Heat technological and ecological aspects of co-combustion of gas and fuel oil in tube furnaces of oil refineries

O Yu Kuleshov, E I Muslimov, A A Ovchinnikov and V M Sedelkin

Saratov state technical university named after Yu A Gagarin, 77 Polytechnic St., Saratov, 410054, Russian Federation

E-mail: o-yu-kul@yandex.ru

Abstract. The article provides a theoretical justification for the effective operation modes of a cylindrical tube furnace with the combined combustion of gas and fuel oil in order to improve heat technological and ecological indicators due to the complex impact of a several factors: 1) burning gas and fuel oil in certain ratios, that provide a sufficiently high heat supply of the radiation heating surface, and 2) reducing the temperature of the flame in the zone of intense burning due to the intensification of radiant heat transfer in the furnace. The latter can be achieved by increasing the emissivity of the flame, and by changing the tube coil binding and reducing the temperature of the inside raw material flow and the wall of the tubes in the zone of intense burning in the combustion chamber of the furnace.

1. Introduction

The oil refineries burn a significant amount of fuel for its own needs, mainly in tube furnaces, which are one of the main types of equipment. In tube furnaces, along with factory gas, 30% or more of fuel (residual) oil is burned due to the lack of refinery gas. Factory gas is obtained during primary distillation and secondary processing of oil and petroleum products. Its quantity and composition depend on the grade (density) of the refining oil and the oil second processing technologies, implemented at the refineries. Fuel from the outside (natural gas) is purchased rarely and in small quantities, when the balance of fuel on own needs of refinery is violated. The burners of tube furnaces are usually combined, and provide for the combustion of gas and fuel oil (separate or joint).

Fuel oil gives a high-temperature radiated flame. This causes, on the one hand, a high heat supply of the radiation heating surface in the combustion chamber of furnace, and on the other hand, an intensive formation of nitrogen oxides NOx, including mainly due to fuel nitrogen. Moreover, the factors, that affect the intensity of formation of fuel NOx, are approximately the same as air NOx: the concentration of atomic nitrogen and oxygen in the combustion products and the temperature level of the process [1].

It is obvious that the combustion of fuel oil leads to a significant increase in NOx emissions due to the fuel component of nitrogen. However, since no one refuses to burn fuel oil at the refinery, it is advisable to consider methods for reducing NOx emissions. The simplest and most effective methods are: 1) joint combustion of gas and fuel oil in certain proportions, providing a sufficiently high heat supply of the radiation heating surface; 2) reducing the temperature of the flame in the zone of intense burning due to the intensification of radiant heat transfer in the combustion chamber. This is especially true when burning low-calorie factory gases, which are by-products of secondary thermal processing of oil fractions, which are becoming more and more at the modern refineries.
When the proportion of fuel oil in the combined fuel decreases, two mutually reinforcing factors affect on NOx output: 1) reducing the burning temperature due to reduced heat generation and high heat transfer of an intensely radiated flame; 2) reducing the concentration of fuel nitrogen in the gas-fuel oil mixture.

Intensification of radiation heat transfer in the combustion chamber and reduction of the flame temperature can also be achieved by changing the binding of the raw coil and reducing the temperature of the raw material and the wall of the radiated tubes in the zone of intense burning.

Thus, the process of heat transfer and the process of NOx formation in the combustion chamber of the furnace are interrelated. Thus, the processes of heat transfer and the processes of NOx formation in the combustion chamber of the furnace are interrelated. Therefore, it is important to study the mutual influence of the efficiency of the heat supply mode in combustion chamber of the furnace (heat-technological factor) and the level of NOx formation (ecological factor).

2. Choosing the research object

Narrow-chamber vertical tube furnaces of cylindrical and box types are the most modern designs of furnaces that are widely used in the domestic and foreign oil refining industry. In this regard, a cylindrical furnace of the CS1 type (figure 1), developed by the Russian company “Vnienieftemash”, was adopted as the object of research [2].

![Figure 1. Cylindrical tube furnace CS1 with a spiral tube coil.](image)

Designations: 1 is the frame; 2 is the walls; 3 is the radiant tube coil; 4 is the bottom; 5 is the burner; 6 is the product inlet; 7 is the convective tube coil; 8 is the transition tubes; 9 is the product outlet; 10 is the chimney.

CS1-cylindrical furnace with volumetric long-flame combustion of gaseous and liquid fuels (joint or separate). Combined burners of the GGM or GP types are located in the bottom of the furnace. The convection chamber is located above the radiation chamber. Gas discharge is carried out through a gas collector and a chimney installed on the furnace. The raw material is preheated in the convective section, and then finally in the radiation section of the coil. The furnace can be with a vertical or spiral
wall-mounted tube coil in the radiation chamber. The CS1 furnace has a series of standard sizes that differ in heating capacity and, accordingly, the heating surface area.

Technical characteristics of the taken furnace size CS1-40/5: heat capacity of the furnace is 2.3 MW; radiation surface of the furnace chamber is 50 m$^2$; internal diameter of the body is 2.1 m; tube coil height is 5 m; diameter of tube is 76×5 mm; tube pitch is 1.8d.

3. Development and justification of methods for joint calculation of heat transfer and formation of nitrogen oxides in the tube furnaces

3.1. Method of calculating of heat transfer in the combustion chamber

Within the framework of the research task, one of the most important features of the method used for calculating tube furnaces should be the determination of detailed (to a greater or lesser extent, if necessary) characteristics of heat transfer: the distribution of radiant and convective flows on the heat-receiving surface, the temperature field in the volume of the furnace, the size of the combustion zone and its physical and chemical characteristics.

To solve this problem, the zoning calculation method [3, 4] is applied in this paper. Within the framework of the method, the radiating system is divided into volume and surface zones, for which a system of algebraic equations of heat balances is written, approximating the original integral-differential equations of radiation-convective heat transfer in the calculated area. Energy characteristics (temperatures or heat flux) are determined based on the heat balance and each zone, taking into account heat release in it, convective and radiation heat transfer of this zone with the rest. The integral character of radiation heat transfer is taken into account by generalized radiation angle factor between all zones of the radiating system. To solve the problem of heat transfer in general, it is necessary to calculate the determining parameters: optical-geometric characteristics of the zones of the radiating system, gas dynamics and convective heat transfer characteristics of the furnace, the length of the flame and the dynamics of fuel combustion, etc. All these basic problems are solved as conditionally separate and require the use of their own specific methodological approaches [4].

3.2. Method for calculation of nitrogen oxide formation

Nitrogen monoxides NO are formed when fuel is burned in furnace under conditions of simultaneous processes of mixing, combustion, and heat exchange. Upon further oxidation of NO formed nitrogen multi oxides NOx.

According to the theory of combustion of hydrocarbon fuels in a flame, the temperature curve can be characterized by two sections. The first section of approximately 0.5 length of flame jet $L_f$ is characterized by an intensive combustion process and heat release (here burns up 80 % of the fuel), which is accompanied by high (close to maximum values) temperature and the emissivity of flame. The second section – the fuel burn-out section, is characterized by lower parameter values. Nitrogen monoxides are intensively formed in the zone of maximum temperatures and heat releases.

In addition to the zoning method for calculating of heat transfer, the following empirical mathematical model was used to determine the kinetics of NO formation.

The equilibrium concentration of "air" nitrogen oxides is determined by the equation of Ya.B. Zeldovich, mg / m$^3$:

$$[NO] = 4.6 \cdot \sqrt{C_{N_2} \cdot C_{O_2}} \cdot \exp[-21500 / RT].$$

(1)

The leading role in the formation of NO in the combustion zone belongs to the process temperature and the concentration of atomic nitrogen and oxygen [5]. In [6], the dependence between the actual and equilibrium concentrations of nitrogen oxide is proposed, mg / m$^3$:

$$NO = \frac{\tau}{[\tau]} [NO],$$

(2)
where \( \tau \) is the residence time of combustion products in the zone of high temperatures, s; \([\tau]\) is the equilibrium time of the reaction of nitrogen oxides formation, s.

The residence time of reactants in the reaction zone depends on the gas velocity in the zone of maximum temperatures of the flame, in the case of straight-jet flow, s:

\[
\tau = \frac{v_{\text{gas}}}{l_{f \text{ max}}},
\]

where \( v_{\text{gas}} \) is the average velocity of gases (m/s) in the section of the flame jet \( l_{f \text{ max}} \) (m), with the maximum temperature.

Time of onset of equilibrium of the reaction of synthesis of nitrogen oxides, s:

\[
[\tau] = \frac{2.06 \cdot 10^{12}}{\eta \cdot C_{N_2}} \cdot \exp\left(-\frac{53750}{T}\right),
\]

where \( T \) is the temperature in the reaction zone, K; \( \eta = \rho / \rho_0 \) is the ratio of the density of the medium in the reaction zone and the density of the initial medium.

The analysis of the above formulas shows that the main factors determining the amount of nitrogen oxides in the combustion products are: temperature, concentrations of reacting components (nitrogen and oxygen) and the dwell time in the reaction zone.

The most important characteristic in the formation of nitrogen oxide is the maximum temperature of the flame, which is determined by the zonal calculation of heat transfer in combustion chamber.

The nitrogen and residual oxygen concentrations in the reaction zone included in the above equations are determined by the ratios, kg / m\(^3\):

\[
C_{N_2} = \frac{0.79 \cdot V_{\text{air} 0} \cdot (\alpha_b + 0.5 \cdot \Delta \alpha_b) \cdot \rho_{N_2}}{[V_{\text{gas}} + (\alpha_b + 0.5 \cdot \Delta \alpha_b - 1) \cdot V_{\text{air} 0}]},
\]

\[
C_{O_2} = \frac{0.21 \cdot V_{\text{air} 0} \cdot (\alpha_b + 0.5 \cdot \Delta \alpha_b) \cdot \rho_{O_2}}{[V_{\text{gas}} + (\alpha_b + 0.5 \cdot \Delta \alpha_b - 1) \cdot V_{\text{air} 0}]},
\]

where \( \alpha_b \) is the coefficient of excess of air in the burner; \( \rho_{N_2}, \rho_{O_2} \) are the density of nitrogen and oxygen, kg / m\(^3\); \( V_{\text{gas} 0}, V_{\text{air} 0} \) are the theoretical volumes of gases (combustion products) and air during fuel combustion, m\(^3\) / m\(^3\).

Using formulas (1)–(6), we will determine the concentrations of airborne nitrogen oxides. In addition to "air" nitrogen oxides, "fuel" nitrogen oxides are formed when nitrogen-containing fuels are burned. As a result, the total amount of nitrogen oxides formed in the combustion chamber will be, mg / m\(^3\):

\[
NO = NO_{\text{air}} + NO_{\text{fuel}}.
\]

According to [7], the following formulas are recommended for determining "fuel" nitrogen oxides, mg / m\(^3\):

a) at the value \( T \geq 1850 \) K

\[
NO_{\text{fuel}} = \left(0.45 - 0.1 \cdot N' \right) \cdot N' \cdot \frac{2100 - T}{125} \cdot \left(\frac{\alpha_{\text{gas}} + k}{1 + k}\right)^2,
\]

b) when the value of \( T < 1850 \) K

\[
NO_{\text{fuel}} = 2 \cdot \left(0.45 - 0.1 \cdot N' \right) \cdot N' \cdot \left(\frac{\alpha_{\text{gas}} + k}{1 + k}\right) \cdot \frac{T}{1850}.
\]
where $N_r$ is the nitrogen content in the fuel as-received, %; $\alpha_{gas}$ is the excess air coefficient in the burner; $k$ is the flue gas recirculation coefficient.

Thus, a method for joint calculation of heat transfer and the kinetics of nitrogen oxide formation in tube furnaces is proposed. It allows to conduct studies of NOx formation under various combustion and heat exchange modes.

4. Calculation study of co-combustion of gas and fuel oil and measures to improve the heat technological and ecological performances of the tube furnace

Using the developed methods, a calculated study of heat transfer and formation of nitrogen oxides in a cylindrical tube furnace CS1 during the combined combustion of gas and fuel oil was carried out. The results of calculated studies of gas and fuel oil co-combustion modes are shown in figure 2. The results of calculated studies of gas and fuel oil co-combustion modes are shown in figure 2.

At the burning of the factory of gas with carbon number $(C'/H')=3.0$, fuel oil and their mixtures (50/50 % by heat release) the characteristic temperature profile (figure 2a) is generally preserved. Wherein, an increase of the average temperature level and heat supply of the radiant chamber take place at an increase of fuel oil proportion in the combined fuel.

![Figure 2](image_url)

**Figure 2.** Changing the heat exchange characteristics along the height of the radiant chamber of a cylindrical furnace for separate and joint combustion of gaseous and liquid fuels.

Designations: 1 is the gas; 2 is the mixture of 0.5 gas and 0.5 fuel oil; 3 is the fuel oil.

For the considered cylindrical tube furnace, the total length of the flame jet is 0.5 $h/H$, where $h/H$ is the non-dimensional height of the radiant chamber. In this case, intense heat generation occurs at the first section of the flame jet with a pronounced maximum at $h/H=0.25$ and is accompanied by high temperatures—about 1400...1550 K. In the second section of the flame jet, the heat release gradually disappear and the temperature decreases intensively, while still remaining high. At the exit from the second section of the flame jet $h/H=0.5$, the average temperatures in the cross-section of the furnace are reached at 1250...1400 K.

In the upper part of the radiant chamber $h/H > 0.5$, the cooling rate of the combustion products slows down and remains approximately the same. At the exit from the radiation chamber, the average temperature of the combustion products reaches 1050...1150 K.

Figure 2b shows the cooling intensity of the combustion products $\phi=\Delta t/\Delta h$ in % to the value of the parameter at the previous equal interval on the height of the radiant chamber.

A special feature of the fuel oil flame is a more intense heat release, a higher temperature level and a more intense heat transfer compared to a gas torch. High heat transfer from the fuel oil flame is due to the increased combustion temperature, intensive soot formation and, accordingly, the of the high
radiation of luminous flame. The emissivity of fuel oil flame reaches 0.8. The emissivity of gas flame is 0.3...0.4. The combined combustion gas and fuel oil gives intermediate values of parameters.

The characteristic heat supply profile of the heating surface along the height of the radiant chamber (figure 2c) is also preserved. There are significantly large heat fluxes in the lower part of the radiant chamber with a maximum at \( h/H \approx 0.25 \). The heat supply profile from a gas flame is more smoothed compared to a fuel oil flame. The unevenness of the heating supply to the tubes surface on the height of the radiation chamber for a fuel oil torch is \( \varphi_3 = 1.7 \), for a gas torch is \( \varphi_3 = 1.5 \).

The fuel oil flame has a more pronounced maximum of incident radiant heat flux to the heating surface of 150 kW/m\(^2\) in the lower part of the combustion chamber, and the gas is 90 kW/m\(^2\). This is due to the fact that the fuel oil flame has higher temperature and radiation parameters, and the highest values of these parameters are reached in the initial section of the flame \( \approx 0.5L_f \), where most of the fuel \( \approx 80\% \) is burned. At combined combustion of gas and fuel oil, intermediate values of parameters are observed, and significantly closer to the fuel oil flame.

Based on the studied distribution of temperatures and heat fluxes along the height of the radiant chamber (figure 2a,c), a change in the binding of the spiral tube coil is proposed (figure 1). This allows to organize the parallel flow of internal raw materials and combustion products in the combustion chamber by additional use of the downpipe from the convective section down to the radiant section of the coil and changing the direction of movement of raw materials in it.

This leads to the following positive heat technological and ecological effects: 1) reducing the temperature (excluding overheating) of the internal flow and the tubes wall in the lower part of the radiant chamber, which is very important for improving the technological performance of the furnace; 2) increase of heat fluxes to the heated surface from the flame and consequently its cooling in the area of maximum temperatures and reduce the formation of NOx.

A numerical assessment of the formation of nitrogen oxides in the combined combustion of gas and fuel oil in the furnace CS1 was carried out (figure 3).

![Figure 3. Output of nitrogen oxides in the combined combustion of gas and fuel oil.](image)

The kinetic curve in figure 3 has a bend in the region of 50% of fuel oil in the combined fuel, gradually approaching as the proportion of fuel oil decreases to the line of constant output of nitrogen oxide 150 mg/m\(^3\), which is typical for burning only gaseous fuel. This character of the curve is explained by the fact that when the proportion of fuel oil in the combined fuel decreases, two mutually reinforcing factors act on the NOx output: 1) reducing the flame temperature due to reduced heat generation and high heat transfer from the luminous flame; 2) reducing the content of fuel nitrogen in the gas-fuel oil mixture.
Combustion of combined fuel with a fuel oil content of more than 50% leads to a sharp reduction in NOx formation (maximum in 4 times). If the fuel oil content is less than 50%, NOx formation is stabilized at low levels.

Analysis of the curve of nitrogen oxides output depending on the ratio of gas-fuel oil shows that the formation of NOx decreases sharply when the proportion of fuel oil reaches 50% or lower (figure 3). At the same time, the intensity of heat transfer of the flame at 50% of fuel oil remains high, closer to the heat transfer of the fuel oil flame (figure 2c).

Based on the experience of operating industrial furnaces and boilers, it is known that the proportion of fuel oil 20...30 heats % provides increased luminosity of the gas flame [8]. This is especially true when burning low-calorie hydrocarbon gases at modern refineries with many thermal processes of secondary oil refining.

Therefore, the value of the proportion of fuel oil 50...20 heat % in the fuel is the most effective in terms of relatively low formation of nitrogen oxides and maintaining a high level of heat transfer of the flame in tube furnaces.

5. Conclusion
Summing up the results we can draw the following conclusions:

- When burning fuel oil, gas and their mixtures the maximum temperatures are observed in the lower part of the flame jet ≈0.5L_f and the combustion camber h/H ≈ 0.25. When gas and fuel oil are burned together (in the ratio of 50/50 heat %), the absolute maximum temperature is reduced by ≈50°C. Then burning gas that is ≈100°C.

- Maximum heat fluxes are observed when burning fuel oil at the level of q_{max} =150 kW/m², uneven of heating of the radiant tubes on height is $\varphi_3 = 1.7$. A more uniformity of the heating is obtained at joint burning of fuel oil and gas: q_{max} = 130 kW/m², $\varphi_3 = 1.6$ and at burning of only gas: q_{max} = 90 kW/m², $\varphi_3 = 1.5$.

- The proposed change in the binding of the spiral tube coil allows to organize the parallel flow of internal raw materials and combustion products in the radiant chamber of furnace and reduce the overall temperature level in the lower, most heat-stressed part of the combustion chamber, which has positive technological and ecological effects.

- Combustion of combined fuel with a fuel oil content of 50...20 heat % allows to simultaneously reduce the output of nitrogen oxides by more then 4 times and maintain a relatively high heat transfer of the flame compared to the combustion of one fuel oil.

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