area; $d_v$, inner diameter of outer tube. Subscripts: $e$, evaporator; $c$, condenser; $f$, friction; $a$, acceleration; $l.r.$, local resistance; $k$, heat transfer coefficient; $e$, external diameter of inner tube; $i$, inner tube; $l$, liquid; $v$, vapor.

LITERATURE CITED


A MATHEMATICAL MODEL OF SOOT FORMATION IN NATURAL GAS COMBUSTION.

1. KINETIC EQUATION AND CRITICAL TEMPERATURE OF THE DEHYDROGENIZATION PROCESS

A. G. Blokh and A. I. Shchelolokov

Elements of a mathematical model are presented for the process of soot formation in natural gas combustion, based on thermal decomposition of the CH₄ methane molecule. The expressions obtained can be used for calculation of the size and concentration of soot particles and their thermal radiation in a natural gas flame.

The thermal radiation produced by a natural gas flame depends significantly upon the size and concentration of soot particles within the flame, which substance, together with the gaseous products of complete combustion ($CO_2$, $H_2O$) determine its optical thickness and emissivity [1].

In turn, the soot-formation process depends on the conditions of internal heat-mass exchange between the various zones of the flame, related mainly to the turbulent microstructure. Analysis of well-known expressions for the turbulent mixing time indicates that increase in the scale of turbulent pulsations increases mass exchange within the flame and leads to a reduction in soot-formation time. On the other hand, retardation of the soot-formation process can be achieved by reducing the scale of turbulent pulsations.

It follows from the above that the possibility of controlling the soot-formation process and, thus, the emissivity of a flame rests upon the ability to control the aerodynamic microstructure of the turbulent flame in the segment where that structure is formed, by controlling the processes of fuel and air mixing. It then becomes possible to organize combustion temperature regimes and the dynamics of the soot-formation process.

Fig. 1. Diagram of turbulent diffusion flame.

Under the conditions which we will consider in a natural gas flame (Fig. 1) the processes of oxidation (combustion) and thermal decomposition (pyrolysis) of methane occur simultaneously. These are accompanied by condensation of carbon and formation of corresponding carbon complexes. Three distinctive zones can be distinguished within the flame as regards the character of the processes occurring and the distribution of combustion products.

The first zone (zone A) is the zone of soot particle generation. In this zone thermal pyrolysis (decomposition) of the CH₄ molecule and its radicals dominates, with subsequent formation of free carbon atoms and complexes thereof in the last stage of the process. Formation of free carbon atoms also occurs simultaneously within the volume due to bimolecular chemical reactions between the radicals CH₃, CH₂, and CH. Reverse chemical reactions also occur, leading to reformation of CH₄ molecules. This zone is characterized by an excess of fuel and lack of oxidizer, with temperature of the order of magnitude of 900-1000 K.

In contrast to zone A, the second zone (zone B) is characterized by an excess of oxidizer. The highest temperature, close to adiabatic, is attained in this zone. Under the conditions indicated, CH₄ oxidation (combustion) reactions predominate, determining the thermal regime of the flame. Simultaneously, interaction of carbon atoms and their complexes leads to disruption of the latter with formation of carbon dioxide.

The third zone (zone C) is the burnup zone, in which all chemical reactions are completed and the equilibrium concentrations of complete combustion products established.

Naturally these zones interact with each other, insuring stability of the methane combustion process. Thus, the temperature regime of zone A is determined mainly by turbulent heat-mass transport between the zone and zone B. Because of turbulent pulsations products of incompleted reactions and oxygen are brought into zone A from zone B. Turbulent heat transport into this zone encourages the process of methane dehydrogenization with formation of radicals and atomic carbon.

Considering that marked thermal decay of methane occurs at temperatures above 900 K [2, 3] we will assume the basic zone of soot particle (carbon complex) formation to be zone B.

Thus, the process of atomic hydrogen formation can be considered as a process of CH₄ molecule dehydrogenization and its radical due to removal of hydrogen atoms therefrom. Depending on temperature conditions hydrogenization reactions may also occur, i.e., reactions wherein hydrogen combines with hydrocarbon radicals with final formation of a CH₄ molecule. We will note that as consequence of the high chemical activity of the radicals bimolecular reactions between radicals can also occur at lower values of activation energy. The carbon atoms formed in the flame act as seed nuclei of soot particles, the dimensions of which are determined by the processes of combination of free carbon atoms and destruction of the corresponding hydrocarbon complexes.

In the final outcome the equilibrium concentration of stable carbon complexes and sizes thereof are determined by two oppositely directed processes: formation and enlargement of complexes, on the one hand, and destruction and decrease in size of complexes on the other. In the final reckoning these two processes determine both the size of soot particles (carbon complexes) and their concentration in the gas volume.

Under equilibrium conditions carbon complexes Cₙ, containing various numbers of carbon atoms n, must always exist in the gas volume. The size rₙ of the complex Cₙ is determined by the number n of carbon atoms forming this complex. If we denote the volume of a single carbon atom by V₀, then for a complex Cₙ of n carbon atoms the volume of the complex can be written in the form