or liquid fuels. The mechanism of formation of prompt NOx was suggested by Fenimore [2]: CHm radicals formed as interim components only in the front of the flame react with the air nitrogen, causing the formation of nitrogen cyanide that undergoes further oxidation to NO [3]. Prompt NOx in the front of the flame are formed during the entire combustion process and presently it is practically impossible to reduce their content. Thermal nitrogen oxides emerge because the heat energy generated in the combustion chamber when burning fuel is sufficient for the nitrogen contained in the air to undergo direct endothermal oxidation reaction [4]

$$\frac{1}{2} N_2 + \frac{1}{2} O_2 \rightarrow 21,5 \times 10^3 J / \text{mole} = NO.$$  

(2)

Most nitrogen oxides are formed through this thermal mechanism and the NOx formation rate dependency from the air excess factor is known. Typical curves showing dependency between NOx content in combustion products and factor $\alpha$ ($C_{NOx} = f(\alpha)$) for two different boilers operating on gas fuel are shown on Figure 1 [5] (data was obtained from tests conducted in the course of start-up operations).

![Figure 1. Dependency between NOx content in combustion products and factor \( \alpha \), data was obtained from tests (upper curve – of TGM-94 steam boiler of Tashkent HPP, lower curve – of BKZ-320-140 of Engelsk HPP).](image)

Figure 1 shows that the graphs are similar: $\alpha_{\text{opt}} = \text{agr max}(f(\alpha))$. Where $\alpha < \alpha_{\text{opt}}$ (overrich fuel mixture and insufficient oxidizer) or $\alpha > \alpha_{\text{opt}}$ (weak fuel mixture), NOx formation is considerably slower. Therefore, NOx content can be reduced if, instead of burning fuel in a single stream at the optimal air access factor $\alpha_{\text{opt}}$ (from the heat losses standpoint), it will be burned in several streams $\alpha_i \neq \alpha_{\text{opt}}$, $i = 1, \ldots, I$ is the stream number, so that $\alpha = \frac{1}{I} \sum_{i=1}^{I} \alpha_i = \alpha_{\text{opt}}$, i.e. the overall air excess factor at the furnace inlet stays optimal. To implement this requirement the air or fuel can be redistributed between tiers of burners. In this solution, the boiler furnace is apparently broken into zones where fuel first is burned at the excess air volume much lower than that required and then the fuel undergoes additional oxidation with air streams supplied through the burners of the top tier. However, this configuration is difficult to control since regulation of the thermal load on the unit requires separately change fuel or oxidizer flowrates for each burner. It also requires agitation of combustion products in each burners by the time they are leaving the chamber in order to prevent chemical underburning and abrupt increase
of the temperature in the downstream heat exchangers that would take place due to afterburning of combustible gases.

We suggest that the shortcomings described above can be removed if, instead of stationary combustion process, combustion will change in time through changes in the excess air factor \( \alpha(t) \), where \( \alpha(t) \) is a time-dependent function, e.g. a periodic one. To control air flowrate a regulation device should be installed in the fuel supply line connected to the burner. That device will change fuel flowrate periodically while the air supply flowrate will be kept unchanged. Under these conditions the excess air factor will change following a similar periodic pattern. This will make the torch consisting of alternating zones where \( \alpha < \alpha_{\text{opt}} \) and \( \alpha > \alpha_{\text{opt}} \) while the average excess air factor per cycle \( \bar{\alpha} \) will be equal to the optimal factor for this unit \( \alpha_{\text{opt}} \). In the course of longitudinal heat and mass exchange in the torch and combustion products in the furnace these zones will mix with each other and the interim combustion products will undergo further oxidation thus ensuring complete extraction of heat and reduced formation of NOx.

Estimates made by the authors show that the optimal pattern \( \alpha(t) \) for excess air factor changes is a sequence of square pulses described as

\[
\alpha(t) = \begin{cases} 
\alpha_1, & t - T_1 \cdot \text{round}(t/T_1) < T_1, \\
\alpha_2, & t - T_2 \cdot \text{round}(t/T_2) < T_2,
\end{cases}
\]

(3)

where \( \alpha_1 < \alpha_{\text{opt}}, \alpha_2 > \alpha_{\text{opt}}, T_1 = T_2 = T \) (pulsation period) where NOx content can be reduced by 65%. This mode will be called pulsation mode hereafter as suggested in (3). As shown in (3), NOx content in combustion products depends on parameters \( \alpha_1, \alpha_2, T \). Right choice of these parameters will ensure creation of torch zones with different excess air factors, as well as achieve such a gas-dynamic mode in the furnace that the zones will have enough time to mix with each other within the furnace and the underburned products will be oxidized completely.

Since the known theoretical combustion models depend on a number of parameters which values are either unknown or greatly differ in estimates made by different researchers, it was not feasible to obtain reliable values for \( \alpha_1, \alpha_2, T \). This necessitated targeted experimental studies of pulsation combustion mode. The outcome of these studies is discussed below.

3. Methodology developed for the experimental studies of pulsation combustion

The experimental study was conducted using an automated unit for pulsation combustion studies specifically developed for that purpose. [6]. The unit includes a direct-flow jet burner with the outlet diameter of 20 mm that creates a turbulent diffusion torch without premixing.

This torch is similar to that conventional torch combustion system create (Figure 2). Two valves are installed into the gaseous fuel supply line. The first valve regulates the total gas pressure and flow rate, the second operates in on/off mode creating pulsations of fuel flowrate in order to arrange pulsation combustion.

![Figure 2. Photograph (taken in the visible spectrum) of the work zone with the burner of the automated measuring unit for pulsation combustion studies.](image)
The experiments were run following the procedure shown below:

1. Burner is ignited and upstream valve adjusted to set gas pressure and, therefore, the average flowrate of gas supplied to the burner.

2. Combustion pulsation mode maintained through opening/closing the on/off valve that changes the excess air in the burner at a preset rate. When studying steady combustion process without pulsations this on/off valve stays open.

3. Sequences of torch images in IR range recorded with thermal imager FLIR 7700M with the resolution of 320 x 240 pixels for the period of 10 seconds at the frame rate of 412 Hz. Each sequence saved as an matrix $T(i,j,k)$ of images $T(i,j)$ with the matrix size of $320 \times 240 \times 4120$. Figure 2 shows an example of a single frame $T(i,j)$.

4. Time series compiled based on the obtained frame sequences. These time series (TS) represent instantaneous sizes of the areas where ignition begins $N_{\text{low}}(k)$ and the torch core $N_{\text{core}}(k)$, $k = 1, 4120$.

5. Power spectral density (PSD) of the time series $N_{\text{low}}(k), N_{\text{core}}(k)$ normalized to the maximum value found through Fast Fourier Transform (FFT).

6. Primary periodic components of the time series $N_{\text{low}}(k), N_{\text{core}}(k)$ found through the singular spectral analysis (7) and their PSD computed.

It should be noted that this methodology can be used not only for pulsation combustion studies but also for studies of torches formed by conventional burning systems, e.g. when precommissioning and tuning existing units.

4. The experiments outcome and discussion

We now will discuss normalized power spectral densities of time series $N_{\text{low}}(k), N_{\text{core}}(k)$ shown on Figures 3 through 5. Other paragraphs are indented (BodytextIndented style).

Figure 3. Normalized PSD for time series $N_{\text{low}}(k)$ (below) and $N_{\text{core}}(k)$ (above). Pulsation combustion mode with fuel supply cycling rate of 2 Hz.
Figure 4. Normalized PSD for time series \( N_{\text{low}}(k) \) (below) and \( N_{\text{core}}(k) \) (above). Pulsation combustion mode with fuel supply cycling rate of 6 Hz.

Figure 5. Normalized PSD for time series \( N_{\text{low}}(k) \) (below) and \( N_{\text{core}}(k) \) (above). Pulsation combustion mode with fuel supply cycling rate of 10 Hz.

Figure 3 shows that the maximal energy belongs to the PSD spectral component with the frequency equal to that of the fuel supply on/off valve cycling rate. On comparison of the absolute energies of these spectral components for on/off valve cycling rate of 1 Hz, 2 Hz, 3 Hz and 4 Hz, the conclusion was drawn that increase of the cycling rate causes the energy of these spectral component to decrease while the energy of other spectral components increases. This findings are supported by the results shown on Figures 4 and 5 demonstrating that maximum energy falls into spectral components of the time series \( N_{\text{low}}(k) \), with frequencies not divisible to the on/off valve cycling rate. One can see on Figure 5 that at the cycling rate of 10 Hz the PSD components of both time series \( N_{\text{low}}(k) \) and \( N_{\text{core}}(k) \) being discussed are similar to PSD components of time series obtained at steady supply of fuel. These combustion modes can be viewed as quasi-continuous processes where, as well as in the steady mode, no heterogeneous zones exist in the torch and, subsequently, reduction of NOx content by means of pulsation combustion is not feasible.

It was also found that at the cycling rate of 3 Hz and below the torch is unstable while the quasi-continuous torch exhibit steady burning. Therefore, even though cycling at the rates of 3 Hz and below creates conditions for NOx reduction in the combustion products, it is not recommended to use this mode in practice due to unstable combustion.

Yet, it is feasible to create such conditions that the fuel burns quasi-continuously at the root of the torch while maintaining pulsation mode in the torch core where the primary volume of fuel is burned (Figure 4). This ensures necessary conditions for reduction of NOx content in flue gases.

5. Conclusion
The outcome of the experimental study supports the assumption that it is possible to create conditions for NOx content reduction in flue gases by means of cycling the fuel supply on/off valve at the rate of 6 Hz. It was found that in this case the fuel supplied to the burner burns quasi-continuously in the torch root while in the torch core, where the main volume of the fuel is burned, the pulsation combustion process is maintained.

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