Improvement of heat and mass transfer process, a mixture of methane and blast furnace gas

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Abstract. This article deals with the aspects that lead to more intensive mixing and combustion of turbulent jet mixture of methane and blast furnace gas used in combustion and other combustion processes. Keywords — heat and mass transfer, combustion, turbulent jet gas

1. Introduction
As practice shows, flammable gases used in combustion and other processes have a complex composition, including several combustible, passive (in terms of chemical reaction) components and oxygen. There are combustible elements in the composition of the air, albeit in small quantities. In addition, a small preliminary addition of fuel to air and air (oxygen) to the combustible gas can be a good help in controlling heat and mass transfer processes in turbulent flows, which will lead to more intensive mixing and combustion.

2. Materials
It is believed that the fuel in its composition has two combustible components ($A_2$ и $A_3$), gross-combustion reactions, which have the form:

$$
\begin{align*}
A_2 + v_1O_2 & \rightarrow v_4A_4 + v_5A_5 + h_i^*, \\
A_3 + v_1O_2 & \rightarrow v_4A_4 + v_5A_5 + h_i^*;
\end{align*}
$$

Where: $v_1$ и $v_k$ - stoichiometric coefficients of the reactants and reaction products; $h_i^*$ - calorific value of the i-th component.

Two products of combustion $A_4$ и $A_5$ and, as well as chemically passive gas $A_6$. Oxidizing agent has in its composition $O_2$ ($A_1$) and $A_6$ is chemically passive gas. Therefore, the boundary conditions in the input sections have the form $\vec{X} = \vec{X}_{+0}$:

$$
C_i = \begin{cases} <C_i>_{+2} & i = 2,3,4,5 \text{ и } 6, \\
0 & i = 1;
\end{cases}
$$

Where: $C_i$ - mass concentration of the gas component of the gas in the mixture (kg kg-1);

And when $\vec{X} = \vec{X}_{+0}$:

$$
C_i = \begin{cases} 0 & i = 2,3,4,5, \\
< C_i >_{+1} & i = 1 \text{ и } i = 6.
\end{cases}
$$
The equations of transport and conservation of the masses of the components have the form

\[ L(C_i) = \omega_i , \]

Moreover \( \omega_6 = 0 \).

Where: - \( \omega_i \) mass rate of formation / disappearance of the \( i \)th component of the gas.

3. Theory

We determine the concentration of the introduced combustion products and inert gases as a function of the conservative function

\[
\begin{align*}
C_4 &= \langle C_4 \rangle_1 + \tilde{C} \langle C_4 \rangle_2 - \langle C_4 \rangle_1, \\
C_5 &= \langle C_5 \rangle_1 + \tilde{C} \langle C_5 \rangle_2 - \langle C_5 \rangle_1, \\
C_6 &= \langle C_6 \rangle_1 + \tilde{C} \langle C_6 \rangle_2 - \langle C_6 \rangle_1.
\end{align*}
\]

It remains to understand the active gases and products of combustion, where it is possible to use, in particular, the provision that part of the oxygen \( C_{1O} = \langle C_1 \rangle_1 - \sum_{i=2}^{N_o} \) is distributed between the combustible \( C_{1O} = \sum_{i=2}^{N_o+1} C_{1O,i} \).

Then the normalized Schwab-Zel'dovich functions are introduced for each individual fuel component, as well as the corresponding parts of oxygen and formed combustion products, the latter of which are equivalent both to each other and to functions introduced for inert gases. The place of the flame front, determined according to the model of Ya.B. Zeldovich [1,2,3], for each of the combustible components will be

\[
C_{1O}^* = \frac{v_{i,j} m_i C_{1O,j}}{v_{i,j} C_{1O,i} + v_{i,j} m_i (1-k_\pi) \langle C_i \rangle_2}.
\]

But in one zone of displacement there can not be several flame fronts; After the first front of the flame from the side of the fuel, the access of oxygen to other combustible components ceases. Such a judgment leads to dependencies:

\[
C_{2O} = \ldots C_{(N_a+1)O}.
\]

These three systems of linear equations uniquely determine the unknown to us \( C_{1O,i} \).

We believe that the initial oxygen in the oxidizer is distributed between the combustible \( A_2 \) and \( A_3 \)

\[
\langle C_1 \rangle_1 + \langle C_{12} \rangle_1 + \langle C_{13} \rangle_1.
\]

And the concentrations of some components consist of three parts
\[ C_i = C_i^O + C_i^' + C_i^" \]

Where \( C_i^O \) - introduced parts, \( C_i^' \) and \( C_i^" \) - corresponding to the first and second combustible components of the concentration part.

The Schwab-Zel'dovich functions for the first fuel are introduced

\[
\begin{align*}
\tilde{C}_2 &= C_2 + \Omega_{24} C_4, \\
\tilde{C}_1 &= C_1 + \Omega_{24} C_4, \\
\tilde{C}_3 &= C_2 + \Omega_{25} C_5.
\end{align*}
\] (1)

Where: \( \Omega_{ik} = \frac{v_i m_k}{(v_i m_k)} \) is the ratio of the moduli of the chemical reaction rates of the first and second components.

Similarly for the second fuel we have:

\[
\begin{align*}
\tilde{C}_3 &= C_3 + \Omega_{34} C_4, \\
\tilde{C}_1 &= C_1 + \Omega_{34} C_4, \\
\tilde{C}_5 &= C_3 + \Omega_{35} C_5.
\end{align*}
\]

We introduce the Schwab-Zel'dovich normalized functions

\[
C^' = \frac{\tilde{z}_i^' - < \tilde{z}_i^' >_1}{< \tilde{z}_i^' >_2 - < \tilde{z}_i^' >_1} \quad z_i^' = C_2, \quad C_1, \quad C_5^'.
\]

\[
C^" = \frac{\tilde{z}_i^" - < \tilde{z}_i^" >_1}{< \tilde{z}_i^" >_2 - < \tilde{z}_i^" >_1} \quad z_i^" = C_3, \quad C_1^", \quad C_5^".
\]

Excluding intermediate functions, the concentration of components in the fuel zone is determined.

For the first fuel:

\[
\begin{align*}
C_2 &= (C_1 >_1 + \Omega_{24} C_4)_1^\sim C - \Omega_{24} < C_1 >_1, \\
C_4 &= (C_1 >_1 \Omega_{24} \left( 1 - C \right)).
\end{align*}
\]

For the second fuel:

\[
\begin{align*}
C_3 &= (C_1 >_1 + \Omega_{34} C_4)_1^\sim C - \Omega_{24} < C_1 >_1, \\
C_4 &= (C_1 >_1 \Omega_{34} \left( 1 - C \right)).
\end{align*}
\]

Concentrations in the oxidant zone for the first fuel:

\[
\begin{align*}
C_1 &= (C_1 >_1 - (C_2 >_1 + < C_2 >_2 \Omega_{i2}) C; \\
C_4 &= (C_1 >_1 - C_2 >_1 \Omega_{i2} C, \quad C_3 = (C_1 >_1 \Omega_{i2} C; \\
C_5 &= (C_1 >_1 \Omega_{i2} C; \\
\end{align*}
\]

For the second fuel...
The flame front for these combustible materials is defined as

\[ \overset{\approx}{C}^{*} = \frac{1}{1 + \Omega_{21}^{r} < C_{2} >_{2} / < C_{1} >_{1}} \]

\[ \overset{\approx}{C}^{*} = \frac{1}{1 + \Omega_{31}^{r} < C_{3} >_{2} / < C_{1} >_{1}} \]

Since the flame front for combustible components is single, the values of (2) and (3) must coincide:

\[ \overset{\approx}{C}^{*} = \overset{\approx}{C}^{*} \]

4. Results

Hence, the proportions of the combustible components corresponding to the initial oxygen concentration

\[ < C_{1} >_{1} = \frac{\Omega_{13}^{r} < C_{1} >_{1} < C_{2} >_{2}}{\Omega_{12}^{r} < C_{3} >_{2} + \Omega_{13}^{r} < C_{2} >_{2}} \]

\[ < C_{1} >_{1} = \frac{\Omega_{12}^{r} < C_{1} >_{1} < C_{3} >_{2}}{\Omega_{12}^{r} < C_{3} >_{2} + \Omega_{13}^{r} < C_{2} >_{2}} \]

Therefore

\[ \overset{\approx}{C}^{*} = 1/\left[ 1 + < C_{3} >_{2} \Omega_{31}^{r} + < C_{2} >_{2} \Omega_{21}^{r} \right] \]

And the concentrations of the components are determined in the fuel zone as

\[
\begin{align*}
C_{1} &= 0, \\
C_{2} &= \left( < C_{2} >_{2} + \Omega_{24}^{r} < C_{1} >_{1} \right) \overset{\approx}{C} - < C_{1} >_{1} \Omega_{24}^{r}, \\
C_{3} &= \left( < C_{3} >_{2} + < C_{1} >_{1} \Omega_{34}^{r} \right) \overset{\approx}{C} - < C_{1} >_{1} \Omega_{34}^{r}, \\
C_{4} &= \left( < C_{1} >_{1} \Omega_{41}^{r} + < C_{1} >_{1} \Omega_{43}^{r} \right) (1 - \overset{\approx}{C}) + < C_{4} >_{1} + \left( < C_{4} >_{2} - < C_{4} >_{1} \right) \overset{\approx}{C}, \\
C_{5} &= \left( < C_{1} >_{1} \Omega_{54}^{r} + < C_{1} >_{1} \Omega_{53}^{r} \right) (1 - \overset{\approx}{C}) + < C_{5} >_{1} + \left( < C_{5} >_{2} - < C_{5} >_{1} \right) \overset{\approx}{C}.
\end{align*}
\]

And in the oxidant zone -
The mass concentration of chemically passive gas is determined by a single formula throughout the heat and mass transfer region:

\[ C_6 = \langle C_6 \rangle_1 + \left( \langle C_6 \rangle_2 - \langle C_6 \rangle_1 \right)^* \]

In favor of the reliability of the expressions obtained for the concentrations of components, the following fact can be cited: the sum of the mass concentrations of the components in each of the zones (fuel and oxidizer) is equal to unity.

5. Discussion of results

As an example, combustion of a homogeneous mixture of natural and blast furnace gases flowing into an infinite space of resting and confused airflow is considered. For simplicity, it is assumed that natural gas consists only of methane \( CH_4 \); Blast furnace gas has a mass composition: 30\% - carbon dioxide \( CO \), 10\% - carbon dioxide \( CO_2 \), 60\% - nitrogen \( N_2 \); Air has in the composition one oxidizer – oxygen \( O_2 \) (23.2\%) and inert gas - nitrogen (76.8\%).

\( C_{\Pi}, \quad C_{\parallel} \) - the mass fractions of natural and blast-furnace gases in the fuel composition are denoted by and denoted by \( C_{\Pi} + C_{\parallel} = 1 \)

Those. The fuel consists only of natural and blast furnace gases.

Each fuel has its own stoichiometric equation:

\[ CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + h_1^* \quad \text{(4)} \]

\[ CO + 0.5O_2 \rightarrow CO_2 + h_2^*. \quad \text{(5)} \]

In calculations for calorific values, the values are: for methane is equal \( (h_1^*) \) to 11985 kcal / kg, and for carbon dioxide \( (h_2^*) \) - 2450 kcal / kg.

The initial concentration of oxygen \( < C_o >_1 \) is distributed between methane \( \langle C_o >_1 \) \) and carbon dioxide \( \langle C''_o >_1 \) \). Therefore

\[ < C_o >_1 = \langle C'_o >_1 + \langle C''_o >_1 \]

Where, on the basis of the generalization of the model described above,

\[ \langle C'_o >_1 = \frac{\langle C_1 >_1 < C_o >_1}{< C_1 >_2 + < C_2 >_2 / 7}. \]
Multiplying equation (4) by \(< C'_o >_1 / (\nu_{o1} < C_o >_1)\), (5) by \(< C''_o >_1 / (\nu_{o2} < C_o >_1)\) and adding the obtained equations, we arrive at

\[ v_0O_2 + v_1CH_4 + v_2CO \rightarrow v_3CO_2 + v_4H_2O + v_1h_1^v + v_2h_2^v \]

Where

\[
\begin{align*}
\nu_0 &= 1, \\
\nu_1 &= < C'_o >_1 \ell (2 < C_o >_1), \\
\nu_2 &= 2 \ell (1 - < C'_o >_1 / < C_o >_1), \\
\nu_3 &= 2 (1 - 0.75 < C'_o >_1 / < C_o >_1), \\
\nu_4 &= < C''_o >_1 / < C_o >_1
\end{align*}
\]

According to the provisions of the generalized model, instead of the N transport and conservation equations for the i-th component (for reagents), we obtain a single equation \( L(\tilde{C}) = 0 \) with boundary conditions in the input section \( < \tilde{C}>_1 = 0, \ < \tilde{C}>_2 = 1 \).

6. Summary and conclusions

In the case of diffusion combustion, the maximum temperature takes place at the flame front. At moderate flow velocities, the temperature at the flame front remains the same.

Figure 1 shows the values of the temperature at the flame front for different values \( T_1 \) and \( T_2 \) in the form of a function of \( C_o \). At a mass ratio of methane to blast furnace gas of 1:1, the temperature at the flame front is reduced by no more than 50 degrees, compared to the combustion of pure methane, and more than 7 percent of natural gas is saved. If the share of natural gas in the fuel mixture is 20% of the total mass, the temperature of the torch is reduced by 100 degrees and the fuel economy is 20%. Along with this, a social effect is achieved, which is expressed in reducing the amount of harmful emissions to the atmosphere.

![Figure 1. Changes in the fraction of blast furnace gas as a function of the mass fraction of methane in the mixture methane + blast furnace gas](image-url)
References

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