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Intensification of Kinetic Combustion Performance in Hydrocarbon Fuels When the Oxidizing Conversion Products are Used

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ABSTRACT

Combustion stabilization problems are discussed. These problems are especially acute when kinetic combustion performance becomes a limiting factor.

Chemical foundations of methane combustion intensification are considered.

The paper describes implementation of operation principles in a gas generator for oxidizing conversion products in hydrocarbon fuels [1].

Performances of gas generator operation process are investigated during oxidizing conversion products exhaust into atmosphere.

A promoting action of incomplete oxidizing products transported out of the flame at the gas generator outlet on flame combustion rate is shown.

A significant extent of steady combustion limits of oxidizing conversion products in a cocurent flow is demonstrated.

A significant extent of steady combustion limits is demonstrated as well for “lean” fuel-air mixture in a low emission burner when the gas generator flame stabilization is used instead of recirculation process.

NOMENCLATURE

a – thermal diffusivity coefficient
D,d – diameter
G – gas flow rate
g – relative gas flow rate
L_0 – stoichiometric coefficient
P – pressure, bar
T – temperature, K
U – velocity
α - air excess ratio, $\alpha = \frac{G_a}{G_f L_o}$
φ - angle for air jets supply into the gas generator
η - combustion efficiency coefficient
τ - time
λ - velocity coefficient

Symbols

a – air
f – fuel
fr – front of chemical reactions
g – gas passage
gg – gas generator
m – mixer
n – normal
mn – mean
p - pilot
rec- recirculation
w – wall

INTRODUCTION

Pollution of environment by adverse exhausts produced during combustion of hydrocarbon fuels led to significant tightening of NO_x and CO in the exhaust gases.

Stationary gas turbines introduce their “input” into contamination of atmosphere. When power stations with gas turbines are located inside the city/town, local authorities in many cases press for reduction of NO_x and CO emissions down to 9-ppm level.

Very strict international and regional requirements to the emissions of adverse exhausts resulted in the necessity to changeover the procedure of diffusion fuel combustion (when combustion takes place in zones with stoichiometric composition of fuel-air mixture with maximal temperatures) to the procedure when “lean” pre-mixed fuel-air mixture is burning**.** Nowadays practically all the world - leading companies are being involved into development of low emission combustors with combustion of lean pre-mixed fuel-air mixture. It makes possible to reduce the temperature in the combustion zone and to decrease the level of NO_x emissions significantly. Calculations show to get NO_x emission in the range $NO_x < 5 \div 9$ - ppm when homogeneous fuel-air mixture is burned, it is necessary to decrease a fuel concentration down to the level that corresponds to air excess coefficient $\alpha \geq 2$. But problems of combustion stabilization and CO emissions increase arise. These two problems are related to a significant decrease of combustion velocity with leaning of a fuel-air mixture. According to [1] with fuel-air mixture leaning (from a stoichiometric composition down to $\alpha = 2$), velocity of a normal flame propagation U_n decreases by $2 \div 3$ times. A stabilizer size or recirculation zone dimension that provides a steady combustion should increase with this in U^2_n i.e. in $4 \div 9$ times.
Reduction of a normal flame propagation rate Un results as well in a significant increase of time for turbulent combustion and, hence, a length for fuel burnout. Thus it was experimentally proved [2],: with leaning of a fuel-air mixture from $\alpha = 1$ down to $\alpha = 1.6$ the fuel burnout length had increased by about a factor of 2. That is why development of low emission combustors is limited by combustion kinetic performance of lean hydrocarbon mixtures. Intensification of hydrocarbon fuels combustion is an important scientific and technological problem.

The present paper shows recent attempt aimed to intensify kinetic performance of combustion for the account of incomplete oxidation products usage in hydrocarbon fuels.

It is known [3] that combustion of hydrocarbons in air is a complicated multistage process that can conventionally be divided

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into two phases: a primary phase and a phase of intensive combustion.

During a primary phase initial hydrocarbons begin to interact with oxygen in air generating active reaction intermediates (peroxides, formaldehydes, carbon monoxide and other radicals). Gas temperature does not increase heavily. This period is accompanied by a weak chemiluminescence [4]. Chemical reactions of oxidizing conversion have autocatalytic nature, i.e. with the concentration increase of oxidizing conversion products the chemical reactions rate of the pre-flame processes increases. The primary phase is over when the concentration of active intermediates achieves the required value. Then the second phase begins – it is a period of intensive combustion that shows an intensive self-heating [3]. The second reaction phase is also a multistage one with intermediate radicals (CH, C_2 and etc.) generated before the final reaction products grow up (CO_2, H_2O).

We can decrease the time for the primary combustion phase increasing both gas temperature and pressure at the combustor inlet and making gas composition approach stoichiometric one.

But with the chosen parameters of a gas generator and a composition of a fuel-air mixture (α) it is impossible to exert an effect on the chemical reactions time.

At the same time it might be possible to reduce the time for chemical reactions proceeding by acceleration of a pre-flame combustion process using promoting additives.

Successful laboratory attempts of promoting were realized in the 30-th of the 20-th century with formaldehyde usage [5,6]. Mechanism of the effect of additives was not revealed.

To realize an intensification process of kinetic combustion performance in hydrocarbon fuels in a gas turbine combustor but not in a laboratory, one has to settle a number of problems, in particular, to develop a gas generator for oxidizing conversion products, to develop a procedure of operation process and to supply these products into a combustor. It would be expedient on the first step to demonstrate a possibility of a small - size gas generator development for oxidizing conversion products to intensify with its help kinetic combustion performance in “lean” fuel-air mixture aimed to increase combustion stability limits.

CHEMICAL KINETIC FOUNDATION OF METHANE COMBUSTION INTENSIFICATION

To accelerate methane combustion a chemical induction phenomenon and a promoting action of incomplete methane oxidizing is used in the present paper. Our approach is based on the acceptance that in gas-phase combustion processes branching – chain mechanism of reaction and avalanche – like multiplication of active intermediates are a determining factor not only in the region with very low pressures but at atmospheric and increased pressures as well [7-9]. It was taken into account that combustion of carbon oxide and hydrogen, that are products of incomplete methane oxidizing, in all criteria is more intensive than combustion of methane itself: concentration limits for ignition, temperature and flame propagation rate [10]. At the same time combustion heat of H_2 and CO is more than by twice less the combustion heat of methane [10]. These principles definitively show that more intensive combustion of H_2 and its mixtures with CO in comparison with CH_4 is a consequence of quicker branching of reaction chains. We have considered as well that in combustion processes both of CH_4 and H_2 and its mixtures with CO free atoms of H, O and radicals participate as active intermediate particles [11, 12].

To explain the accelerating action mechanism of the chosen products, let us first of all examine the reasons of their higher combustion rate in comparison with the rate of methane combustion.

As far as these processes have branching-chain character, the reactions rate of their combustion is determined, first of all, by multiplication intensity of active intermediates - free atoms and radicals that are regenerated and multiplied periodically in their reactions with initial reagents. Self-heating role of a burning mixture becomes only significant in developing chain combustion and enhances the chain avalanche [8, 9].

In a hydrogen flame H atoms and OH radicals originally generated out of initial molecule reagents:

$$H_2 + O_2 = OH + OH \ (0) \text{ and } H_2 + O_2 = H + HO_2 \ (0a)$$

undergo quick regeneration and multiplication reactions:

$$OH + H_2 = H_2O + H \quad (I)$$
$$H + O_2 = OH + O \quad (II)$$
$$O + H_2 = OH + H \quad (III),$$

realizing branching reaction chain. The key role belongs to atomic hydrogen resulting in reaction (II) in the increase of free valences number (atomic oxygen is two-valence).

There is also a recombination of atoms and radicals, for example, as:

$$H + O_2 + M = HO_2 + M,$$

where HO_2 is low active radical that is not practically able to regenerate active particles, and M is any third particle that removes energy excess and stabilizes HO_2 radical.

Recombination is equivalent to chains termination. If the branching is quicker than the termination, multiplication of active particles and reaction rate increase acquire avalanche nature and achieve high values. This is the chain ignition.

During combustion of CO mixtures with H_2 together with reactions (I), (II) and (III) quick reaction takes place as well

$$CO + OH = CO_2 + H \ (Ia)$$

in the course of which atomic hydrogen is formed realizing, as it was already mentioned, branching of chains by the reaction (II).

As compared with initial reactions (0) and (0a) feasible during burning of hydrogen in generation act during methane oxidation:

$$CH_4 + O_2 = CH_3 + HO_2$$

CH_3 radical is generated that is capable in a lesser extent to branch reaction chains than atomic hydrogen. Its reaction with O_2 mainly proceeds in a way that formaldehydes and hydroxyl radicals are formed,

$$CH_3 + O_2 = CH_2O + OH, \ (IV)$$

i.e. without any increase of the free valences number**.**

H atoms formation and their branching take place only as a reaction between formaldehydes with O_2 in the course of which CO is formed. Reacting with OH it results in atomic hydrogen emergence:

$$CH_2O + O_2 = HCO + HO_2 \ (V)$$
$$HCO + O_2 = HO2 + CO \ (VI)$$
$$CO + OH = CO_2 + H \ (VII)$$

But reaction rate constant (IV) is significantly less than the constant of reactions rate (I) – (III), (Ia) [13, 14]. That is why methane burns worse than hydrogen in terms of all the process performance, in spite of higher mole combustion heat [10]. The second stage of methane oxidizing proceeding with participation of CH_2O and CO is more intensive in comparison to the 1-st stage (where formaldehyde only begins its formation) is determined as well by the above mechanism. Atomic hydrogen not only undergoes branching reaction (II), but reacts as well with methane:

$$H + Ch_4 = CH_3 + H_2.$$

Molecular hydrogen favours chains development in reactions (I) and (III).

The given explanation of two methane oxidizing stages when the second stage is much more intensive has been proved by experiments when the addition of only 0.02% (volume) of formaldehyde into the initial mixture of methane and air reduces significantly the induction period [6]. The increase of this addition results in further induction period decrease. It is obvious that such small additives of a promoter cannot exert a perceptible influence on the process thermal effect. That is why the influence of the additive is caused by changes in reaction mechanism (it has a kinetic nature) but not in thermal performance of a system.

Theoretical conclusion about CO accelerating influence on methane combustion was also proved during the experiments. In our experiments that are not described in details in the present paper combustion took place in a closed reactor with simultaneous high-speed recording of pressure and chemiluminescence. It was established that substitution of 2% of CH_4 for the same amount of CO in methane-air mixtures comprising 8-12% of methane, results in intensification of developing combustion self-acceleration rate, maximal temperatures increase and chemiluminescence intensity. As far as a mole (volume unit) CO combustion heat is significantly less than methane combustion heat, in this case an additive action has a kinetic nature.

Whereas, thus, CH_2O, CO and H_2 accelerate methane burning promoting the chain branching, and the mentioned substances are the intermediate products of its burning, it follows that introduction of products with incomplete oxidizing CH_4 into an initial mixture should accelerate combustion. This was one of the main goals for this work. The second part of the stated problem was to intensify combustion with its own products inside the gas generator i.e. realizing a continuous promotion within a “closed-loop cycle”.

OPERATION PRINCIPLES IN GAS GENERATOR

During development of oxidizing conversion products gas generator to settle problems related to combustion stabilization, the authors of the article were guided by the below principles:

1. Gas generator dimensions should be the minimal and comparable with a combustor dimensions.
2. Gas generator should operate on the same fuels as a main combustor does, that is on natural gas and air.
3. In order to settle combustion stabilization fuel flow through the gas generator should be ~ 1% of the fuel through the combustor.
4. It is advisable to realize low-temperature oxidizing conversion, $T_g \sim 500 \div 800$ K, as it is a realistic temperature range at the combustor inlet. As compared with high temperature oxidizing conversion there is no need to settle the cooling problem in such gas generator.

A preliminary analysis of kinetic performance of pre-flame processes in low temperature oxidizing conversion and aerodynamic performance of such gas generator when the limits for overall dimensions fulfilled showed, it is not possible to realize pre-flame processes without acceleration of chemical reaction rates of “cold” and “blue” flame by 1÷ 2 orders of magnitude. It is possible to accelerate pre-flame processes by addition into a fuel-air mixture some quantity of incomplete oxidizing products producing in the flame during a primary combustion phase.

Thus, to preliminary realize a pre-flame process of low temperature oxidizing conversion in real combustors with limitations both in overall dimensions and time, it is necessary to organize closed-loop gas dynamic and thermal chemical pre-flame and flame combustion periods (See Fig.1).

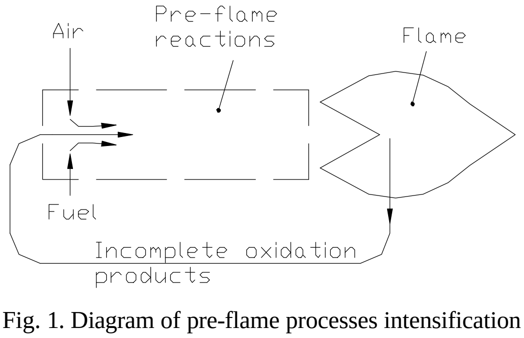

Fig. 1. Diagram of pre-flame processes intensification

In the suggested diagram showing organization of a process inside the gas generator to intensify an oxidizing conversion of a carbon-air mixture inside the gas generator casing, part of oxidizing conversion products out of the flame developing downstream the gas generator shear is extracted and transported into the pre-flame processes zone. Another problem is a preclusion of intensive combustion inside the gas generator casing.

We were able to organize to a considerable extent a process of mass transfer and a localization of the pre-flame process inside the gas generator together with organization of intensive combustion immediately downstream the gas generator shear due to vortex flow described in Fig.2. Air jets in the suggested aerodynamic procedure create a swirling flow with high-pressure gradient and tangential velocity component along the gas generator radius. Close to the axis the rarefaction relative the ambient pressure at the gas generator outlet is produced in a wide range of gas supply modes. The rarefaction region is extended on the whole gas generator length, sucks gas out of the gas passage shear and creates in the near-axis zone in a radius $r < 0.5\ r_g$ a return flow the length of which is from the gas passage shear up to the beginning of the swirling chamber. Toroidal recirculation flow is generated at the gas passage outlet creating favorable gas dynamic conditions for flame stabilization both in a stationary air and in the airflow.

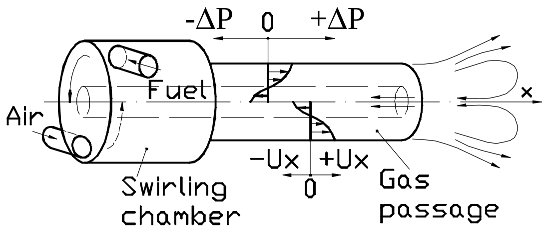

Fig. 2. Vortex flow in the gas generator.

After vortex aerodynamic flow starts up, after gaseous fuel is supplied into the swirling chamber and when favorable composition of fuel-air mixture ($\alpha = 0.7 \div 1.5$) is created, this mixture is ignited with the help of the electric discharge inside the gas generator. Generated combustion products and the products of incomplete oxidation are carried towards the gas generator gas passage shear by the flow into toroidal recirculation zone where combustion process stabilizes and develops. Then part of combustibles out of the flame is sucked into the rarefaction near-axial zone of the gas generator. After the incomplete oxidation products (in the first instance aldehydes, CO and H_2) enter adjoining fuel-air mixture layers, the oxidizing conversion processes of hydrocarbon fuels develop in these layers. The oxidizing conversion is accompanied by chemiluminescence (Fig.3). In addition to that favorable time conditions for pre-flame reactions of oxidizing conversion running are only realized in a comparatively narrow annular zone, $r_{fr} \approx 0.7 r_g$, around the reverse flow zone. With bigger radius, $r > r_{fr}$ the pre-flame processes do not have time enough to progress due to quick velocity increase and residence time decrease. Localization of favorable conditions for pre-flame processes proceeding only in an annular zone does not create any conditions for intensive combustion development inside the gas generator. The swirling flow decreases very quickly at the gas generator outlet, pressure and velocity gradients reduce and intensive mass transfer of toroidal recirculation zone results in a quick propagation and development of pre-flame and flame processes. A flow of the fuel-air mixture additionally saturated with oxidizing conversion products runs out of the gas generator gas passage into the outer toroidal recirculation zone, accelerates combustion giving rise to a stable flame in the whole volume of this zone. A preliminary organization of the pre-flame process should result in the limits increase for a steady combustion at the gas generator outlet. It should be possible as well to organize very small flames that are not possible with a standard combustion procedure in hydrocarbon fuels.

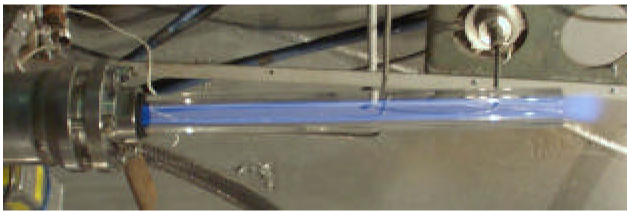

Fig.3. Flame downstream the gas generator shear and a glimmer inside the gas passage.

GAS GENERATOR PERFORMANCE INVESTIGATION DURING PRODUCTS EXHAUST INTO ATMOSPHERE

Several versions of gas generator were developed where the suggested procedure of the operation process was investigated. The difference of the gas generators was in overall dimensions shown in Table 1.

Table 1

Swirling chamber diameter D, mm	15 ÷ 50
Swirling chamber length L, mm	30 ÷ 100
Gas passage diameter d, mm	10 ÷ 28
Gas passage length l, mm	0 ÷ 1000

Gas generators were investigated under given below conditions. Methane - air mixture was used as a fuel (Table 2).

Table 2

Air mass flow G_a, g/s	5 ÷ 50
Air temperature T_a, K	270÷700
Air excess ratio, α	0.6 ÷ 2
Gas pressure in the gas generator P_g, bar	0.5 ÷ 50

Air was heated up to 700 K in the electric pre-heaters. We used a special test cell to realize the tests up to 50 bar pressure.

In addition to the geometrical dimensions we varied the swirling of the airflow supplied into the gas generator. It was done by variation of an angle between the vector for air jets supply into the swirling chamber and this chamber radius. This variation was fulfilled in the range $\varphi = 0 \div 90^0$ in the plane perpendicular to the gas generator axis. Depending upon φ inside the gas generator casing we saw either intensive combustion modes or oxidizing conversion modes with a flame only downstream the gas passage. When the angle of the air swirling inside the gas generator was small, $\varphi < 30^0$, only intensive combustion modes were observed with the flame torching at the gas generator outlet. Both gas generator and gas passage walls become hot very fast. Gas temperature and pressure inside the gas generator increase significantly. With large angles of the air swirling in the gas generator, $\varphi > 60^0$, with the mixer diameter D > 30 mm we saw both the intensive combustion and the oxidizing conversion combustion. When small air mass flows with low rates is supplied into the gas generator (there is no rarefaction and reverse flow at the near-axis zone), the intensive combustion might take place inside the gas generator. With air mass flow increase, and with the increase of the air jets rates supplied into the gas generator (after that when the near-axial reverse flows zone is formed), only the pre-flame oxidizing conversion processes proceed inside the gas generator. Wall temperature and gas pressure do not practically change. Gas glimmer indicates low-temperature oxidizing conversion (Fig. 3). With gas generator diameter decrease D < 30 mm the intensive combustion was not found.

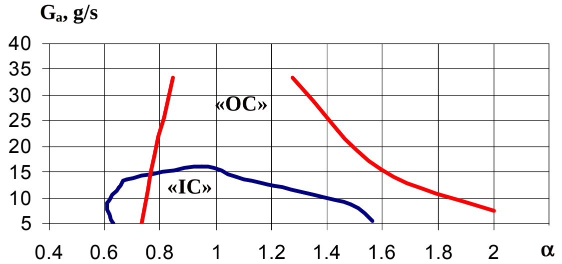

Fig. 4 Steady operation region of a gas generator on modes “IC” and “OC”.

Investigations of ignition and steady combustion limits in the gas generator with D = 50 mm, d_g = 28 mm, l = 600 mm were fulfilled with combustion products exhaust into atmosphere. Air and methane temperature was T = 270 ÷ 300K. The air was supplied at two angles: $\varphi_1 = 0^0$ and $\varphi_2 = 60^0$. The test results are presented in Fig.4. In the variant when $\varphi_1 = 0^0$ and air excess ratio is in the range α = 0.7 ÷ 1.5 with air mass flow $G_a \le 15$ g/s the intensive combustion was observed inside the gas generator with torching of incomplete combustion products in the flame. With air mass flow increase $G_a > 15$ g/s there was a flame out both inside the gas generator and at its outlet.

When the gas generator was investigated with the air swirling $\varphi_2 = 60^0$ and with air mass flow $G_a < 5$ g/s the intensive combustion occurs inside the gas generator with products torching in the flame downstream the gas generator shear. With air mass flow increase, $G_a > 5$ g/s, combustion inside the gas generator stops and changes over into the oxidizing conversion process. The burning flame at the outlet remains but it becomes shorter and thicker. The maximal gas temperature in the oxidizing conversion mode achieves 1800K. During this mode steady combustion runs in the range α = 0.8 ÷ 1.5 with air mass flow increase up to $G_a \ge 35$ g/s.

Comparison of steady combustion limits of a flame at the gas generator outlet during the intensive combustion mode “IC” and the oxidizing conversion mode “OC” (Fig.4) shows a significant increase (more than twice) of steady flame combustion limits in air and fuel mass flows when changing over for oxidizing conversion.

Changing over from the “IC” mode inside the gas generator to the “OC” mode is accompanied with changes of wall temperature both in the gas generator and its gas passage (Fig. 5). In case there is a combustion inside the gas generator in the 30-th second in the mode α = 1 the walls temperature at the beginning of the gas passage achieves 1100K. It decreases towards the end of the gas passage down to about $T_w \approx 600$K. Gas generator operation on this mode results in overheating and gas passage damage. After the gas generator changes over into the oxidizing conversion mode, the walls temperature reduces very abruptly, and achieves on the 45-th second its steady temperature value. During this mode the walls temperature at the beginning of the gas passage is about 270K ($T_w \approx 270$K) and it slightly increases to the end of the gas passage up to $T_w \approx 500$K. A significant temperature decrease of the gas generator walls after changing-over for the oxidizing conversion mode is the outcome of the intensive combustion stoppage inside the gas generator. But it does not exclude that proceeding of the pre-flame processes of the low-temperature oxidizing conversion occurs without any intensive heat release. A slight increase of walls temperature to the gas passage end is explained by the high temperature products suction out of the lame into the near-axial reverse flows zone and limited heat transfer during the “OC” mode.

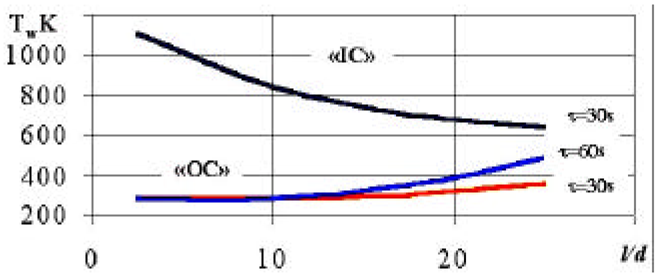

Fig. 5. Temperature of gas passage wall during intensive combustion (mode “IC”) and oxidizing conversion (mode “OC”) inside the gas generator.

Equality of gas temperature at the gas generator outlet and the gas generator walls along its major length shows adiabatic thermal process in this part of the gas generator.

It is known [3] that in the first phase of hydrocarbon fuel oxidation together with the final oxidation products high concentrations of incomplete oxidation products are formed: aldehydes, peroxides, CO and H_2. We have investigated as well difference of gas composition in non-intensive and intensive combustion zone. That is why radiation spectra (emissions spectra) were investigated. To fulfill spectra investigations a transparent quartz gas passage (d = 20 mm at l = 600 mm) was introduced in the gas generator with D = 50 mm. It was possible to observe and record on the spectrograph the radiation inside the gas passage (Fig. 3).

Visual observations and the photos of a glimmering zone inside the gas generator showed that a hollow glimmering cylinder with diameter $d_{fr} \approx 0.7\ d_g$ extends for the whole gas passage length and the gas generator length and becomes a flame glimmer zone at the gas generator outlet. In the near-axis zone of the gas passage the glimmer is not observed, but it can be observed from the gas passage shear side. The thickness of the glimmer zone, according to visualization, is about 1 mm.

The spectra investigations were fulfilled with the help of spectrograph “Spectra Pro-308” from Action Research Company.

In a focal plane of the outlet mirror of this spectrograph a cooled (down to -50^0C) CCD camera NTE/CCD-400EB (1340 x 400 pixels) was installed. A diffraction lattice installed in the spectrograph 300 strokes/mm with a “blaze” 500 nm makes it possible to register a spectrum in a visible range about 270 nm width with 11 nm/mm dispersion and with a width of an inlet slot 10 μm and provides with 0.5 nm resolution.

Gas radiation spectra inside the gas passage and the flame at the gas generator outlet are shown in Fig. 6 and 7. Investigations showed a significant difference in spectra in the wavelength range 380 ÷ 650nm both in nature and the signal value. The spectrum of a flame downstream the gas generator shear and in the gas turbine combustor (Fig.7) is typical for hydrocarbon flames. Coincidence of waves length of main bands in the spectra 1 and 2 (Fig. 7) indicates that both downstream the gas passage shear and in the combustor the main intermediate active particles are radicals comprising CH and C_2 groups. The wave length 431.2 nm corresponds to CH radicals and wave lengths 473.7; 512.9; 516.5nm and others indicated in this figure correspond to C_2 radicals. The difference in the lines width is explained by difference in gas pressure inside the combustor and the gas generator outlet that causes different impact of lines broadening.

The strongest radiation signals are from excited radicals C_2 and CH that directly precede the combustion products.

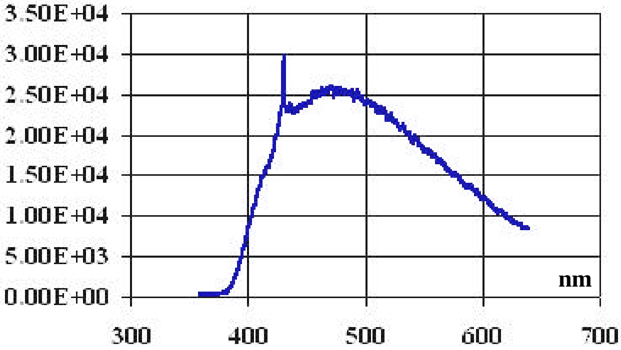

Fig.6. Emission spectrum measured in the gas passage.

There are no pronounced C_2 lines in the spectrum measured in the gas passage zone (Fig. 6) but there is a weak CH signal. The signals from the flame radiation are about by two orders of magnitude stronger than the signals from the radiation in the gas passage. Comparison of the spectra shows there are no intensive combustion processes inside the gas generator. The radiation spectrum of gas out of the gas passage is close to the spectra of the pre-flame processes described in [4].

Together with the spectra investigations we had analyzed as well stable components that had been extracted out of the gas generator gas passage close to its shear at a distance 0.8 – 0.9 radius (r_g). Special miniature probes were used. Formaldehydes and CO were found in the samples.

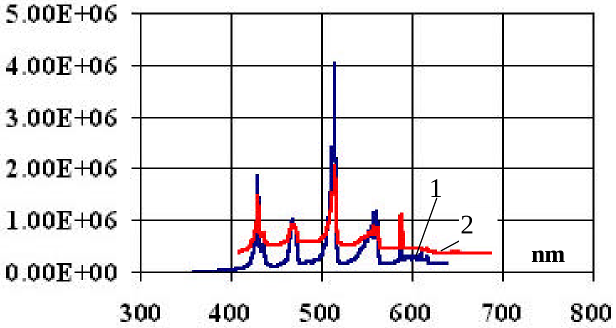

Fig.7. Flame spectra at the gas generator outlet and in the gas turbine combustor.

FLAME COMBUSTION STABILITY IN THE COCURENT AIRFLOW

To find out what is the influence of the pre-flame process inside the gas generator on chemical reaction rates in the flame downstream the gas generator shear, we had fulfilled investigations of steady flame combustion limits in the cocurent airflow. According to Michelson’s criterion the boundary conditions of combustion stabilization in recirculation zone formed by airflow over a stabilizer are determined by a relationship of the time for combustion of chemical reactions to a residence time in recirculation zone:

$$\tau_{ch}/\tau_{\mathbf{res}} \le 1 \qquad (1)$$

The first expression is usually written as following:

$$\frac{U_a a}{D_{stab} U_n^2} \le 1\ , \qquad (2)$$

where $D_{stab.}$ is a stabilizer diameter. In our case $D_{stab.} \sim d_g$, U_{fl} is a normal rate of flame propagation that depends on components concentration and temperature. That is why we can rewrite the expression (2) as:

$$\frac{U_a}{d_g\,\overline{T}_a^{\,g}\,\overline{P}_a^{\,\text{â}}}\left(\frac{a}{U_n^2}\right)_{\text{î}} = f(\text{á}), \qquad (3)$$

where a is a thermal diffusivity coefficient, $\overline{T}_a = \frac{T_a,}{300}$ - is a relative air temperature, γ - is a severity of $\overline{\text{Ò}}_{\text{à}}$ exposure on $\left(\frac{\text{à}}{U_n^2}\right)_{\text{î}}$ variation.

$\overline{\text{Ð}}_{\text{à}} = \frac{\text{Ð}_{\text{à}}}{1}$ - is a relative air pressure in the recirculation zone, β is a severity of $\overline{\text{Ð}}_{\text{à}}$ exposure to $\left(\frac{\text{à}}{U_n^2}\right)_{\text{î}}$.

$\left(\frac{\text{à}}{U_n^2}\right)_{\text{î}}$ - is a parameters complex that determines the time for chemical reactions with initial conditions $T_a = 300$ K, $P_a = 1$ bar, $\alpha = 1$.

Via parameters complex obtained on a flame out limit out of the expression (3) it is possible to determine $\left(\frac{U_n^2}{\text{à}}\right)$

$$\left(\frac{U_n^2}{\text{à}}\right)_{\text{î}} = \hat{\text{E}}_{stab} = \frac{U_a}{d_g\,\overline{\text{Ò}}_{\text{à}}^{\,g}\,\overline{\text{Ð}}_{\text{à}}^{\,\text{â}}} = f(\text{á}) \qquad (4)$$

Out of the expression (4) according to K_{stab} obtained on the basis of experimental data, it is possible to estimate a normal flame propagation rate and estimate as well changes in kinetic combustion performance.

Investigations of flame out limits in the gas generator in the cocurent airflow was fulfilled in the experimental rig schematic diagram of which is shown in Fig.8. The rig comprised D 160 mm air stilling chamber with a D100 mm convergent nozzle at its end. The vortex gas generator was 50 mm in diameter and was installed on the stilling chamber wall, but its d_g 20 mm gas passage had 300 mm length that had been bended in a such a way that the gas passage shear was directed to the axis of the air nozzle and it finished in the shear plane of the aerodynamic nozzle. During the tests we varied with the air velocity coming out the shear of the aerodynamic nozzle in the range 10 ÷ 310 m/s at air temperature 270 ÷ 300 K. The air jet ran out into the open space with 1 bar pressure (P_a = 1 bar).

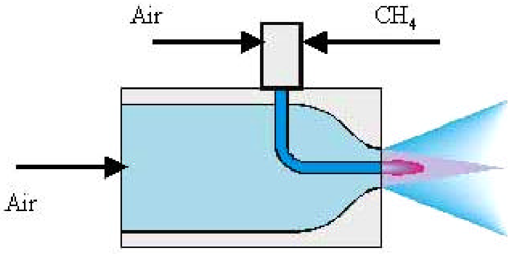

Fig.8. Schematic diagram of a facility to investigate flame out in a cocurent airflow.

The gas generator was used in two cases:

- to produce oxidizing conversion products and their burning in the flame downstream the gas passage shear of the gas generator in the cocurent airflow.
- to supply natural gas through the gas generator; natural gas was mixed with air in recirculation zone forming a torch.

In both cases gas composition was constant (α ≈ 1) in the gas generator and the recirculation zone. After mixture was ignited downstream the gas passage shear, the air velocity, flowing over the gas passage, was increased up to flame out. After that we had repeated the tests.

Investigations showed that combustion flame out of methane-air mixture in recirculation zone (the gas generator did not operate) occurred with the airflow velocity increase at the shear of the aerodynamic nozzle up to U_a ~ 30 ÷ 35 m/s. It was not possible to have a flame out of the oxidizing combustion products at the air velocity increase up to U_a ~ 310 m/s ($\lambda_a \approx 1$) when the vortex gas generator was in operation.

Investigation results analysis on kinetic combustion performance fulfilled with a modified Michelson's criterion (4) is presented in Fig. 9. K_{stab} for methane-air mixture flame out (• - Fig.9) had practically coincided with the data achieved before [15].

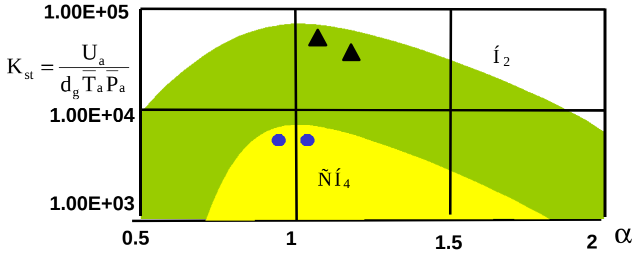

Fig.9. Change of K_{st} with combustion intensification.

When the products of the oxidizing conversion are burning in the flame, K_{stab} value for the maximal air velocities exceeds about 7 times K_{stab} values for methane-air mixture **(**Δ - Fig. 9). This figure represents comparative data on combustion limits of hydrogen-air mixture [16]**.** Data comparison shows good agreement with data on oxidizing conversion products combustion.

Thus, usage of preliminary oxidizing conversion in hydrocarbon fuels might intensify the kinetic performance making them more realistic in terms of their kinetic performance in hydrogen-air mixture.

STABILIZATION OF FUEL - AIR MIXTURE COMBUSTION WITH GAS GENERATOR PILOT FLAME

Combustion stabilization of a fuel-air mixture in a low emission combustor is usually realized with the help of recirculation zones formed by intensive gas flow swirling or by steps in the combustor channel with unexpected expansion. In order to provide a steady combustion of "lean" mixture and to extend "lean" flame out limits, pilot fuel is supplied to recirculation zones. A fraction of fuel supplied into recirculation zones in the best low emission combustors achieves during the main modes 5 ÷ 10% of main fuel flow rate through the combustor. NO_x emission significantly increases. Pilot flame usage with oxidizing conversion products with fuel flow rates ~ 1 ÷ 3% of the main fuel consumption may significantly improve stabilization performance of combustion with reduced NO_x values.

With the aim to verify an efficiency of the flame combustion stabilization procedure (using a flame with oxidizing conversion products), an experimental burner had been developed (Fig. 10). The burner comprises: a test cell fuel-air mixer, a vane swirler, a vortex gas generator for oxidizing conversion products and a diffuser. Homogeneous fuel-air mixture (CH_4 + Air) was produced in a test cell mixer. A vain swirler with the 45^0 angle of the vain rotation created an attached flow at the diffuser walls and the recirculation zone downstream the gas passage shear. A vortex gas generator was used in two cases:

1) to supply additional pilot fuel into recirculation zone;
2) to supply the oxidizing conversion products to the gas passage shear to organize combustion of these products in the flame.

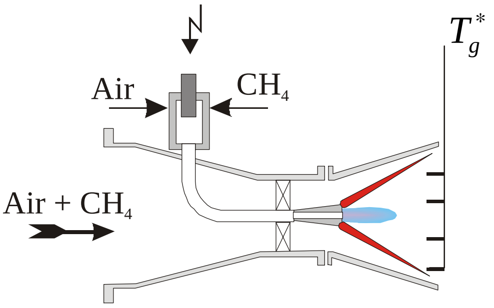

Fig.10 Low emission burner with flame or recirculation stabilization.

A 6-point water - cooled thermocouple rake was installed in the burner diffuser shear at 200 mm distance from the gas generator gas passage shear.

Such installation provided with the following operation modes: G_a = 0.3 kg/s, air velocity at the vain swirler inlet was 60 m/s at 270K of air. Investigations of “lean” flame out limits were fulfilled at three conditions of combustion stabilization:

a) with the help of recirculation zone without any additional fuel supply**;**
b) with the help of recirculation zone with the additional fuel supply to this zone through the gas passage;
c) with the help of the oxidizing conversion products flame burning downstream the gas passage shear of the gas generator.

The flame out of the combustion was recorded with the thermocouples introduced into the rake that had been installed at the diffuser shear. We would like to point to the fact that to the end of the diffuser, where the thermocouples rake was installed, combustion of the main fuel-air mixture was not over. That is why thermocouples readings corresponded not to the maximal temperature values for the given mixture composition. But these temperature measurements registered very precisely flame out or significant additional reduction in fuel combustion efficiency. The results of “lean” flame out limits are depicted in Fig. 11 in coordinates $T_{mn} = f(\alpha)$, where T_{mn} is a mean temperature of the thermocouples rake. During the experiment when the combustion of methane-air mixture was stabilized with the help of recirculation zone without additional fuel supply in it, the flame out occurred with fuel-air mixture leaning, $\alpha \approx 1.5$ (Fig.11).

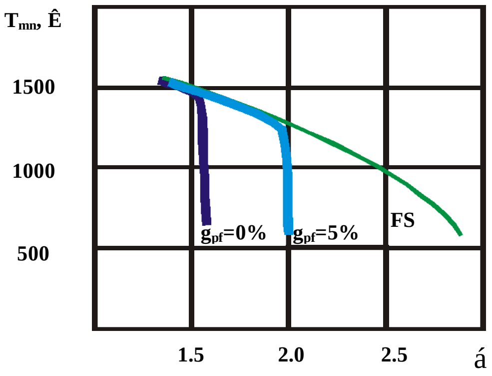

Fig.11. Flame out limits for methane air mixture at different stabilization conditions.

With additional fuel supply g_{pf} = 5% of the main fuel, the flame out occurred with mixture leaning down to $\alpha \approx 2$. When combustion was stabilized with the help of the flame with oxidizing conversion products (g_{gg} = 3%, FS), there was no flame out even with $\alpha > 2.5$ ($\alpha \rightarrow \infty$). But with $\alpha > 2.5$ the mean temperature of the combustion products began to decrease more intensively. This temperature decrease, T_{mn}, is caused by combustion efficiency decrease in the area that is placed at the maximal distance from the burner axis and the gas generator axis. More intensive gas temperature decrease close to the burner walls indicates it.

Thus, it is shown when the flame with oxidizing conversion products was used as a combustion stabilizer, “ lean” flame out limit extends significantly even with smaller fraction of additional fuel supplied into the recirculation zone. In addition to that when the gas generator flame is used as a stabilizer, a flame out nature changes: it is not an instantaneous combustion stoppage, but a gradual flame failure of main fuel-air mixture during its leaning. It is also a positive factor resulting in pressure oscillations diminish inside the combustor during the modes that precede a complete flame out.

The flame with oxidizing conversion products remains a constant ignition source that stabilizers combustion independently of main fuel-air mixture composition.

Let us draw the attention, that emission performance of the burner with operating and non-operating gas generator ($g_{gg} = 1 \div 3\%$) do not practically change. It shows that the gas generator input on emission performance is insignificant.

The fact that intensification of pilot flame is determined to the first instance by kinetic factors, means independently, that the influence of this main fuel-air mixture burning flame in low emission burner is determined to a considerable degree by reactions of intermediate particles. It is natural that more intensive burning of a pilot flame increases the temperature of the surrounding fuel mixture. But it is well known that the temperature increase accelerates chain reaction very severely according to the double exponent law [17]. As far as self-heating and chain avalanche in positive reverse linkage [17], it is not possible to separate kinetic and thermal factors.

CONCLUSIONS

1. An effective mean for combustion intensification of hydrocarbon mixtures has been developed with usage of incomplete oxidizing products extracted out of the flame into the zone of preliminary organization of low-temperature oxidizing conversion**.**
2. The small - size vortex gas generator for oxidizing conversion products has been developed. It made possible to accelerate by about an order of magnitude the rates of chemical reactions in the flame.
3. The significant extension of “lean” flame out limits has been demonstrated in a fuel-air mixture with the usage of the developed method.

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