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Pulsating Combustion: Theoretical and Empirical Substantiation of Ecological Effect

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Abstract. There are two primary parameters that characterize operation of modern energy generation units that burn fuel, namely – unit efficiency and the amount of noxious emissions. Usually units that operate at the maximum efficiency produce maximum potential emissions of noxious substances (as NOx) into the atmosphere. This work provides theoretical substantiation for control of the combustion process by superimposing controlled irregularities to the fuel supply rate in order to suppress NOx generation while retaining the unit's technical parameters and cost efficiency. The substantiation uses known empirically obtained NOx generation dependency from the air excess ratio. Evaluation of the generated NOx content was performed using numerical integration of the composed time sequences describing changes in the NOx concentration in the combustion products for various types of control actions. Evaluation of bands of operating frequencies for the proposed method of combustion control are presented. The proposed theoretical substantiation made it possible to determine conditions and technics for experimental work.

INTRODUCTION

Nowadays fuel combustion is a fundamental process in different industry fields. 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.

Because of combustion, a number of environmentally harmful substances that belong to the group of nitrogen oxides (NOx) are formed. Reduction of NOx content in exhaust gases is one of the primary ways to improve environmental safety of combustion processes and make the process cleaner [1]. In most cases, the application of NOx reduction methods directly affects the degradation of combustion efficiency. Therefore, to implement each method, it is necessary to develop a substantiation of NOx reduction mechanism and evaluate its effectiveness.

Unfortunately, existing combustion models are quite simple, and can adequately describe only stationary processes [2]. Therefore, it is often necessary to perform experimental studies and develop new mathematical models for each new NOx reduction mechanism.

B This paper presents a theoretical and empirical substantiation for the reduction of nitrogen oxides content in power equipment exhaust gases by pulsating of the prime thermal parameters in the combustion zone, which makes possible to maintain the efficiency of equipment at the same level and avoid increasing of heat losses.

PRINCIPLE OF DETERMINING THE VALUE OF THE AIR EXCESS FACTOR

A critical parameter to take into account when burning fuels in power generation units, industrial furnaces, etc., is the excess air factor, which is the ratio between the actual volume of air supplied to the furnace or combustion chamber and the minimum amount of air necessary to completely burn the fuel fed to the furnace at the given flowrate. This factor is usually referred to as α. It specifies 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 at the given flowrate

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$$\boldsymbol{\alpha} = \frac{V^{в}}{V^{0}}. \qquad (1)$$

The volume of the needed air can be analytically 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. Apparently, at α = 1 the combustible fuel-oxidizer mixture is stoichiometric, meaning that it contains oxidizer in the amount it equal to that necessary for complete oxidation of the fuel.

The excess air factor shall be selected based on the composition of losses in the thermal balance of the unit. Generally, the thermal balance of a power boiler can be expressed as the equation [3]:

$$Q_p^p = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6, \qquad (2)$$

where Q_p^p - heat available in 1 kg of solid or liquid fuel or 1 m3 of gaseous fuel,

Q_1 - utilized heat, i.e. the heat passed to the working medium, Q_2 - heat lost due to residual gases, Q_3 - heat lost due to underburning, Q_4 - heat lost due to mechanical incompletion of burning (for solid fuel), Q_5 - heat lost due to external cooling, Q_6 - heat lost with ash (for solid fuels).

Dividing both parts of the equation (2) by available heat one can expressed the thermal balance in a dimensionless form:

$$1 = \eta^{бр.} + q_2 + q_3 + q_4 + q_5 + q_6, \qquad (3)$$

where $\eta^{бр.} = \frac{Q_1}{Q_p^p}$ - gross thermal boiler efficiency factor, $q_2 \ldots q_6$ - related losses of heat expressed in fractions.

Since this work discusses combustion of gaseous fuel, heat losses due to mechanical incompletion (q_4) and heat losses with ash (q_6) are assumed to be equal to 0.

In practical applications to determine the best value for the excess air factor two aspects are taken into account: heat losses with residual gases and those due to chemical underbirning. Both parameters are used when computing thermal balance of a power unit. Typical dependencies of losses q_2 and q_3 from the excess air factor in the furnace are presented in the Figure 1.

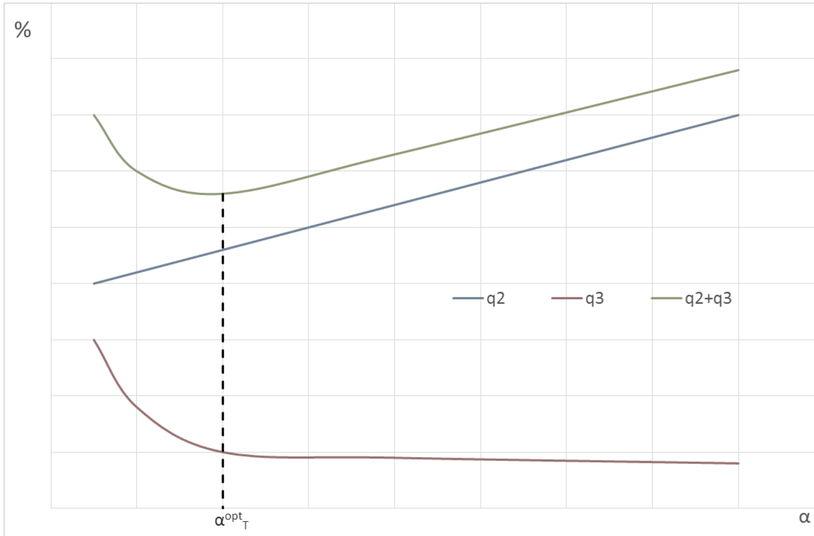

FIGURE 1. Typical dependencies of losses q_2 and q_3 from the excess air factor in the furnace.

Figure 1 demonstrates that the best excess air factor is determined as the x-axis value for the minimal value of the curve. The torch-type combustion systems described above ensure efficient burning of fuels and low losses of heat. During the period of investigation and application of torch combustion systems, there were constructed several mathematical models, which allow to create efficient automated control systems. 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.

PECULIARITIES OF THE NITROGEN OXIDES FORMATION IN THE TORCH COMBUSTION SYSTEM

As described above, the maximum reduction in heat losses and, consequently, the maximum efficiency of the unit (in line with the Equation 3) is achieved when fuel is burned at the optimal value of the air excess factor. In this mode of combustion, fuel and oxidizer (air in our case) are mixed efficiently, which increases the rate of chemical oxidation reactions. This results in generation of large amount of heat in a relatively short section of the gas-air path in the boiler's combustion chamber. This amount of heat is sufficient for the endothermic reaction of oxidation of nitrogen contained in the air. A model describing the formation of nitrogen oxides in this process was introduced by Zeldovich [4] and named "thermal nitrogen oxides". Formation of nitrogen oxides is inevitable where air serves as an oxidizer because the nitrogen content in the air is about 78%.

The dependence of nitrogen oxides generation on the excess air factor in the combustion zone follows a well-known pattern. Figure 2 shows the relation of the volumetric share of NO_x and the excess air factor in the combustion zone. The data was obtained for methane combustion in the air in a mixing reactor [5]. This data represent the “perfect case” in terms of mixing conditions, so we will discuss the rationale for pulsating combustion based on this curve.

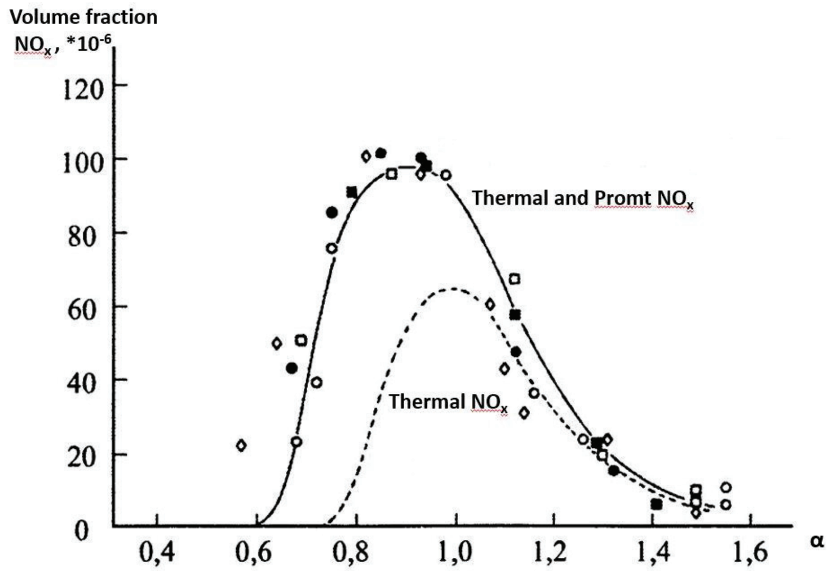

FIGURE 2. Dependency between NOx content in combustion products and factor α, for methane combustion in the mixing reactor.

Fig. 2 demonstrates that the greatest amount of thermal nitrogen oxides formation takes place at the optimal value of excess air factor, which is equal to 1.0 for the mixing reactor (due to the almost perfect conditions for mixing gases in the combustion zone). The figure also shows that where the value of air excess factor deviates in either direction from the optimal value, a significant decrease in the intensity of formation of nitrogen oxides is observed. This is due to the fact that combustion modes when air excess factor is greater or lower than the optimal value, which translates into too lean or too rich fuel-oxidizer mixes respectively, the reaction rates and heat release levels are considerably lower.

REDUCTION OF THE NITROGEN OXIDES FORMATION BY PULSATING

It is possible to reduce the content of nitrogen oxides without increasing thermal losses by creating inhomogeneous areas in the combustion zone where the air excess factor differs greatly from the optimal value and subsequently mixing these areas so that the average value of the excess air factor in combustion products is equal to the optimal value. The most efficient methods for NOx reduction are based on this concept [6].

However, in order to implement this methods it is necessary to arrange several fuel and oxidant supply lines to the combustion zone and then ensure that the combustion products are mixed completely in the boiler furnace. This is often difficult or impossible to implement in practice.

The intensity of formation of nitrogen oxides can be reduced 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 excess value a regulation valve should be installed in the fuel supply line connected to the burner. That valve 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 $\alpha < \alpha_{opt}$ and $\alpha > \alpha_{opt}$ while the average excess air factor per cycle $\bar{\alpha}$ will be equal to the optimal factor for this unit α_{opt}. In the course of longitudinal heat and mass trnsfer 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 NO_x.

We will now discuss the case where the immediate excess air factor changes following a sine pattern. The dependency of the air excess factor for this case can be described by typical sin low. The Figure 3 shows result of computations based on empirically obtained dependency (Fig. 2) for burning methane in the air.

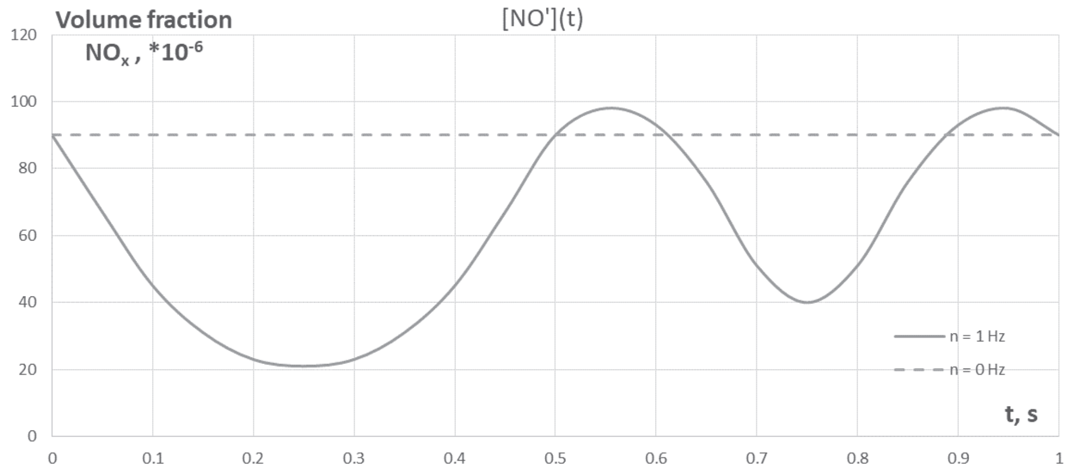

FIGURE 3. Dependency of NO_x content in combustion products during one period of air excess factor changing by sin pattern. Horizontal dotted line is represent NO_x volume fraction value for stationary mode (without pulsations).

It can be seen that by superimposing periodic pulsations of the excess air factor even in the range of 30% from the optimal value results in reduction of NO_x in the combustion products. When changing the excess air factor following a sine pattern for some period of time, the torch operates in the area of elevated formation of NOx due to chemical underburning and generation of prompt nitrogen oxides. Most of the time though the torch operates in areas where formation of NO_x is considerably less than in case of operation at the constant excess air factor.

Nonetheless, it is possible to get rid of the modes where the torch operates with increased NO_x generation as compared with the pulsation-free combustion. This can be achieved by changing the excess air factor following a pattern of periodic square pulses. In this case the combustion process can be only in two alternating modes that differ by the values of the excess air factor. The Figure 4 shows result of computations based on empirically obtained dependency (Fig. 2) for burning methane in the air, during one period of air excess factor changing by sequence of square pulses.

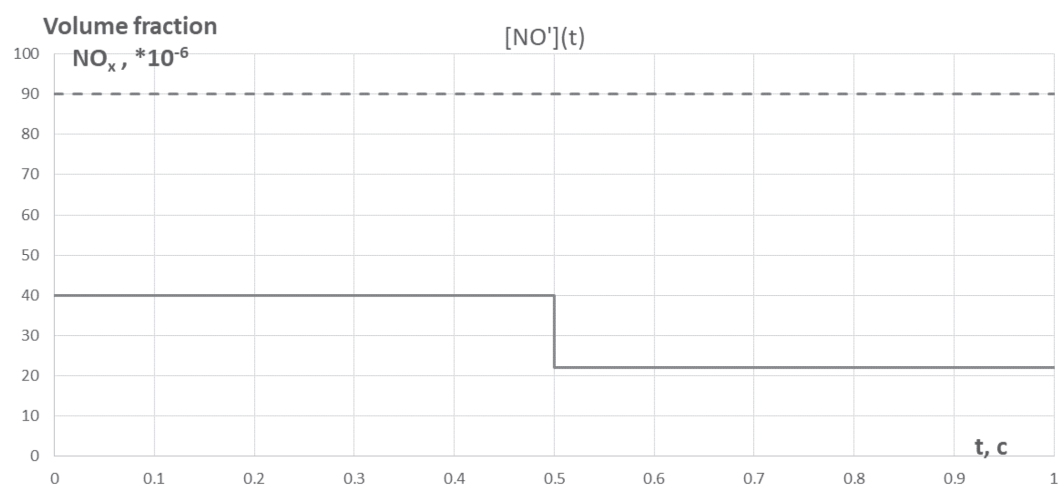

FIGURE 4. Dependency of NO_x content in combustion products during one period of air excess factor changing by sequence of square pulses. Horizontal dotted line is represent NO_x volume fraction value for stationary mode (without pulsations).

The analysis showed that when the air excess factor value is changed following a periodic pattern consisting of square pulses, the total amount of NO formed during 1 period in combustion products is reduced by 65.6% as compared with the operation of a torch with a steady air excess factor equal to the optimal value.

The introduction of periodic changes in the value of excess air factor results in formation of zones with different excess air in the combustion area. To that end, the primary factor that controls the combustion process is the rate of these periodic changes. Let's evaluate the pulsation rate range.

The lower boundary of that range is driven by the length of time Tc when the fuel and oxygen are in the furnace or combustion chamber. It is necessary to make sure that the combustion process comes to completion in the furnace or combustion chamber. Nonetheless, it is clear that full oxidation won't achieved if pulsation half-period is equal or greater than the time when the gases are in the furnace/combustion chamber, so the lower boundary of the range can be found frequency, that corresponds to period, that equal to doubled residence time of gases in the furnace.

The upper boundary of the range of operating rates corresponds to the rate at which transient processes start distorting the square sequence. This takes place due to compressibility of gaseous fuels that causes changes in gas density and introduces inertia to the process.

DISCUSSION AND CONCLUSIONS

At present, there are no math models that would adequately describe combustion process under non-stationary values of the excess air factors. Since the available 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 parameters for pulsating combustion mode. This necessitated targeted experimental studies of pulsation combustion.

The analysis of the possibility of using pulsating combustion mode, based on the empirical dependence of the nitrogen oxides content on the air excess factor in the combustion zone, showed that pulsating combustion improves the environmental qualities of power units. The control cycle rate, i.e. the rate of pulsations of excess air factor in the combustion zone is the primary parameter of pulsating combustion. There is a range of rates where pulsating combustion applications make positive impact on unit operation

The outcome of the analysis made it possible to design an experimental setup and develop a research plan. To determine the influence of the pulsation frequency on the mechanism of pulsating combustion, experiments are run using measurements of the concentration of nitrogen oxides in the combustion products by a gas analyzer and optical diagnostics of the combustion zone in the infrared band with subsequent frequency-domain analysis [7].

The results of the experiments together with the theoretical rationale will help develop a mathematical model of the pulsating combustion mode that will enable developers to design new power generation equipment and complex automatic combustion control systems.

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