EXPERIMENTAL STUDY RESULTS OF THE FRONT-END DEVICE WITH TWO-TIER AIR BURNER AS PART OF THE GAS TURBINE ENGINE COMBUSTION CHAMBER

by

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In recent years, the gas turbine power plant has been increasingly used in various industries in Kazakhstan. The reasons for this are: thermal efficiency, simplicity of the thermal scheme and design, small mass per power unit, high maneuverability, low toxicity, and relatively simple automation of operation. This paper presents the experimental study results of a two-tier air burner as the part of the gas turbine engine combustion chamber at burning liquid fuel. A new design of a microflame device was developed. Two-tier burner makes possible the combustion process in a number of discrete zones, i.e. microflame combustion. During the experiment, the installation angles of the blades of the external and internal registers, as well as the ratio of the coefficients of excess air in the tiers, were changed. The experimental studies of a two-tier burner confirmed the possibility to increase fuel combustion efficiency, a low degree of temperature field unevenness and to decrease NO_x emission.

Key words: *gas turbine engine combustion chamber, two-tier burner, combustion efficiency, temperature field unevenness, total pressure loss, NO_x emission*

Introduction

Increasing air pollution forced scientists around the world to pay attention again to combustion processes, namely to the working processes in the gas turbine combustion chamber. Currently, new bold schemes for the design of front devices of gas turbine engine combustion chambers are being considered: combustion chambers with modular nozzles [1, 2], combustion chambers with microflame devices [3-5], combustion chambers with counter-swirling jets [6, 7]. One of the promising schemes of design solutions that differ from traditional gas turbine combustion chambers is short combustion chambers [8-10]. Among them, a special place is occupied by two-tier combustion chambers [11-13].

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Promising design methods for reducing pollutants should meet the most stringent requirements in terms of emissions, *i.e.* it is necessary to create a new type of chamber that can reduce emissions of all harmful components at the same time (CO, NO_x). The most suitable is the concept of a variable geometry camera [13-17].

The degree of non-uniformity of the fuel-air mixture composition is significantly influenced for NO_x formation, as it is noted in the papers [18, 19].

Further improvement of the gas turbine engine combustion chambers required the development of a multi-fuel burner that would ensure efficient fuel combustion and reduce pollutant emissions (CO, HC, NO_x) over the entire operating range of engine modes. For this purpose, a new design of a microflame device was developed. Two-tier burner makes possible the combustion process in a number of discrete zones, *i.e.* microflame combustion. In this case, a radial arrangement of zones is taken place. The zone combustion concept focuses on the optimizing the fuel distribution. The goal of zone combustion is to regulate combustion in order to achieve low toxic emissions under all operating conditions. In a two-tier burner, preliminary mixing of fuel with air and a zone supply of a combustible lean mixture to the combustion zone are used, *i.e.* the bulk of the air is supplied through the front-line device. In the conducted experimental studies, the excess air ratio of the internal combustion layer varied in the range $\alpha_{n,\text{int}}$ = 0.61-1.84, and the excess air ratio of the external layer varied $\alpha_{n,\text{ext}}$ from 1.34-2.64. Aviation kerosene TC-1 and diesel fuel were used as fuel. The analysis of testing results of a two-tier pneumatic nozzle (burner) as the part of a standard combustion chamber of the gas turbine is carried out.

Detailed description of the experimental test bench of the gas turbine engine combustion chamber, methods of measuring the main characteristics and estimating the experiment error are presented in [20-22].

Experimental results and discussions

Fuel combustion efficiency coefficients

The dependence of the coefficients of fuel combustion efficiency $\eta_g = (\alpha_\Sigma)$ at different operating modes of the injector is shown in fig. 1. In this case, Curves 1 and 2 correspond to different operating modes of the injector. Curve 1 was obtained with a two-tier injector operating when fuel is supplied to both tiers (Mode A). Curve 2 was obtained when fuel is supplied only to the internal tier of the injector (Mode B). The same operating modes were investigated when fuel was supplied only to the external tier (Mode C). However, the high combustion efficiency was achieved only in individual cases. In general, this mode of operation was characterized by unsatisfactory performance.

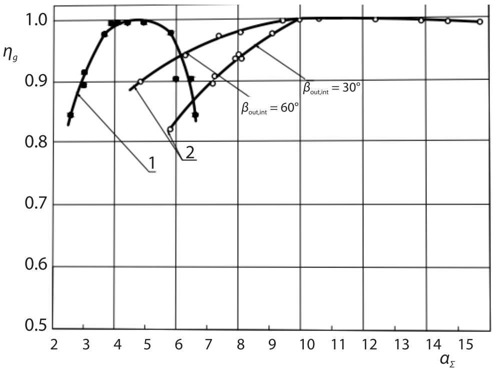

Figure 1. Dependence of combustion efficiency on the total air excess; • – *Mode A (Curve 1), fuel is supplied to both tiers and* **o** – *Mode B (Curve 2), fuel is supplied only to the internal tier*

Experimental studies have shown that $\eta_g \geq 0.98$ is achieved in a wide range of α_Σ = 3-22. It should be noted that the nature of the dependence $\eta_g = (\alpha_\Sigma)$ for operating Modes A and B is significantly different.

Two-tier *air* nozzle has a positive design feature. When it operates in Mode B the swirling jet of the fuel-air mixture of the inner tier entering the combustion zone is picked up, *shielded* by an air-flow with a lower swirl parameter entering through the outer tier. The formation of a specific flow structure in the primary zone of the combustion chamber prevents large droplets of fuel from entering the cold receiving areas of the combustion chamber and provides a high combustion efficiency $\eta_g \geq 0.98$ significantly lean air-fuel mixture in a wide range of $\alpha_{n,\text{int}} = 0.61$-$1.84$.

Earlier, according to the study of a single-tier air nozzle, the optimal geometric parameters of the nozzle were determined, providing high basic characteristics of the combustion chamber, therefore, the main attention was paid to the study of the operation of the nozzle in mode A. The dependence of fuel combustion efficiency on the total coefficient of excess air when the combustion chamber operates in mode A is shown in fig. 1.

For convenience of analysis, we represent the combustion efficiency at the outlet of the combustion chamber as the sum of the combustion efficiency of the total fuel consumption attributable to the internal and external tiers of the nozzle, *i.e.*:

$$\eta_g = g_n \eta_{g,\text{int}} + g_n \eta_{g,\text{ext}} \tag{1}$$

where $g_i = G_f/G_{f,\Sigma}$ is the relative fuel consumption through the corresponding tier of the nozzle and $\eta_{g,\text{ext}}$ – the fuel combustion efficiency for the corresponding tier.

The investigated two-tier nozzle was designed in a way that the air-fuel mixture flow rate through the external layer of the nozzle is 70% of the total air-fuel mixture flow rate. So the influence on the total combustion efficiency of changes $\eta_{g,\text{ext}}$ of fuel share entering through the external tier are twice more significant as the changes in $\eta_{g,\text{int}}$ entering through the internal tier.

As will be shown in the analysis of subsequent experimental dependences, it is the quality of the air-fuel mixture formed by the external tier mainly determines the general nature of the dependence $\eta_g = f(\alpha_\Sigma)$.

In this nozzle design, fuel is dispensed into the external tier through peripheral or axial annular fuel nozzles. At the same time, due to technological and structural difficulties, the axial annular nozzle was made not in the form of a conventional annular manifold with uniform fuel distribution, but in the form of a manifold with sequential fuel distribution along its length. It is known, in that design, the flow rate of the medium through the holes along the length of the nozzle decreases, *i.e.* there is an uneven distribution of fuel over the cross-section of the external tier. This drawback is especially pronounced when the nozzle is operating in variable modes. So, with an increase of α, due to a decrease of fuel consumption $G_{f,\text{ext}}$ of the external tier, there is an uneven reducing in the range of the fuel jets along the cross-section of the channel of the external tier. At the same time, the processes of periodic ignition of the fuel-air mixture coming through the external tier were visually observed, and, as a result, in general, vibration combustion in chamber is taken place. The further increase in the passage area of the last holes of the fuel manifold made it possible to expand the range of operation with high combustion efficiency to $\alpha_\Sigma \approx 7$, as well as significantly reduce both the radial and circumferential unevenness of the temperature field.

Experimental studies have shown that fuel combustion efficiency, η_g, in a combustion chamber with a two-tier nozzle is determined not only by the angles of blades installation of the outlet swirlers of the internal and external tiers, but also by the composition of the fuel-air mixture formed by the nozzle, that is, by the values of $\alpha_{n,i}$ of the corresponding tiers of the nozzle.

In a two-tier nozzle, depending on the operating modes, the conditions for changing the composition of the air-fuel mixture can be implemented:

$$\alpha_{n,\text{int}} = \text{const},\ \alpha_{n,\text{ext}} = \text{var},\ \alpha_\Sigma (f_r'^*) = \text{var} \tag{2}$$

$$\alpha_{n,\text{int}} = \text{var},\ \alpha_{n,\text{ext}} = \text{const},\ \alpha_\Sigma(f_r'^*) = \text{var} \tag{3}$$

$$\alpha_{n,\text{int}} = \text{var},\ \alpha_{n,\text{ext}} = \text{var},\ \alpha_\Sigma(f_r'^*) = \text{const} \tag{4}$$

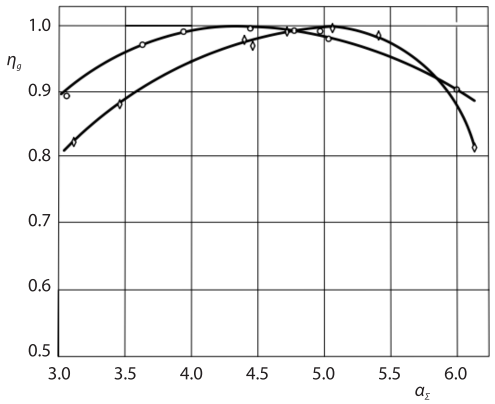

Figure 2. Dependence of fuel combustion efficiency on the total air excess ratio, Mode A; o – *$\beta_{out,int}$ = 60°, $\beta_{out,ext}$ = 25°, $G_{f,int,\Sigma}$ = 2.15 kg/s and ◊ – $\beta_{out,int}$ = 30°, $\beta_{out,ext}$ = 25°, $G_{f,in,\Sigma}$ = 2.1 kg/s*

At the same time, the study of the combustion chamber operation according to Law 1, eq. (2) and Law 2, eq. (3) is of interest from the point of view of choosing the optimal law and compositions of the air-fuel mixture on variable systems, and according to Law 3, eq. (4) the chamber of combustion operates both on variable and design modes.

The experimental dependence of the fuel combustion efficiency when changing the composition according to Law 1 is shown in fig. 2. It should be noted that there is a certain relationship between the signs $\alpha_{n,\text{int}}$ and $\alpha_{n,\text{ext}}$. So, high values of fuel combustion efficiency η_g at $\alpha_{n,\text{int}} = 0.82$ are achieved with a significant depletion of the fuel-air mixture of the outer tier, and an increase in $\alpha_{n,\text{int}}$ to 1.6 requires a corresponding decrease in $\alpha_{n,\text{ext}}$.

Figure 3 shows the dependence of fuel combustion efficiency η_g changing the composition of the mixture according to Law 2. It is shown, with a significant depletion of the outer tier, $\alpha_{n,\text{ext}} = 2.5$, high fuel combustion efficiency ($\eta \geq 0.98$) can be achieved only with a *rich* composition of the mixture of the inner layer, $\alpha_{n,\text{ext}} \approx 0.8$. At the same time, the changing range of α is very low: α = 0.75-0.86.

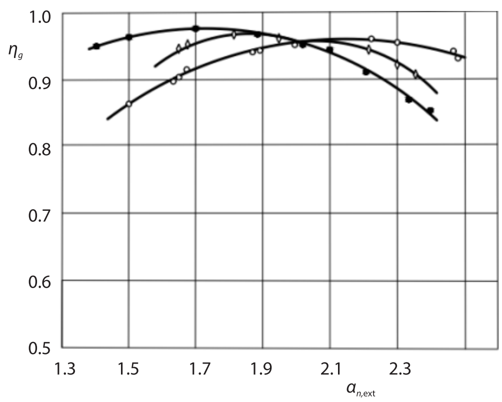

Figure 3. Dependence of combustion efficiency coefficient on $\alpha_{n,\text{ext}}$ at $\alpha_{n,\text{int}}$ = constanta, $\beta_{\text{out,int}}$ = 60°

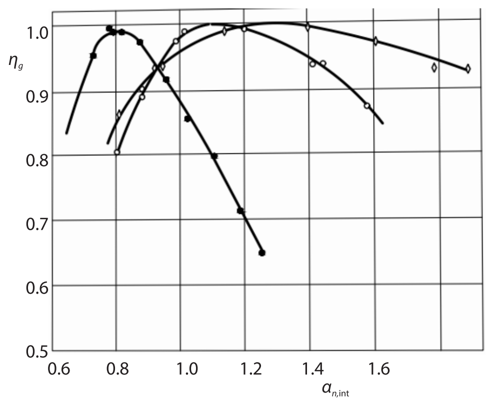

Figure 4. Dependence of combustion efficiency coefficient on $\alpha_{\text{n.int}}$ at $\alpha_{\text{n.ext}}$ = constanta; ● *during operation of two tiers, fuel is supplied to both tiers,* ○ *during operation fuel is supplied only to internal tier*, ○ *$\beta_{out,int}$ = 60°, $\beta_{out,ext}$ = 25°, $G_{f,int,\Sigma}$ = 2.15 kg/s and* ◊ *$\beta_{out,int}$ = 30°, $\beta_{out,ext}$ = 25°, $G_{f,int,\Sigma}$ = 2.1 kg/s*

As in the case of regulation according to Law 1, the range of optimal change expands significantly from 1.06-1.55 with a decrease in $\boldsymbol{\alpha}_{n,\mathbf{ext}}$ to 1.6.

The results of an experimental study of the combustion chamber operation when regulating the mixture composition according to Law 3 are shown in fig. 5.

The interval of variation of the air excess coefficients was $\alpha_{n,\text{int}} = 0.61\text{-}1.84$, $\alpha_{n,\text{ext}} = 1.34\text{-}2.64$. It is seen, when operating at $\alpha_{\sum,\text{calc}} \approx 4$, high fuel combustion efficiency ($\eta_g \geq 0.98$) is achieved in a wide range of changes in the composition of the air-fuel mixture by tiers $\alpha_{\text{n.int}}/\alpha_{n,\text{ext}} = 0.4\text{-}1.1$.

The operation in variable modes reduces this interval to 0.7-1.07 in the case of enrichment and to 0.4-0.9 in the case of combining the total composition of the mixture.

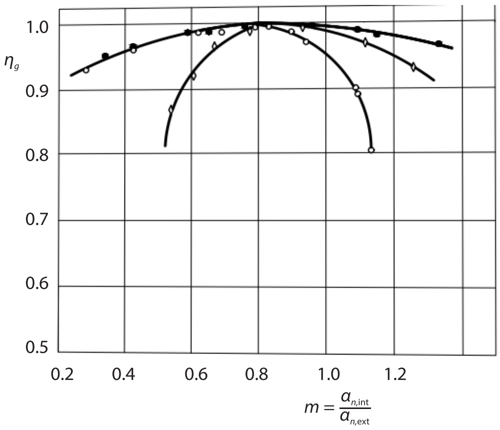

Figure 5. Dependence of combustion efficiency coefficient on *m* at $\alpha_\sum$ = constant, $\beta_{\text{out.int}}$ = 30°, 45°, 60° – outlet swirler of internal tier, $\beta_{\text{out,ext}}$ = 25°, 30°, 15° – outlet swirler of external tier; ● *during operation of two tiers, fuel is supplied to both tiers,* ○ *during operation fuel is supplied only to internal tier,* ○ $\beta_{out,int} = 60°$, $\beta_{out,ext} = 25°$, $G_{f,int,\Sigma} = 2.15$ *kg/s and* ◊ $\beta_{out,int} = 30°$, $\beta_{out,ext} = 25°$, $G_{f,int,\Sigma} = 2.1$ *kg/s*

Control characteristics of a two-tier "air" nozzle

The generalized control characteristics (by composition) of a two-tier *air* nozzle for $\eta_g \geq 0.98$ are shown in fig. 6.

It can be seen that for a nozzle there is both a region of fuel-air mixture compositions where control is possible only according to the law $\alpha_{n,\text{int}}$ = constant and $\alpha_{n,\text{ext}}$ = constant, and a region (central) where control is possible according to both of these laws. It should be noted that most of the optimal compositions lie in the *lean* region, and for them the range of possible changes is much wider than for compositions with a *rich* mixture of the internal tier.

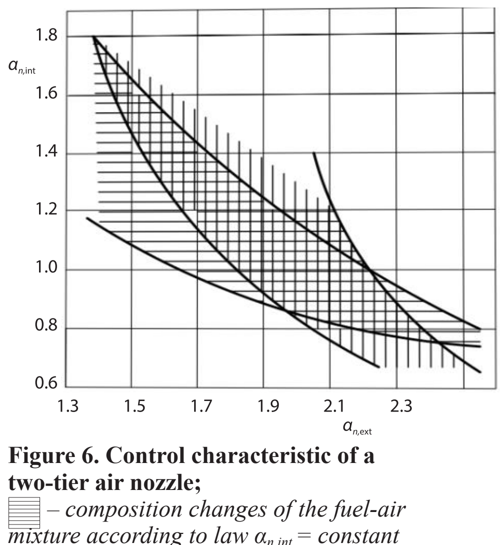

Figure 6. Control characteristic of a two-tier air nozzle; ▤ *– composition changes of the fuel-air mixture according to law* $\alpha_{n,int}$ = *constant and* ▥ *– composition changes of the fuel-air mixture according to law* $\alpha_{n,ext}$ = *constant*

With the deviation of the total compositions both towards depletion and towards enrichment, the range of variation of the dimensionless parameter $m = \alpha_{n,\text{int}}/\alpha_{n,\text{ext}}$ remains approximately constant, while the qualitative composition of the fuel-air mixture changes in the diametrically opposite direction.

So, for the compositions of the fuel-air mixture, characterized by *rich* and *lean* mixtures of the internal and external tiers, the combustion chamber has a narrow control range, especially when the composition changes according to Law 2. This is due to a significant fuel enrichment of the reverse current zone and an inefficient mixing process occurring in a system of propagating coaxial flows with the same swirl. The range of optimal compositions of the mixture expands significantly when the excess air coefficients change to values of 1.06-1.55 for the internal tier and 1.5-2.05 for the external tier, and it is typical for microflame combustion devices.

Since the combustion zone through a two-tier *air* nozzle was supplied by up to 50% of the total air consumption, in order to obtain acceptable pressure losses in the transport gas turbine engine chamber, a scheme of the same swirling of flows in the inlet and outlet swirlers was chosen.

The influence of blades angles installation of a two-tier swirler

To study the influence of blades installation angles of a two-tier swirler on the main parameters of the combustion chamber, tests were carried out with the different angles of the outlet swirlers.

At the same time, options were tested both with the ratio of angles $\beta_{\text{out,int}} \leq \beta_{\text{out.ext}}$ and $\beta_{\text{out,int}} \geq \beta_{\text{out,ext}}$.

Experimental studies have shown that nozzle options with an angle of blade installation of the outlet swirlers $\beta_{\text{out,int}} \leq \beta_{\text{out,ext}}$, in particular 30°, 45°, do not allow for a high quality operation process in the combustion chamber. The inefficient aerodynamic flow structure resulting from this combination of angles in the primary zone leads to low fuel combustion ($\eta_g < 0.9$), excessive smoke, unstable combustion process, difficulties in starting the combustion chamber.

More efficient are options with angles $\beta_{\text{out,int}} > \beta_{\text{out,ext}}$. At the same time, for all the studied combinations of the angles of blades installation of the outlet swirlers, it was determined that the greater the difference between the angles $\beta_{\text{out,int}}$ and $\beta_{\text{out,ext}}$, the more efficient the operation of the combustion chamber.

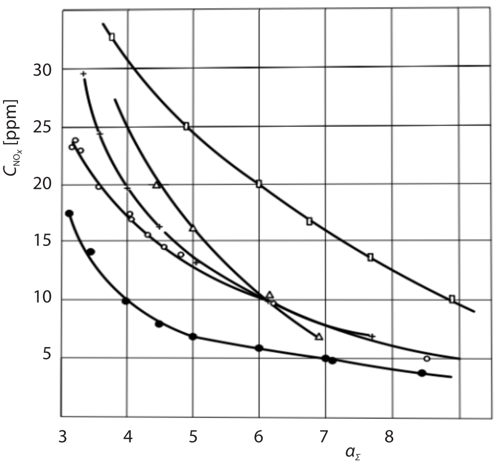

Figure 7. Dependence of the formation of NO_x emission for various microflame devices; □ – *one-stage burner (kerosene TC-1),* Δ – *jet-stabilizing burner (natural gas),* + – *microflame front device (kerosene TC-1),* • – *burner with integrated swirling jets (natural gas), and* **o** – *two-tier air nozzle (kerosene TC-1)*

Thus, high fuel combustion efficiency at the exit from the combustion chambers with a two-tier *air* nozzle can be achieved already at the values $\beta_{\text{out,ext}}$ = 25-30°, and for the internal layer $\beta_{\text{out,int}}$ = 45-60°, the greater the value of $\Delta\beta_{\text{out}}$, the wider the range of operation of the combustion chamber with high fuel combustion efficiency η_g.

The toxicity of combustion products

At the conducting of experimental research, a great care was paid to the issues of toxicity of combustion products, in particular, emissions of NO_x, as the most toxic components.

As it was shown by the experiments, the microflame principles of fuel combustion, applied in the development of a multi-tiered *air* nozzle and providing for dispersed combustion zones along the cross-section of the combustion chamber, burning of a *lean* fuel-air mixture, provided a reduced NO_x emission in the combustion chamber of a transport gas turbine engine.

Figure 7 shows the dependence $NO_x = f(\alpha_\Sigma)$ for a two-tier *air* nozzle in comparison with other types of microflame devices. As it is seen from the figure, the emission of nitrogen oxides strongly depends on the composition of the air-fuel mixture (values of $\alpha_{n,\text{int}}$, $\alpha_{n,\text{ext}}$), formed by the injector, and this dependence increases with decreasing α_Σ.

The minimum toxicity of combustion products was achieved at the $\alpha_{n,\text{int}} = 1.31\text{-}1.6$, $\alpha_{n,\text{ext}} = 1.58\text{-}1.7$. In this case, in the design modes the content of nitrogen oxides in the combustion products during the burning of kerosene TC-1 does not exceed 20 ml/n. The highest NO_x emission was obtained at the operating on a fuel-air mixture with $\alpha_{n,\text{int}} \approx 1\text{-}1.12$ and $\alpha_{n,\text{ext}} = 2.22$.

As it is known, the rate of NO_x formation is maximum at $\alpha_{\text{mix}} = 1\text{-}1.1$, therefore, even despite the significant depletion of the external layer, the emission of NO_x in the design mode in this case is greater than for a single-stage *air* nozzle.

A further decrease in the excess air ratio of the internal layer of the nozzle ($\alpha_{n,\text{int}} = 0.8$) leads to the fact that the total amount of formed NO_x decreases. In this case, the volume of zones with a mixture composition $\alpha_{\text{mix}} = 1\text{-}1.1$ is also significant, however, the time interval required to achieve stoichiometric compositions ensures the burnout of the air-fuel mixture in the combustion chamber zones with values of the excess air coefficient in the primary zone higher than in the previous case.

The interaction of these two competing processes determines the numerical value of the NO_x concentration and the different intensity of its decrease with increasing α_Σ.

So, the lowest concentration of NO_x in combustion products is achieved with the following composition of the air-fuel mixture in the nozzle:

$$\alpha_{n,\text{int}} = 1.3\text{-}1.6, \ \alpha_{n,\text{ext}} = 1.58\text{-}1.7$$

Temperature field unevenness degree

One of the tasks posed when developing a multi-tiered the *air* nozzle was the creation of a burner device that allows you to obtain a controlled adjustable temperature field at the exit from the combustion chamber with a low degree of unevenness of the temperature field.

For a straight-through cylindrical combustion chamber with a two-tier *air* nozzle, the following approximating dependences of the degree of unevenness of the temperature field at the outlet of the combustion chamber were obtained: for the composition region $m = 0.1\text{-}1.0$:

$$\delta = 1 - \exp\left(-0.543 \frac{L_{f,t}}{D_{f,t}} \frac{\Delta P_{f,t}}{q} \left(\frac{\alpha_{n,\text{int}}}{\alpha_{n,\text{ext}}} \right)^{0.59} \right)^{-1} \tag{5}$$

$$\delta = 1 - \exp\left(-0.543 \frac{L_{f,t}}{D_{f,t}} \frac{\Delta P_{f,t}}{q} \left(\frac{\alpha_{n,\text{int}}}{\alpha_{n,\text{ext}}} \right)^{-2.27} \right)^{-1} \tag{6}$$

where $L_{f,t}$ is the flame tube length, $D_{f,t}$ – the flame tube diameter, $\Delta P_{f,t}$ – pressure loss on the flame tube, and q – dynamic pressure.

To determine the value of the composition parameter of the fuel-air mixture, providing the required unevenness of the temperature field and used as a constructive one in the design of a two-tier injectors, the ratios given previously have been converted:

$$m = \left[0.54 \frac{L_{f,t}}{D_{f,t}} \frac{\Delta P_{f,t}}{q} \ln\left(\frac{1}{1-\delta} \right) \right]^{1/b} \tag{7}$$

where $m = \alpha_{n,\mathrm{int}}/\alpha_{n,\mathrm{ext}}$ is the dimensionless composition parameter, δ – the specified degree of the temperature field unevenness, and $b = f(m)$ – a degree index.

It should be noted that, in comparison with a single-stage *air* nozzle with $m = 1$ and other conditions being equal ($C_{f,\Sigma}$ = idem), a two-stage nozzle made it possible to obtain θ (error) in the range of 5-6.2%.

Thus, the two-tier *air* nozzle meets the most stringent requirements for the parameter δ and allows to obtain a controlled and adjustable temperature field of the gas at the outlet from the chamber combustion.

The pressure losses and coefficients of hydraulic resistance

The dependence image of the pressure loss when using an air nozzle with different angles of blades installation of the outlet swirlers $\beta_{\mathrm{out,int}}$ and $\beta_{\mathrm{out,ext}}$ is similar to the dependence σ^* of the two-tier register and the nozzle on these geometric parameters.

As a result of the experimental data, a relation was obtained for the resistance coefficient of combustion loss $\xi_{\mathrm{c,ch}}$:

$$\xi_{\mathrm{c,ch}} = \xi^*_{\mathrm{c,ch,h}} + 0.32\left(\frac{T_g}{T_{\mathrm{int}}} - 1\right) \tag{8}$$

where $\xi_{\mathrm{c,ch,h}}$ is the coefficient of hydraulic resistance of the combustion chamber and for a given chamber depends on the design of a two-tier air nozzle.

It was possible to ensure an acceptable level of pressure loss in the combustion chamber during operation at rated power modes when using a nozzle with outlet swirler installation angles:

$$\beta_{\mathrm{out,int}} = 45\text{-}60^\circ,\ \ \beta_{\mathrm{out,ext}} = 25\text{-}30^\circ$$

Therefore, taking into account the influence of the angles $\beta_{\mathrm{out,int}}$ and $\beta_{\mathrm{out,ext}}$ on the fuel combustion efficiency η_g, temperature T_w, the degree of temperature field unevenness and the relative losses of total pressure σ^* established as a result of the research, for further research the most optimal variant of the two-tier *air* nozzles with angles of blades installation of the output registers: $\beta_{\mathrm{out,int}} = 60^\circ$, $\beta_{\mathrm{out,ext}} = 30^\circ$ was chosen.

Conclusions

The experimental studies of a two-tier burner as the part of the gas turbine combustion chamber confirmed the possibility of achieving of high fuel combustion efficiency η_g, a low degree of temperature field unevenness and a decrease in NO_x emission.

High basic characteristics of the combustion chamber are achieved at the blades installation angles of the outlet swirlers $\beta_{\mathrm{out,int}}$ = 45-60° and $\beta_{\mathrm{out,ext}}$ =25-30° and the coefficients of air excess in the nozzle layer at the design mode $\alpha_{n,\mathrm{int}}$=1.05-1.55, $\alpha_{n,\mathrm{ext}}$ = 1.5-2.05.

For the optimal variant of the *air* nozzle in the design mode, the conclusions are as follows.

- Fuel combustion efficiency η_g = 0.98-0.995.
- Wall temperature T_w = 1200 K.
- Degree of the temperature field unevenness δ = 6.5%.
- Relative loss of total pressure σ^*= 2.5%.
- Concentration of nitrogen oxide s C_{NO_x} < 20 ppm.

Nomenclature

C_{NO_x} – concentration of NO_x, [%]
$D_{f,t}$ – diameter of burner, [m]
$f_r^{\prime *}$ – tier area flow, [m^2]
$G_{f,ext}$ – fuel consumption for external tier, [kgs^{-1}]
$L_{f,t}$ – length of burner, [m]
m – composition parameter, (= $\alpha_{n,int}/\alpha_{n,ext}$) [−]
$\Delta P_{f,t}$ – burner pressure loss, [Pa]
q – dynamic pressure, [Pa]
T_w – wall temperature, [K]

Greek symbols

$\alpha_{n,int}$ – coefficient of air excess for internal tier of nozzle, [−]
$\alpha_{n,ext}$ – coefficient of air excess for the external tier of nozzle, [−]
α_{mix} – coefficient of air excess of the mixture, [−]
α_{Σ} – excess air coefficient total, [−]
$\beta_{out,int}$ – angles of blades installation of the outlet for internal tier, [°]
$\beta_{out,ext}$ – angles of blades installation of the outlet for external tier, [°]
δ – degree of temperature field unevenness, [°]
η_g – fuel combustion efficiency coefficient, [−]
$\eta_{g,ext}$ – fuel combustion efficiency for external tier, [−]
$\eta_{g,int}$ – fuel combustion efficiency for internal tier, [−]
θ – error, [%]
$\xi_{c,ch,gh}$ – combustion chamber hydraulic resistance coefficient, [−]
σ^* – relative loss of total pressure, [%]

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