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Experimental Investigations of a Low-Emission Combustor Designed for Mid Power Gas Turbines

The paper describes the main mechanisms of NO_x formation (thermal, prompt NO_x and through N_2O). It is shown that, for combustion products when the gas temperature is less than 1650 K (T_{gas}<1650 K), the residence time has a weak influence on NO_x formation.

A concept for the simultaneous reduction of NO_x and CO in low-emission combustors with large residence time is suggested. Some methods to organize an operation process with low NO_x and CO formation are suggested as well. The low-emission combustor configuration is presented.

The paper describes both the experimental results of investigated model combustors and investigations of a low-emission combustor designed for mid power gas turbines, developed with the suggested operating process mechanism.

Introduction

Changing over to a mechanism of lean premixed burning of fuel-air mixtures resulted in a strong reduction of NOx and CO emissions in the combustors designed for industrial gas turbines, which operate on natural gas. Nowadays, the best low-emission gas turbine combustors, such as Siemens and General Electric, show no more than 10 μmol/mol in the main operating modes. Calculation investigations by some authors [1] reveal that, by means of enhancing the air-fuel mixing quality and mixture leaning, it is possible to achieve NO_x and CO emissions of about 1 μmol/mol.

However, in order to obtain such low amounts of adverse emissions with real low-emission combustors, it is necessary to solve a number of related complex scientific and technical problems, in particular, by intensifying the fuel and air mixing inside the burners. It is also necessary to increase the lean blow-off limits without any pilot support of the recirculation zone to stabilize combustion, and to carry out a purely convective cooling of the flame tube without any air supply to the lean mixture burning zone.

The main goal of the given work is the experimental verification of the performance of the low-emission combustor developed by the Central Institute of Aviation Motors (CIAM). The combustor, which operates on natural gas, had been developed for industrial gas turbines with $\pi_{compr.}$=20-23 [2]. The CIAM combustor is distinguished from other well-known combustors by its individual gas-dynamic flow and structural design. In order to stabilize the flame in the CIAM low-emission combustor, a conical stabilizer installed in the central tube at the burner outlet is used. To organize the recirculation zone for flame stabilization, intensive air swirling is not used, unlike with many well-known combustors. In addition to this, the flame tube walls in its first part are made as a conical diffuser. The combination of a conical flame stabilizer and a conical diffuser for the flame tube results in a significant increase in the recirculation zone dimensions, the residence time in the zone, and all of these significantly increase the lean blow-off limits, even without any pilot supply. The gas-dynamic pattern developed and the structural lay-out of the low-emission combustor make it possible to significantly reduce the combustible temperature during the steady burning of a lean mixture, as well as to reduce the emissions. In order to intensify the lean mixture burning and to reduce CO emissions, flame turbulators located on a conical surface of the flame stabilizer are used. In addition to this, it is important to mention that the configuration of the flame tube end for the low-emission combustor has dimension limitations specified with the casing design for the gas turbine.

Analysis of kinetic mechanisms for NOx and CO formation

The reduction of adverse emissions during combustion is achieved by means of mixture homogenization and its leaning. However, the reduction of the flame temperature results in an increase in CO and unburnt hydrocarbon emissions. Investigations [3] have shown that, when methane is burning, the combustion efficiency reduction and the CO concentration increase in the mixture occur very abruptly if the temperature achieves the critical level, ~1500 K. It is possible to finalize the oxidation of CO to CO_2 by increasing the residence time within the admissible ranges for NO_x emission.

Let us analyze the kinetic aspects of NO_x formation with temperature variation. Several mechanisms are used in the models for nitrogen oxidizing with NO, NO_2 and N_2O formation:

1. A thermal mechanism according to the Zeldovich mechanism [4], which includes N_2 oxidizing and the interaction of N atoms with OH radicals (enlarged mechanism):

$$N_2 + O = NO + N$$
$$N + O_2 = NO + O$$
$$N + OH = NO + H$$

2. N_2O – the mechanism specified with the reaction group, where N_2O acts as an intermediate substance during NO formation:

$$N_2O + CO = NCO + NO$$
$$N_2O + H = NO + NH$$
$$N_2O + O = NO + NO$$

3. NO_2 – the mechanism resulting in NO formation by the way of the continuity of reactions below:

$$NO_2 + CO = NCO + NO$$
$$NO_2 + OH = HO_2 + NO$$
$$NO_2 + H = OH + NO$$
$$NO_2 + O = O_2 + NO$$
$$NO_2 + M = O + NO + M$$

4. A Fenimore mechanism (prompt NO mechanism) [5]. Prompt nitrogen oxides are formed at the stage when the fuel is burning in the flame front. The beginning of their formation involves N_2 interaction with CH and CH_2 radicals, which appear at fuel molecular decomposition:

$$N_2 + CH = HCN + N$$
$$N_2 + CH_2 = HCN + NH$$

The estimation of the input of Mechanisms 1, 3 and 4 into NO_x formation is described in [6]. It is shown that the temperature and the mixture composition define which N_2 oxidizing mechanism is the leading one. The time influences the type of leading N_2 oxidizing mechanism in stoichiometric mixtures. Mixture leaning reduces the role of the thermal and prompt NO mechanisms.

The analysis of Mechanisms 1– 4 shows that nitrogen oxidizing takes place with a large number of components in the reacting mixture. Taking this into account, nitrogen oxide formation at various temperatures has been calculated on the basis of the detailed kinetic scheme by Bowman-Miller [7], within the framework of a direct kinetic problem: $\rho dc_i/dt$ - W_i=0, dH/dt - q_r=0 [6]. Here, c_i and W_i are concentrations and velocities for the formation of the mixture i-component; ρ and H are the density and enthalpy of the reacting mixture; q_r is the heat flux divergence; and t is time.

The scheme [7] comprises 235 convertible phases, with 52 participating components. It is widely approved in calculations for the burning of lean methane - air mixtures.

Using the model above in Reference [8], nitrogen oxide formation has been investigated in two stages for methane burning. The obtained results [8] show that, when combustion occurs within the interval of 3 to 10 ms, the temperature reduction in the second stage below 1700 K resulted in a significant reduction of NO_x formation, despite the reacting mixture composition. It proves that temperature variation has a determinant effect on NO_x emission. The obtained result is a universal one, because all of the mechanisms for NO_x formation (1-4) mentioned above were taken into account in calculations [8].

Let us evaluate a kinetically attributed reserve residence time increase in the combustor to reduce the decrease in the CO concentration during the temperature drop. This reserve is an additional time required to achieve the ultimately admissible (prescribed) NO level with the temperature decrease.

The combustible temperature in the calculations was varied by means of the change in the initial composition of lean methane-air mixtures.

The NO emission level is related to the burnt gas residence time in the combustor. The relationship between the formation of given amounts of NO (5 and 10 μmol/mol have been selected as the upper emission limits) and the temperature of burnt gas has been estimated using the global set of mechanisms presented above (Mechanisms 1 to 4) or using the Zeldovich mechanism alone. These calculations were performed for a mixture containing 15% of O_2 (i.e., burnt gas) and are presented in Figure 1.

As can be seen, the temperature reduction by 100 K over the entire examined range of temperature variations results in a time increase by practically an order of magnitude for NO formation. This effect occurs both for the whole process and for the thermal nitrogen oxidizing mechanism as well. Thus, nitrogen oxide formation at relatively low temperatures is not a factor for residence time, and it can be chosen from the calculated duration required for the CO oxidation into CO_2.

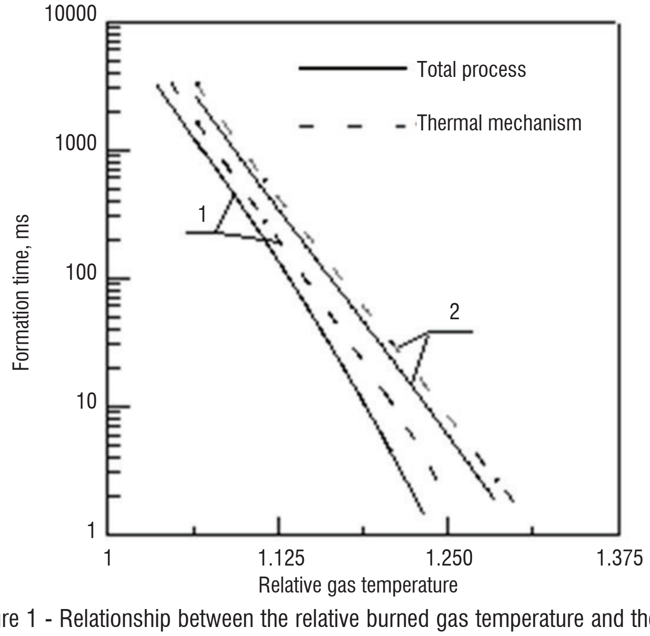

Figure 1 - Relationship between the relative burned gas temperature and the residence time of a given amount of NO. (at 15% of O_2): 1 – NO=5μmol/mol, 2 – NO = 10 μmol/mol. The combustion mode: P_c=0,1 MPa, T_a=720 K

The analysis performed is representative of a homogeneous mixture burning within the whole combustor volume.

Gas-dynamic methods to increase lean blow-off limits

In order to reduce NO_x emissions, first of all, the flame temperature must be reduced. To manage this, the lean blow-off flame limits must be increased in the low-emission combustor. The lean blow-off flame limits are described by Mikhelson's criterion for the combustion process in the recirculation zone:

$$K_m = \frac{W}{l_{REC}} \frac{a}{U_n^2} \geq 1$$

where W is the gas velocity in the combustor; l_{REC} is the length of the recirculation zone; U_n is the laminar flame velocity; and a is the themal diffusivity coefficient. Taking this criterion into account, the lean blow-off flame limits can be extended by means of either gas-dynamic or kinetic methods.

In low-emission combustors, this problem is usually solved by means of kinetic methods, at the expense of mixture enrichment with fuel or additional pilot fuel supplied to the recirculation zone, resulting in an increase in U_n. Such a method to extend the lean blow-off limits results in a significant NOx increase, due to the temperature increase in the recirculation zone.

In order to extend the flame lean blow-off limits with gas-dynamic methods, it is necessary to increase the dimensions of the recirculation zone and to decrease the gas flow in the combustor. The gas velocity in the combustor (W) can be reduced by increasing the combustor cross-section. The possibilities to enlarge the dimensions of the combustor central recirculation zone grow with the initial conical extension of the channel cross-section area [9].

Both calculations and experimental investigations showed (Fig. 2) that, in the combustor with a conical diffuser, the length of the recirculation zone is proportional to the combustor diameter D_C, and at $L_C/D_C > 2.5$ can achieve $l_{REC} \sim 1.6\ D_C$. Compared with a combustor having an abrupt extension, it will be possible to increase the length of the recirculation zone by more than 2 times. Experimental investigations performed in the combustor with the conical diffuser at $T_a = 740\ K$, $P_a = 1$ MPa proved the possibility of extending the flame blow-off limits up to the air-fuel equivalence ratio $\alpha = 3.1$ ($T_g = 1420\ K$) without any additional fuel supply into recirculation zone. Extending the flame blow-off limits will make it possible to move the low-emission operation range to the area with lower flame temperatures.

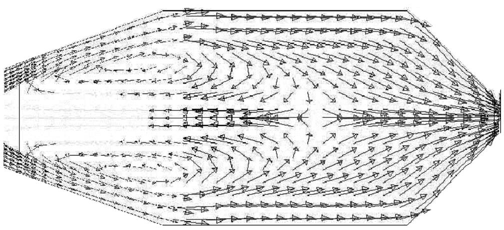

Figure 2 - Gas flow pattern in the low-emission combustor

Burner performance with low concentration field non-uniformity

Another very important condition for NO_x reduction in low-emission combustors is the maximal possible (admissible) reduction of the fuel concentration field non-uniformity at the combustor inlet. In one of the best Siemens burners, HR-3, the root-mean-square non-uniformity of the fuel concentration field at the burner outlet is 8% [1]. It is possible to improve the mixing quality at the expense of increasing the mixer length. However, other problems arise, such as flashback. Due to gas flow swirling, the flashback is especially strong near the central hub.

In this work, this problem is solved with a burner designed without any mixture swirling. Figure 3 shows a schematic diagram to measure concentration non-uniformity in the fuel-air mixture of the designed burner. Figure 4 shows the measurement results for the fuel concentrations in the fuel-air mixture. Investigations of the fuel concentration field in an annular slot at the burner outlet were performed with a 2-point gas-sampling probe and gas analyzer post-processing. The first sampling point was at 1/3 of the channel height, located between the stabilizer and the diffuser. The second one was at 2/3 of the channel height. Two measurements were performed. During each measurement, the sampling points in turn were switched into the gas analyzer. The sampling probe rotation speed was 1 degree per second. Figure 4 shows the measurement data. The measurements showed that the root-mean-square non-uniformity of the fuel concentration field at the outlet of the CIAM burner is ≈6 %.

This result, together with the leaning of the mean fuel-air mixture composition, is a basis for significant NO_x emissions reduction.

Influence of residence time on NO_x emission

The flame temperature, pressure in the combustion chamber and residence time influence the level of NO_x emissions when homogeneous mixtures are burned.

In real combustors, besides the mentioned parameters, fuel concentration oscillations and the quantity of pilot fuel supplied into the recirculation zone affect the NO_x level.

Investigations relating to model combustors with various calculated residence times ($\tau_{res.} \sim 25$ ms and $\tau_{res.} \sim 85$ ms) have been performed at the inlet temperature $T_a = 740$ K and combustor pressure $P_a \sim 0.5$-0.7 MPa.

In the low-emission combustors under consideration, the concentration field non-uniformity has been minimized; the diffusion pilot fuel has not been supplied into recirculation zones. Under such conditions (low non-uniformity and absence of pilot fuel), the residence time effect on NO_x should be similar to the effect of this parameter during ideal homogeneous fuel-air mixture burning.

Investigation results relating to the residence time effect on the NO_x formation are presented in Figure 5.

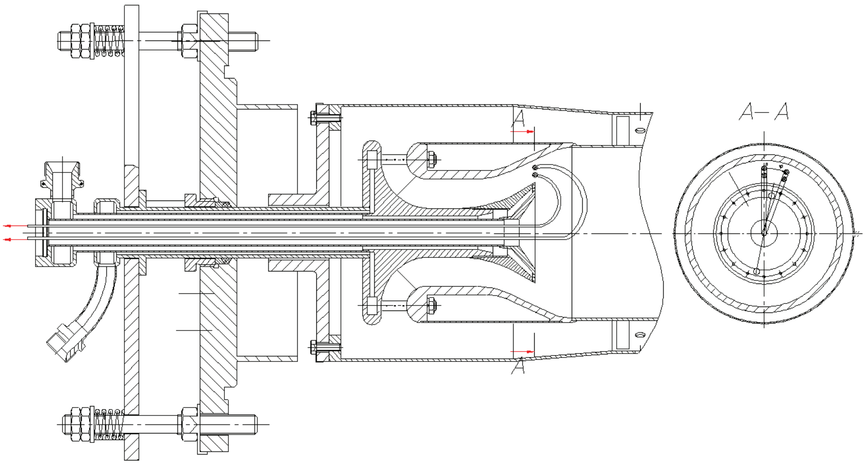

Figure 3 - Schematic diagram to measure fuel concentration non-uniformity in the fuel-air mixture

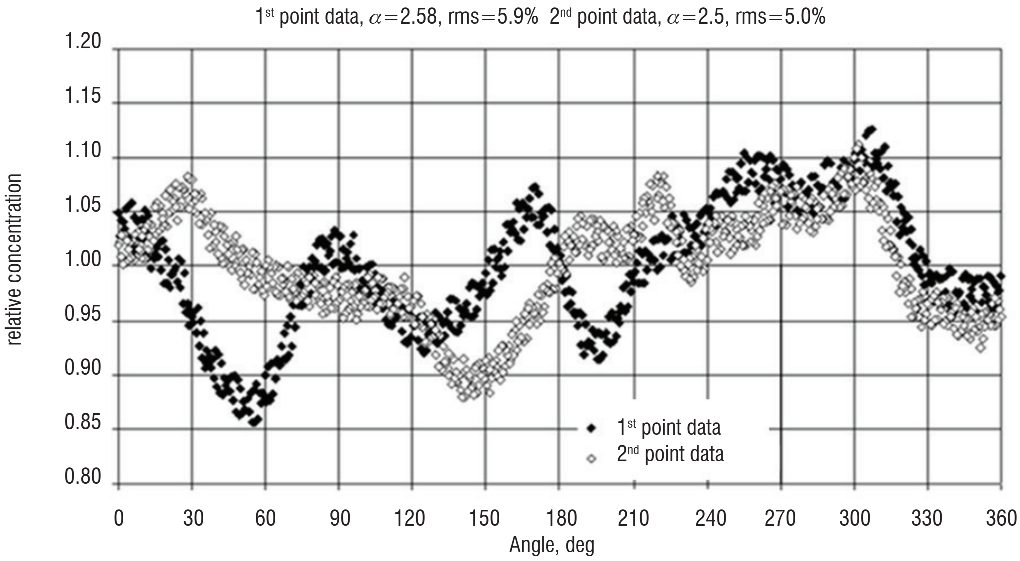

Figure 4 - Measurement results of fuel concentration non-uniformity at the burner outlet

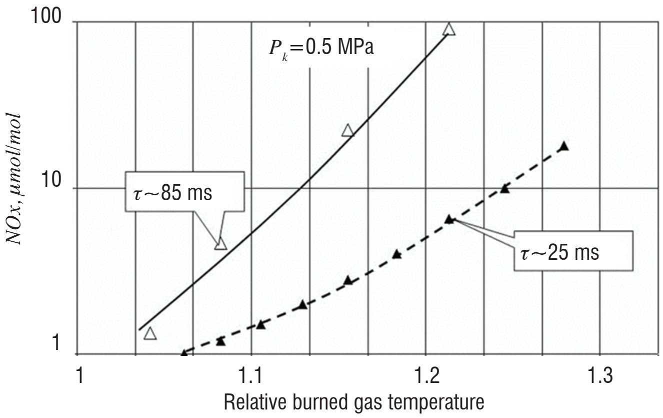

Figure 5 - Effect of the residence time on NO_x emissions

Investigations showed that, in the relatively high gas temperature area, the residence time effect is strong, and that a $\tau_{res.}$ increase results in a significant NO_x rise. By reducing the temperature of the combustion products and leaning the fuel-air mixture, the effect of the residence time decreases very quickly (i.e. the residence time for very lean mixtures practically does not have any effect on NO_x formation). When the relative gas temperature corresponds to $T_g < 1.1$ this effect is negligibly small and at $T_g < 1.07$ NO_x emissions is practically one and the same at $\tau_{res.} \sim 25$ ms and $\tau_{res.} \sim 85$ ms. The reduction of the residence time effect on NO_x emissions during the flame temperature decrease is a consequence of the thermal mechanism input on NO_x formation.

The results of experimental investigations prove the possibility of reducing NO_x formation during the combustion product temperature decrease in the combustors with high residence time.

Influence of residence time on CO emissions

Decreasing the combustion product temperature influences the increase in the CO emissions. An increase in the residence time may reduce CO emissions and extend the low-emission operating range of the combustor. Another parameter that affects CO emissions is the temperature of the flame tube walls, which causes additional gas cooling in the boundary layer at the combustor walls.

Investigations with different residence times ($\tau_{res.}$ ~ 25 ms and $\tau_{res.}$ ~ 85 ms) have been performed at the inlet temperature T_a = 740 K and combustor pressure P_a ~ 0.5-0.7 MPa. The results of experimental investigations relating to the residence time effect on CO formation in the low-emission combustor are presented in Figure 6.

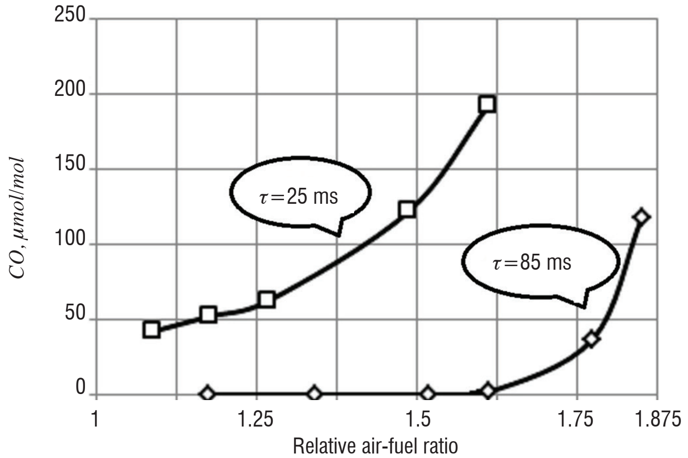

Figure 6 - Effect of the residence time on CO emissions

Investigations showed that by increasing the residence time $\tau_{res.}$ ~ 25 ms up to $\tau_{res.}$ ~ 85 ms, the low-emission operating range in terms of CO is extended significantly. A quick increase in CO emission is noticed for $\tau_{res.}$ ~ 25 ms at the relative air-fuel ratio ≈ 1.38. Changing-over to $\tau_{res.}$ ≈ 85 ms made us possible to shift the quick rise of CO emission to the relative air-fuel ratio ≈ 1.75. The CO level in the low-emission operating range (at the relative air-fuel ratio ≈ 1.65) decreased to ~1 μmol/mol.

Thus, the experiments demonstrated the possibility of simultaneously decreasing CO and NO_x emissions by means of increasing the residence time.

Low-emission combustor performance for mid power industrial gas turbines

The configuration of the low-emission combustor developed with limited dimensions in the gas turbine casing differs from the model combustors presented in the first part of the paper. The differences are less combustor sectional areas, higher flow velocities and shorter residence time.

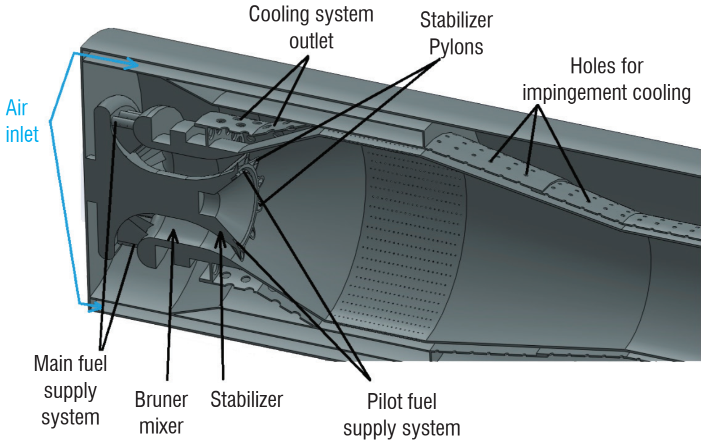

Figure 7 - Low-emission combustor

In addition to that, two new components have been added to the combustor configuration:

- acoustic holes to damp combustion instabilities;
- pylons located on the stabilizer to intensify combustion.

Low-emission combustor tests for the mid-power gas turbine have been performed in the axisymmetric single burner segment (Fig.7). NO_x and CO emission levels have been investigated in the range of 50 to 100 % load for industrial gas turbine operation.

Table 1 describes the main combustor operation modes and emission results.

N	P_a kPa	G_a kg/s	T_a K	PRF %	α	NO_x μmol/mol	CO μmol/mol
1	2013	3.15	7476	10.41	2.79	23	4
2	2005	3.14	746	10.2	2.60	39	4
3	2004	3.14	747	10.1	3.01	12	12
4	2302	4.00	781	10.0	3.00	12	3
5	2285	4.00	782	9.7	2.80	19	3
6	2283	4.01	783	12.3	2.62	53	4

Table 1 - Main results of combustor tests on low-emission operation modes, P_a, G_a, T_a are the pressure, air mass flow and temperature at the segment inlet, respectively. PFR is the pilot-fuel ratio; α is the air-fuel equivalence ratio.

Figure 8 shows the temperatures of the flame tube wall for the modes under study. The emission performances in the mode P_a=2 MPa, T_a=746 K, α=2.79, PFR=10 % corresponded to NO_x = 23 μmol/mol, CO = 4 μmol/mol. The mode P_a=2.3 MPa, T_a=781 K, α=3.0, PFR=10 % emission performances achieved NO_x= 12 μmol/mol, CO=3 μmol/mol.

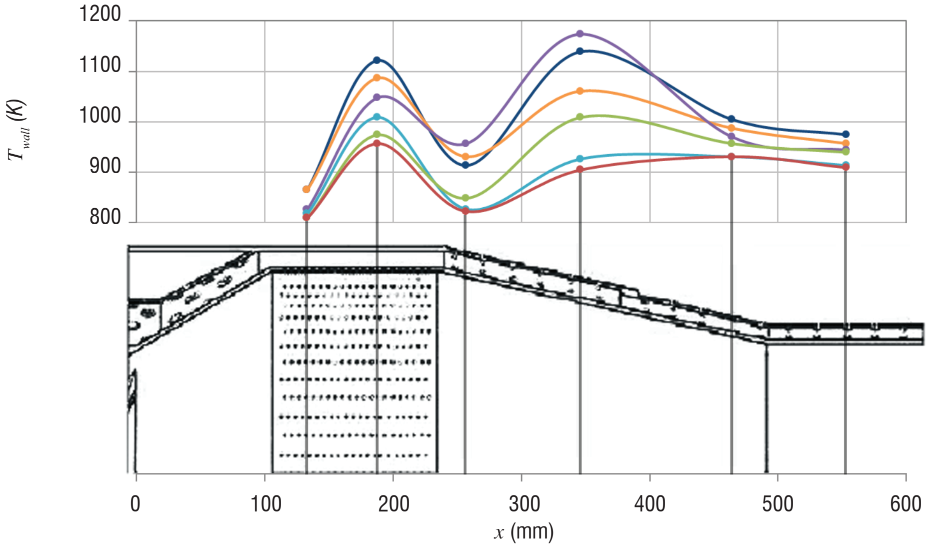

Figure 8 - Wall temperatures of the flame tube for various low-emission combustor operation modes

Conclusions

Based on the analysis of kinetic mechanisms for NO_x and CO formation, a concept to organize the operation process in the low-emission combustor has been made. The main feature of the concept is the combination of a rather long residence time and very lean mixtures at the burner outlet. This made it possible to achieve 5 μmol/mol of emission in the model combustors.

On the basis of investigated model combustors, CIAM specialists have developed and tested in the facilities a low-emission combustor designed for industrial gas turbines with natural gas as fuel. The described combustor differs from the majority of the well-known combustors, since it does not have any air swirling. It has a conical flame stabilizer at the burner outlet and a conical diffuser at the flame tube inlet. A lobe system has been incorporated at the flame stabilizer outlet in order to stimulate the burning of lean mixtures and to reduce CO. The tests on the combustor have been performed under conditions corresponding to those of a gas turbine with $\pi_{compr.}=20$ and 23. During the tests at $P_a=2$ MPa, $T_a=746$ K, $\alpha=2.79$, PFR=10 %, the emission levels are: $NO_x=23$ μmol/mol, $CO=4$ μmol/mol. During the tests at $P_a=2.3$ MPa, $T_a=781$ K, $\alpha=3.0$, PFR=10 %, the emission levels are: $NO_x=12$ μmol/mol, $CO=3$ μmol/mol ■

Acknowledgements

The emission performances achieved with the CIAM low-emission combustor meet the International Standards. Work supported by the Russian Ministry of Education and Science; the unique project ID is RFMEFI62815X0003

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Nomenclature

a – temperature conductivity coefficient
D - diameter
G – gas flow rate
L, l - length
$L0$ – stoichiometric coefficient
P - pressure
PFR – pilot-fuel ratio
rms – root-mean square
T - temperature
T_g - relative burned gas temperature
U – flame velocity propagation
UH – unburnt hydrocarbons
W – gas velocity
τ - residence time, $\tau = L_c/U$
α – air-fuel ratio, $\alpha = G_a/G_f*L0$
$\pi_{compr.}$ – pressure ratio in the compressor, $\pi_{compr.} = P_{compr.}/P_0$

Indices

a - air
c - combustor
com – combustion products
f - fuel
fl - flame
m - main
n - normal
$res.$ - residence time
$rec.$ - recirculation
w - wall

Georgy Vedeshkin joined the Central Institute of Aviation Motors in 1968 after receiving a degree in Aerospace Engineering at Samara Aerospace University.
Head of the CIAM Gas Turbine Division, program leader, he is a skilled specialist in investigations of operating processes in jet engines, gas turbines, testing and development of combustors.
Georgy Vedeshkin has been involved in, combustor testing and development, gas turbine testing. Dr. Vedeshkin has been the leader of several international contracts with GE, ALSTOM Power, Siemens, and AIRBUS. He is the author of more than 20 inventions and patents and more than 110 publications in Russian and foreign collected books

Evgeniy Sverdlov graduated from the All Union Engineering Institute. He joined the Central Institute of Aviation Motors in 1971. In 2010, he defended his thesis for a doctor's degree on Low-Emission Combustors designed for Industrial Gas Turbines. Head of Department in the Gas Turbine Division, program leader, he is a skilled specialist in, investigations of combustor operating processes, testing and development of burners and combustors.
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