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Results of investigation of the GTE combustion chamber with a two-stage burner

Resultados de la investigación de la cámara de combustión GTE con un quemador de dos etapas

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ABSTRACT:

The experimental studies of a two-stage burner in the combustion chamber of a transport gas turbine engine (GTE) were carried out, which confirmed the possibility of achieving high combustion efficiency, ηfuel, a low degree of temperature field unevenness and a significant decrease in NOx emission. The concentrations of NOx and CO were measured for various excess air factors in two tiers of the burner. The effect of various air supply modes, i.e. changes in the excess air factor in the tiers, on fuel efficiency was tested. A computational modeling of the flow in a two-stage burner was carried out. The contours of the recycle zones and the calculation of the non-mixture coefficient were presented. The findings corresponded to the obtained experimental data. For the best option of the "air" nozzle in the design condition, the following indicators were obtained: - combustion efficiency ηfuel = 0.98-0.995; - wall temperature Tw = 3200C; - degree of irregularity of the temperature field θ = 6.5%; - NOx concentrations CNOx <20 ppm.

Keywords: burner, combustion efficiency, reduction of hazardous emission, mixture improvement

RESUMEN:

Los estudios experimentales de un quemador de dos etapas en la cámara de combustión de un motor de turbina de gas de transporte (GTE) se llevaron a cabo, lo que confirmó la posibilidad de lograr una alta eficiencia de combustión, combustible, un bajo grado de desigualdad en el campo de temperatura y una disminución significativa en Emisión de NOx Las concentraciones de NOx y CO se midieron para diversos factores de exceso de aire en dos niveles del quemador. Se probó el efecto de varios modos de suministro de aire, es decir, cambios en el factor de exceso de aire en los niveles, en la eficiencia del combustible. Se llevó a cabo un modelado computacional del flujo en un quemador de dos etapas. Se presentaron los contornos de las zonas de reciclaje y el cálculo del coeficiente de no mezcla. Los hallazgos correspondieron a los datos experimentales obtenidos. Para la mejor opción de la boquilla "aire" en las condiciones de diseño, se obtuvieron los siguientes indicadores: - eficiencia de combustión η combustible = 0.98-0.995; - temperatura de la pared Tw = 3200C; - grado de irregularidad del campo de temperatura θ = 6.5%; - Concentraciones de NOx CNOx <20 ppm.

Palabras clave: quemador, eficiencia de la combustión, reducción de emisiones peligrosas, mejora de la mezcla

1. Introduction

Particular attention in the development of new combustion chambers of gas turbine units (GTUs) currently is paid to creating an optimal temperature field in the diluent zone, developing the efficient methods of fuel injection, which operated at different pressures and rates, decreasing the size of units and reducing the formation of hazardous substances.

As many researches and practice show (Lefebvre, 2010), a significant part of NOx formations is nitrogen, which is formed during the building-up process of local volumes (areas) of high temperatures and the long time stay period of gases in the combustion zone.

Previous works by the authors (Umyshev et al., 2016(a, b); 2017(a, b)) showed that the reduction of hazardous emissions and flame stabilization is possible by means of high-drag bodies in the form of angle stabilizers. However, the use of angle stabilizers has one minus – significant route pressure losses in the combustion chamber. Based on this, the authors conducted an analysis of the methods that ensure low pressure losses and NOx emissions. The main problem in the reduction of NOx is the heat.

To reduce the heat, the technology of lean-premixed combustion is widely used and studied. This technology is explored by many researchers. The authors of this article suggest a lean-premixed mixture that burns in discrete zones – microflame combustion.

The analysis of operation of the Alstom EnVironmental (EV) burners is carried out by Cho et al. (2013). These types of burners have been used relatively recently. Their distinctive feature is the mixing of the fuel-air mixture before it is fed into the combustion chamber. The burner consists of two cones, between which the gas is mixed with primary air. By this specific form, the burner provides good mixing, thereby increasing the mixture homogeneity, which reduces the formation of local volumes of high temperatures and improves combustion stability. The flame stability is maintained by the destruction of the whirl at the burner outlet. The authors also showed that the premixing of the fuel in the burner itself reduces the emission of hazardous substances, in particular NOx. This was noticed when using a different number of bores made in the burner.

Microflame combustion also includes burning behind high-drag bodies.

For example, Fan et al. (2014) studied the combustion processes behind angle stabilizers. The authors figured out that flame stabilization by high-drag bodies allows improving the stall characteristic. The article states that the stall occurs in areas with the speeds of 36 and 43 m/s and in the depletion region.

Another direction is the use of swirling motion of the fuel-air mixture to stabilize the flame and improve performance (Stöhr et al., 2009; 2012). The authors of these papers proposed a gas turbine model combustor in which air passes through two radial vortex generators at room temperature. Afterwards, these two swirling flows enter the combustion chamber through a central bore. The fuel is fed through the ring opening. The experimental studies showed good stabilization rates.

Belohradský et al. (2013) use a two-stage combustion chamber. In the combustion chamber, the gas is fed from two groups of nozzles. On the axis of the combustion chamber, swirled vanes – flame stabilizers – are installed. They consist of eight blades and are mounted on a central tube.

The experimental study by de Almeida and Lacava (2015) covers a two-stage burner for a gas turbine, in which such parameters as total air excess, Reynolds numbers and swirler angles were changed. The research showed that when these parameters contribute to recirculation zone intensification formed at secondary chamber, i.e. higher swirler angles and smaller Reynolds numbers, CO and UHC are reduced.

Fernando and Felic (2007), Kim et al. (2015), Gao et al. (2012) studied the effect of various options for creating recirculation zones that ensure low hazardous emissions. The results of an experimental study of the so-called vortex trap are given in the paper by Kim et al. (2015). The results showed that the vortex trap reduces NOx emissions by 21.2%, and CO – by 13.3%.

Gao et al. (2012) studied a two-stage burner separated by pellets. The influence of the size of pellets on hazardous emissions was determined. The authors found the optimal ratios of parameters ensuring low NOx emissions.

Jing et al. (2011a) carried out an analysis of a burner with two vortices and the effect of diluent air. The results showed that an increase in diluent air reduces the number of particles in the secondary air supply, but increases the number of particles in the near-wall zone. A study by Jing et al. (2011b) on the influence of the angle of the secondary blades on the particle flux showed that a decrease in the angle leads to a decrease in the root-mean-square value of the axial, radial velocities in the near-wall zone, but results in an increase in the tangent velocities, as well as a slight increase in the recirculation zone. A study by Tia et al. (2017) on the influence of the outer secondary air vane angle on the parameters of the combustion process and NOx emissions showed that at 20°-30° angles the emission of NOx is reduced by 25% (from 325 mg/m3 to 237 mg/m3). The cold (non-burning) studies of solid fuel burners by Li et al. (2012a) and Li et al. (2012b) showed that there is a central recirculation zone located at x/d=0.1-0.3 and r/d=0.25-0.4 at a velocity of 4 m/s saturated with oxygen that potentially produces NOx.

The further improvement of GTE combustion chambers required the development of a multifuel burner that would ensure the efficient combustion of fuels and the reduction of hazardous emissions (CO, HC, NOx) throughout the operational range of engine conditions. To this end, a new design of the microflame device was developed, a two-stage burner, which makes it possible to organize the combustion process in a number of discrete zones, i.e. microflame combustion. In this case, the transverse arrangement of zones takes place. In the concept of zone combustion, the focus is on optimizing the fuel distribution, and the purpose is to regulate combustion to achieve the low levels of toxic emissions under all operating conditions. A two-stage burner uses a fuel and air premixing and zone feeding of the combustible lean mixture into the combustion zone, i.e. the bulk of air is fed through the combustion chamber flame tube head.

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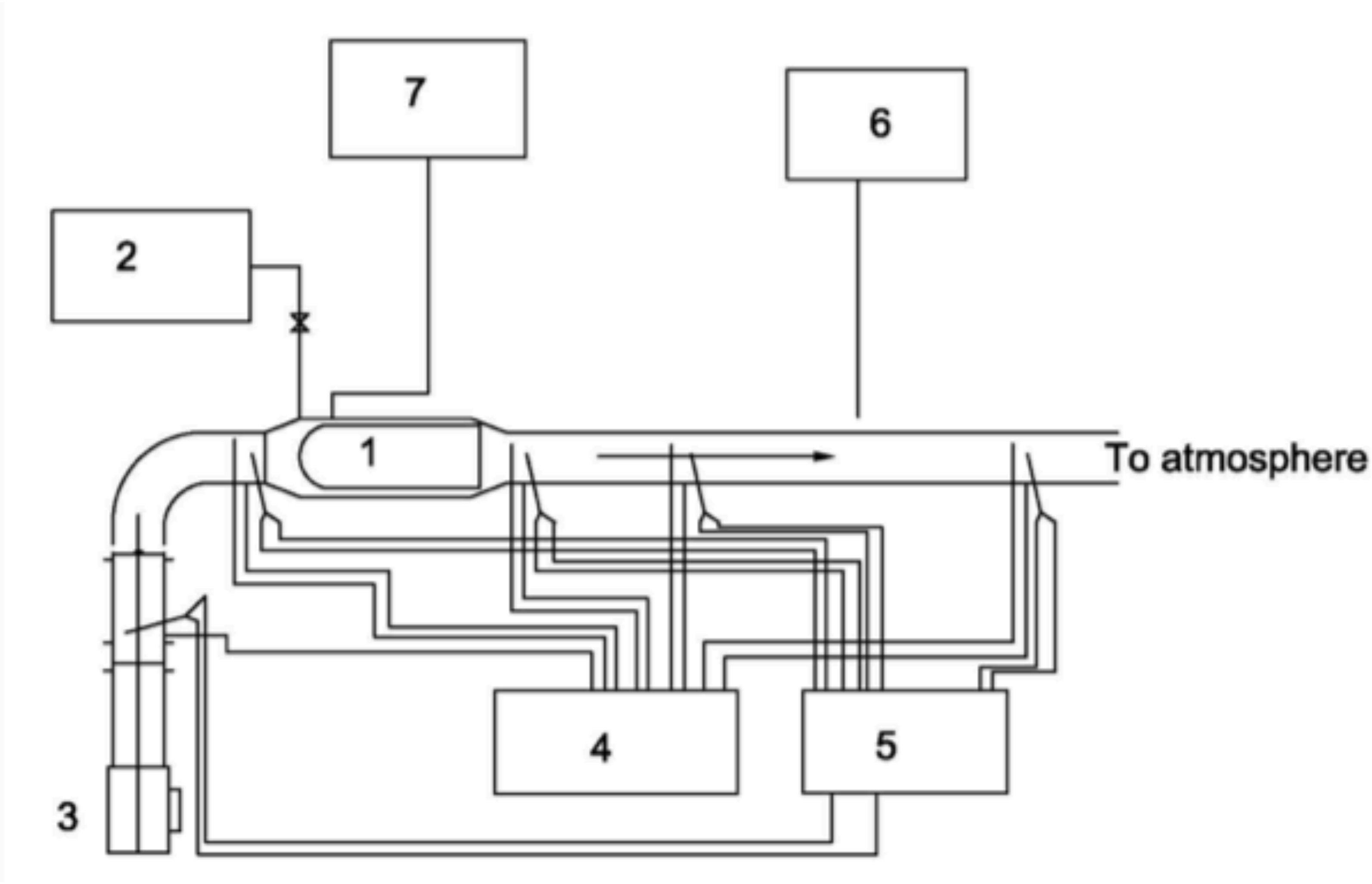
2. Experimental set-up and method

The layout diagram of the experimental set-up is shown in Figure 1.

Figure 1
Layout diagram of the experimental set-up



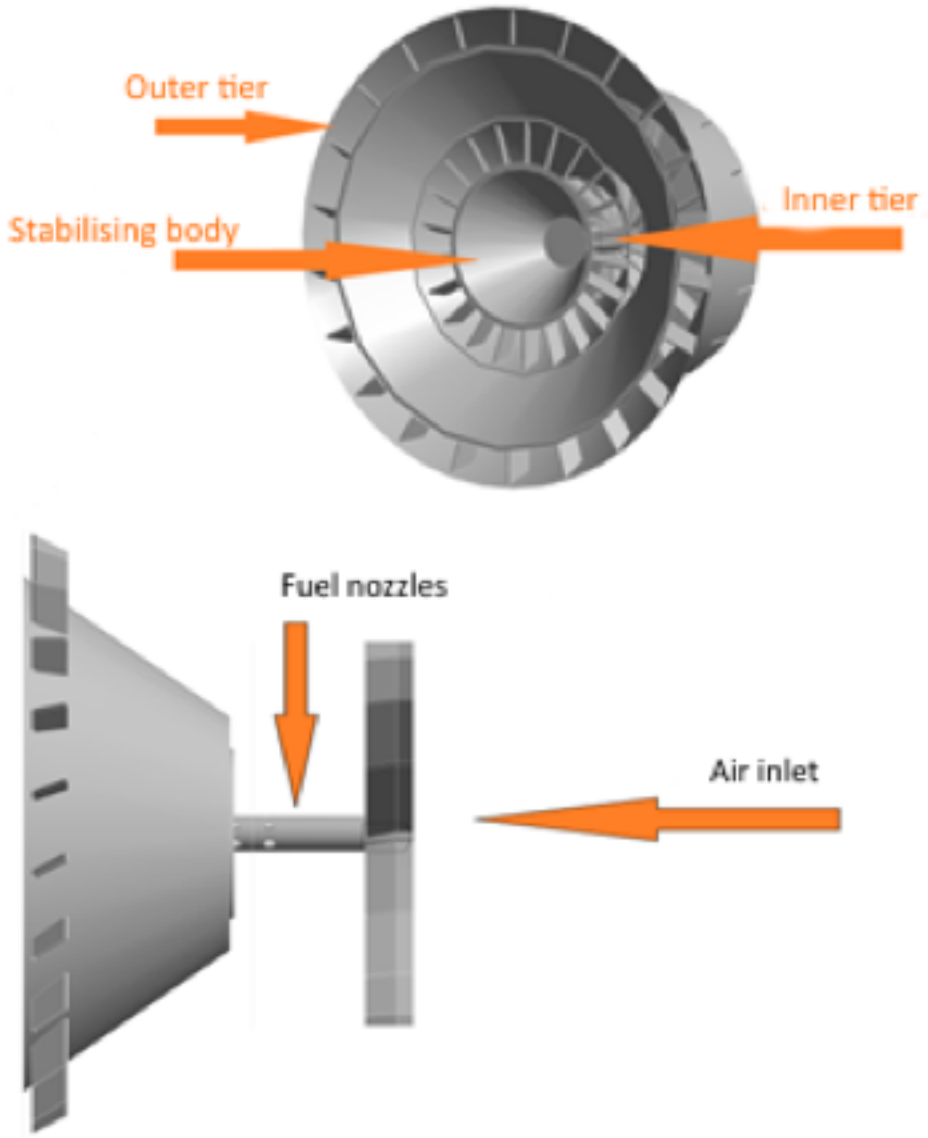
1 - combustion chamber; 2 - fuel supply; 3 - air compressor; 4 - group of U-shaped manometers; 5 - group of thermocouples; 6 - gas sampler for analysis; 7 - current supply for the spark plug.

The experimental set-up consists of an air compressor that supplies air under pressure to the combustion chamber. A line for supplying liquid fuel is connected to the combustion chamber. The combustion chamber is equipped with a spark plug connected to a current transformer operating from the main power supplies. In the sections shown in Figure 1, U-shaped manometers and thermocouples are installed. To study the concentrations of NOx and CO, a stationary gas analyzer is used.

Figure 2 presents a 3D model of the studied two-stage burner, which consists of a liquid injector, an inlet vane swirler and a vane swirler around it, and a ring nozzle. On the output front, the burner is equipped with coaxial shells separating the front of the burner into tiers. Each tier has a group of vane swirlers. The inner circle is installed around the stabilizing cone. Input and output vane swirlers were manufactured at different angles – from 20º÷60º.

The material of the blades used in the MFP is a heatproof high alloy. Naturally, the choice of the material for the blades of microflame combustion should be determined by the conditions of their operation and, primarily, by the temperature regime.

Figure 2
3D model of the burner under study



In the conducted experimental studies, the excess air factor of the inner tier of combustion changed in the range $\alpha_{ex.in} = 0{,}61 \div 1{,}84$, and the excess air factor of the outer tier – $\alpha_{ex.out.} = 1{,}34 \div 2{,}64$. Aviation kerosene TS-1 and diesel fuel were used as fuel. The flame tube is cylindrical, with a diameter of 228 mm; the nozzle installation diameter is 72 mm. During the test period, the following parameters were maintained: the air flow rate – Gb=1.2÷1.5 kg/s, air temperature – 335-364 K, inlet pressure in the combustion chamber – P=0.106÷0.13MPa.

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3. Results and discussion

3.1. Dependence of combustion efficiency

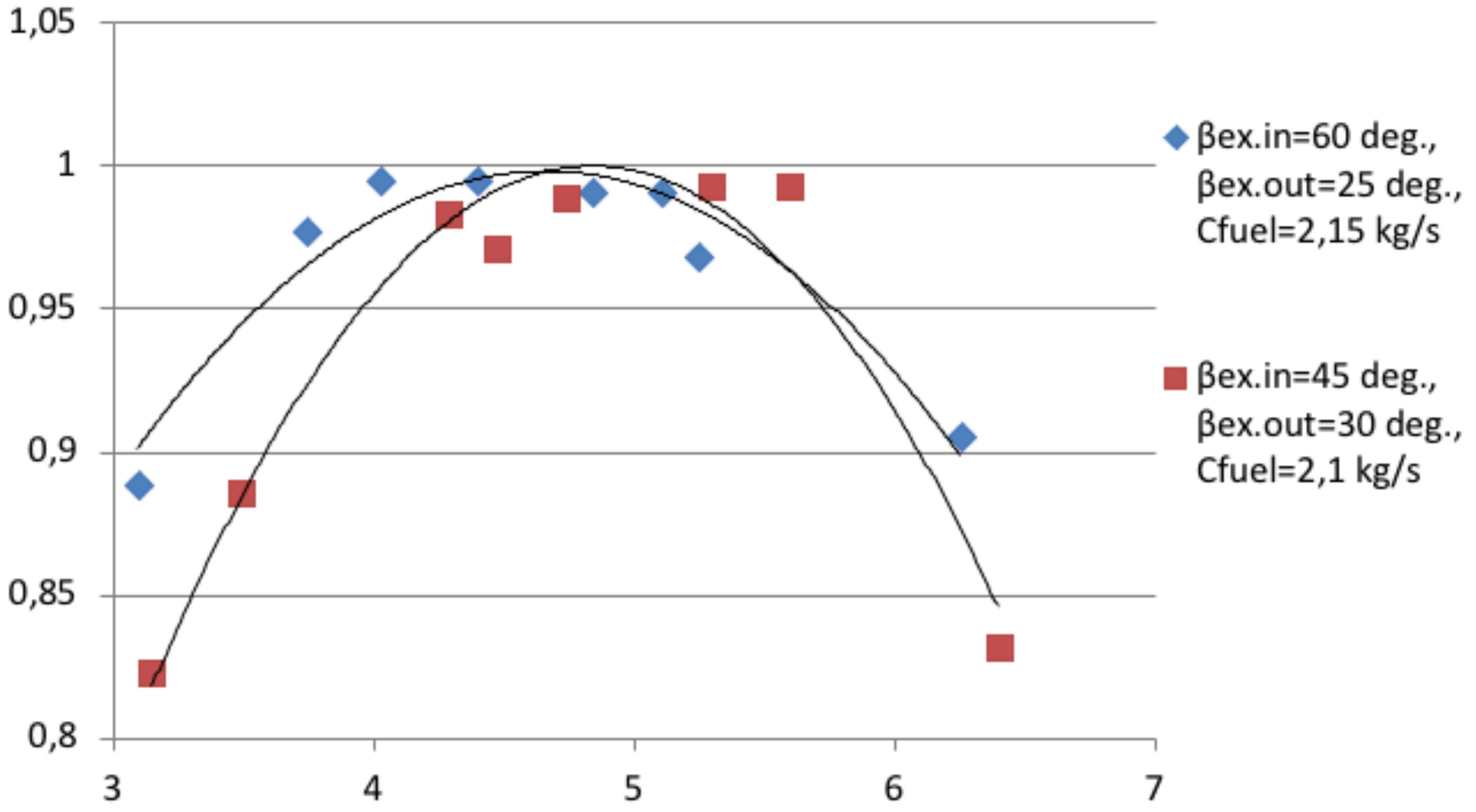
The dependence of fuel combustion efficiency $\eta_{fuel} = f(\alpha_{\Sigma})$ on different operating modes of the injector is shown in Figure 1. In this case, curves 1 and 2 correspond to different operating modes of the injector. Curve 1 is obtained when a two-stage nozzle operates, when fuel is supplied to both tiers, mode A. Curve 2 is obtained when fuel is supplied only to the inner tier of the injector, mode B. Such operating modes were considered when supplying fuel only to the inner tier (mode C). However, in this case, high combustion efficiency was achieved only in individual cases, and, in general, this operating mode was characterized by non-compliant indicators.

Experimental studies have shown that $\eta_{fuel} \geq 0{,}98$ is achieved in a wide range at $\alpha_{\Sigma} = 3 \div 22$.

The dependence of fuel combustion efficiency on the total excess air factor during the operation of the combustion chamber is shown in Figure 1.

Figure 3

Dependence of fuel combustion efficiency on total excess air



For the convenience of analysis, combustion efficiency at the exit of the combustion chamber is represented as a sum of the combustion efficiency of total fuel consumption shares falling on the inner and outer tier of the injector:

I.e. $\eta_{fuel} = g_{in}\eta_{fuel.in} + g_{out}\eta_{fuel,out}$

where $g_i = \frac{G_T}{G_{T\Sigma}}$

η_i - combustion efficiency of fuel for the corresponding tier.

The investigated two-stage nozzle was designed in such a way that the fuel-air mixture consumption through the outer tier of the injector is 70% of total fuel-air mixture consumption. Thus, the effect of the variation of $\eta_{fuel.out}$ of the fuel fraction supplied through the outer tier on total combustion efficiency is more than twice as significant as the changes $\eta_{fuel.in}$. As will be shown in the analysis of subsequent experimental dependencies, it is the quality of the air-fuel mixture formed by the outer tier that largely determines the nature of the dependence $\eta_{fuel} = f(\alpha_\Sigma)$.

In this nozzle design, fuel was distributed to the outer tier through peripheral or axial ring fuel nozzles. At the same time, due to technological and structural difficulties, the axial ring nozzle was made not in the form of a conventional manifold ring collector with uniform fuel distribution, but in the form of a collector with sequential fuel distribution along the length. It is commonly known that in such a design, the flow of the medium through the bores along the length of the nozzle is reduced, i.e. showing uneven distribution of fuel along the cross-section of the outer tier. This disadvantage is particularly pronounced when the nozzle operates in variable modes. Thus, with an increase in α_Σ due to a decrease in $G_{air.out}$ an uneven decrease in the range of fuel jets along the cross-section of the outer tier channel occurs. At the same time, the processes of periodic ignition of the air-fuel mixture fed through the outer tier and, as a result, vibrating combustion in the combustion chamber were visually observed. A further increase in the throughput area of the last bores of the fuel collector allowed us to expand the range of operation with high combustion efficiency to $\alpha_\Sigma \approx 7$, and significantly reduce both the radial and circumferential unevenness of the temperature field.

Experimental studies have shown that η_{fuel} in the combustion chamber with a two-stage nozzle is determined not only by the stagger angle of the outlet swirler of the inner and outer tiers, but also by the composition of the air-fuel mixture formed by the nozzle, i.e. $\alpha_{ex.i}$ corresponding to the tier of the nozzle.

In the two-stage nozzle, depending on operating modes, the following conditions for changing the composition of the air-fuel mixture can be realized:

1. $\alpha_{ex.in.} = const\ \alpha_{ex.out.} = var\quad \alpha_\Sigma(\overline{f_r^*}) = var$
2. $\alpha_{ex.in.} = var\ \alpha_{ex.out} = const\quad \alpha_\Sigma(\overline{f_r^*}) = var$
3. $\alpha_{ex.in.} = var\ \alpha_{ex.out} = var\quad \alpha_\Sigma(\overline{f_r^*}) = const$

In this case, the study of the combustion chamber in accordance with the laws 1 and 2 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 the law 3 – when operating in both variables and design conditions.

The experimental dependence of fuel combustion efficiency with a change in composition according to the law 1 is shown in Figure 2. It should be noted that there is a definite relationship between the signs of $\alpha_{ex.in}$ and $\alpha_{ex.out}$. The high values of η_{fuel} for $\alpha_{ex.in}$=0.82 are achieved with a significant depletion of the air-fuel mixture of the outer tier, and the value of $\alpha_{ex.in}$ to 1.6 requires a corresponding decrease in $\alpha_{ex.out}$.

Figure 4

Dependence of fuel combustion efficiency on $\alpha_{ex.in}$ at $\alpha_{ex.out=const}$

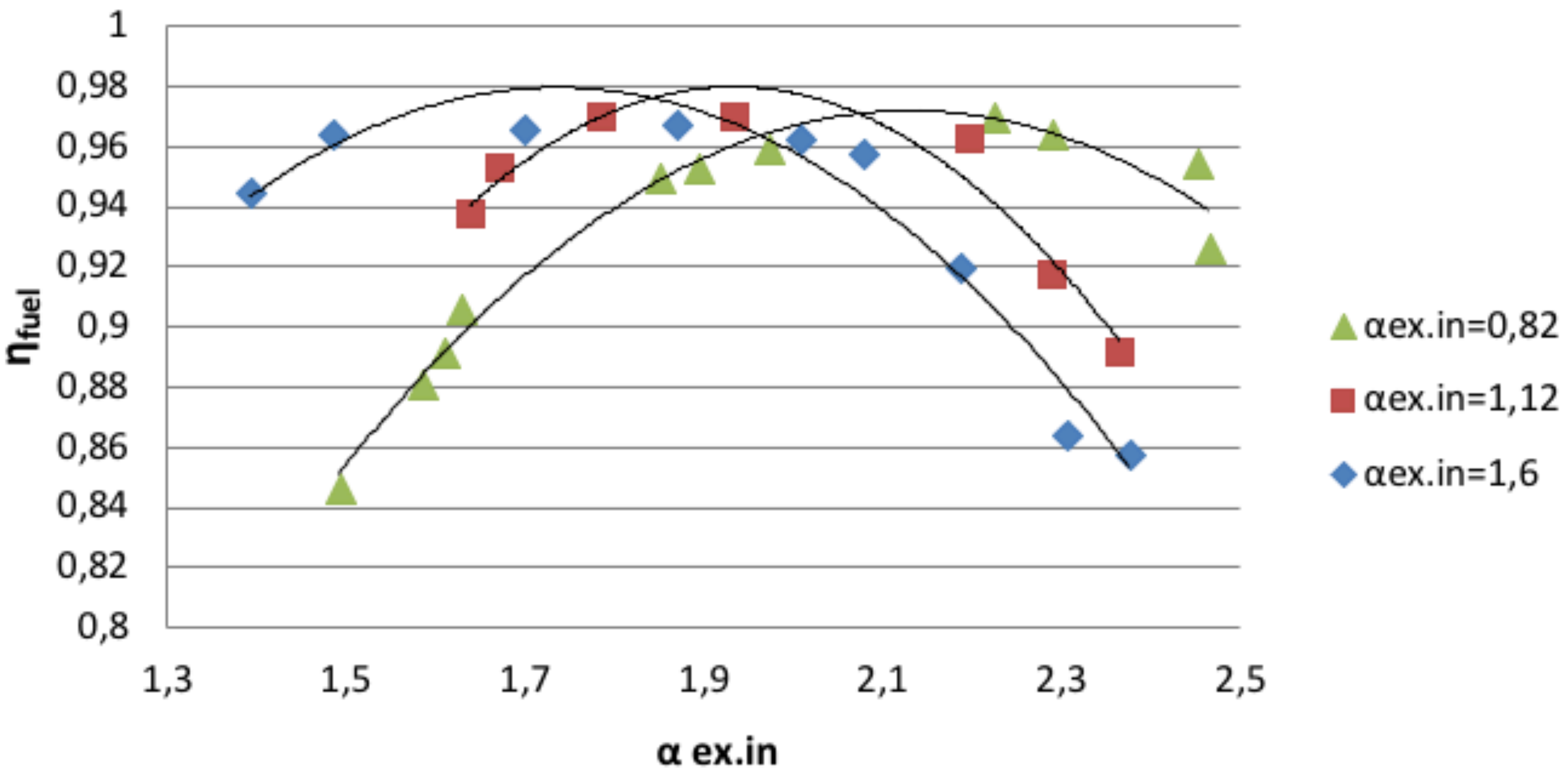
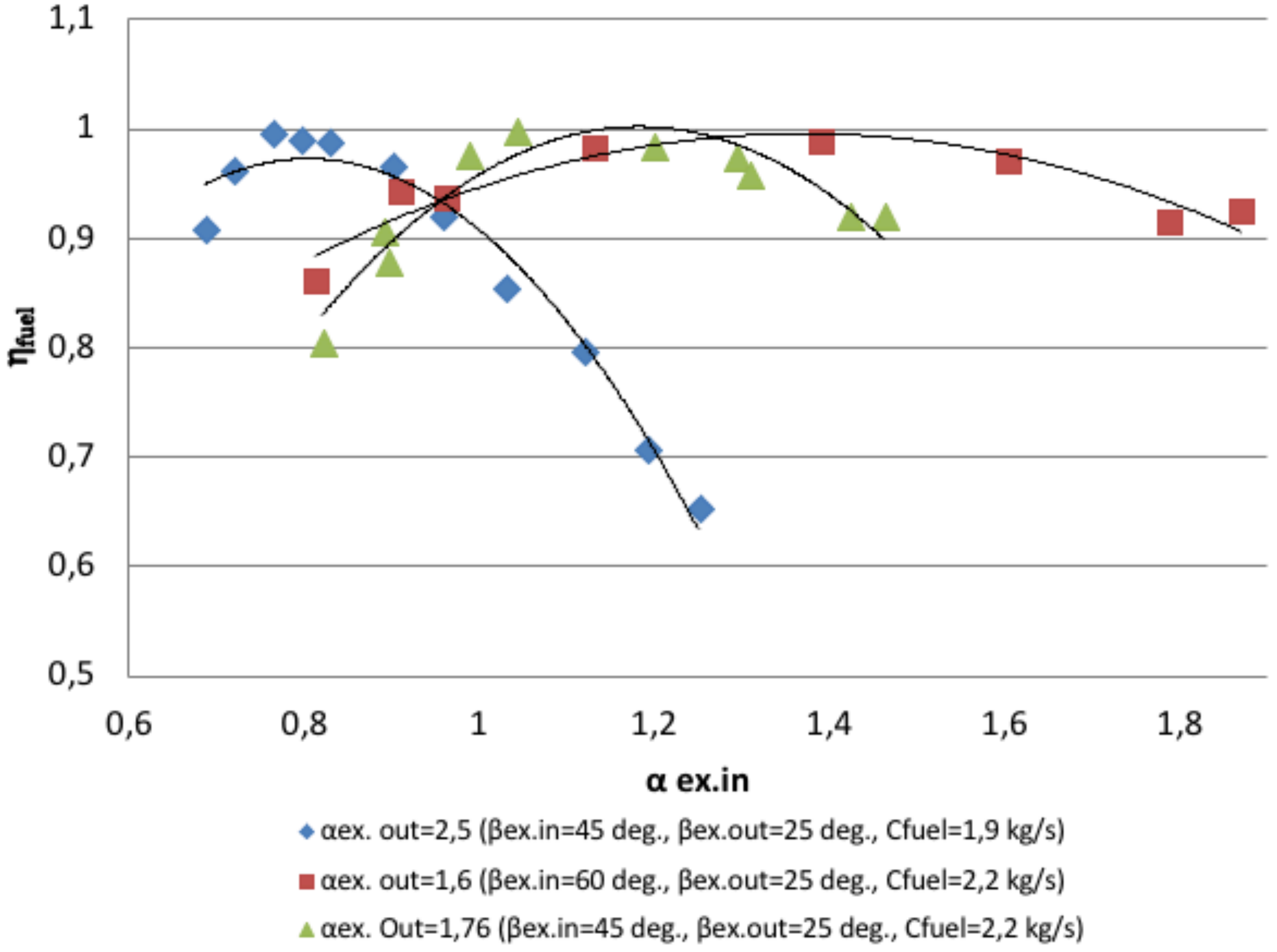


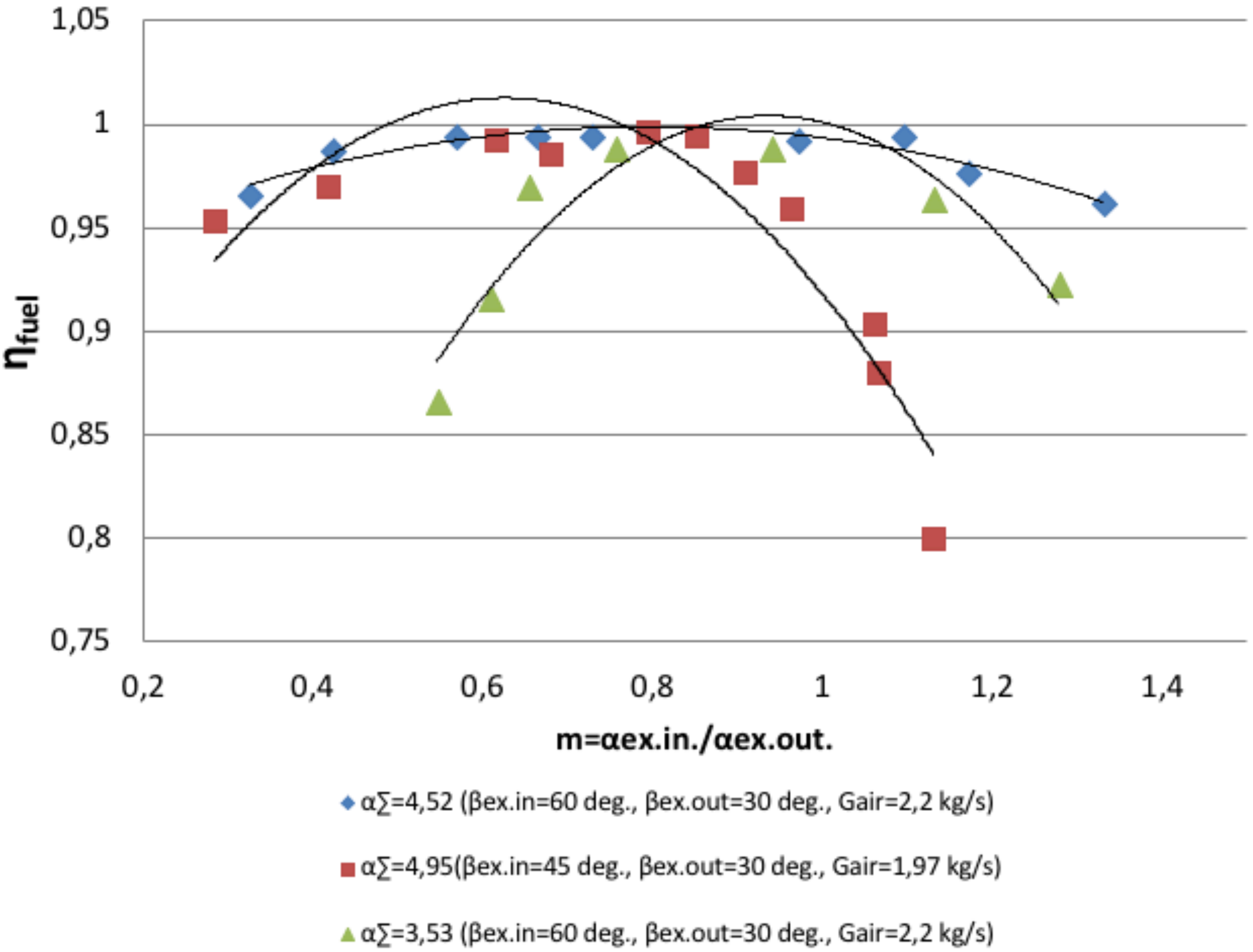
Figure 4 depicts the fuel dependence η_{fuel} when the composition of the mixture changes in accordance with the law 2. As can be seen, with a significant depletion of the outer tier, $\alpha_{ex.out}$=2.5, high combustion efficiency $\eta_{fuel} \geq 0{,}98$ can be achieved only with the "rich" composition of the mixture of the inner tier, $\alpha_{ex.in}$≈0.8. At the same time, the range of α is very low – 0.75-0.86.

Figure 5
Dependence of fuel combustion efficiency on $\alpha_{ex.in}$ at $\alpha_{ex.out}$=const.



As in the case of regulation according to the law 1, the range of the optimal change greatly extends from 1.06÷1.55 with decreasing $\alpha_{ex.out}$. up to 1.6.

Figure 6
Dependence of fuel combustion efficiency on the parameter m at $\alpha\Sigma$=const.



The variation interval of the excess air factor was $\alpha_{ex.in.}=0{,}61\div1{,}84$, $\alpha_{ex.out.}=1{,}34\div2{,}64$. As can be seen, when $\alpha_{\Sigma calc.}\approx4$ is used, high combustion efficiency $\eta_{fuel} \geq 0{,}98)$ is achieved over a wide range of the air-fuel mixture in the $\alpha_{ex.in.}/\alpha_{ex.out.}=0{,}4\div1{,}1$ tier.

Operation on variable modes ($\alpha_{\Sigma}=4$) reduces this interval to 0.7÷1.07 in the case of enrichment and to 0.4÷0.9 in the case of depletion of the total mixture composition relative to $\alpha_{\Sigma calc}$.
In the deviation of the total composition of modes, both in the direction of depletion and enrichment, the range of variation of the dimensionless parameter $m=\alpha_{ex.in.}/\alpha_{ex.out.}$ remains approximately constant, while the qualitative composition of the air-fuel mixture changes in a diametrically opposite direction.
Thus, with the air-fuel mixture compositions characterized by "rich" and "poor" mixtures of the inner and outer tiers, the combustion chamber has a narrow regulation range, especially when the composition is changed in accordance with the law 2. This is due to the significant enrichment of the recirculation mixing zone by fuel and the inefficient process of mixing of the propagating coaxial flows with the same spin in the system. The range of the optimum mixture composition is significantly expanded when the excess air factor is changed to 1.6÷1.55 for the inner tier and 1.5÷2.05 for the outer tier, i.e. when operating on the "poor" air-fuel mixture, which is typical for microflame incinerators.
Since up to 50% of the total air flow rate entered the combustion zone through a two-stage "air" nozzle, the scheme of the same spinning of flows in the inlet and outlet swirlers was chosen in order to obtain permissible pressure losses in the transport GTE chamber.

3.2. Stagger angle effect

Special attention was paid to the study of the stagger angle effect of a two-stage swirler on the main parameters of the combustion chamber.

The numerical values of the experimentally verified angles were as follows:

$\beta_{ex.in}=30^0, 45^0, 60^0$ – output swirler of the inner layer;

$\beta_{ex.out}=25^0, 30^0, 45^0$ – output swirler of the outer layer.

In this case, both variants as with the ratio of the angles of $\beta_{ex.in}\leq\beta_{ex.out}$, and $\beta_{ex.in}\geq\beta_{ex.out}$ were tested.

As shown by experimental studies, the variants of the nozzle with the stagger angle of the output swirlers $\beta_{ex.in}\leq\beta_{ex.out}$, in particular $30^0/45^0$, do not make it possible to realize a qualitative operating process in the combustion chamber. The ineffective aerodynamic structure of the flow in the primary zone formed at this combination of angles leads to low combustion efficiency ($\eta_{fuel}<0,9$), excessive smoke generation, unstable combustion process, and difficulties in starting the combustion chamber.

The variants with the angles $\beta_{ex.in}\geq\beta_{ex.out}$ are more effective. At the same time, for all the combinations of stagger angles of the output swirl vanes, the greater the difference between the angles $\beta_{ex.in}$ and $\beta_{ex.out}$, the more efficient the combustion chamber is.

Thus, high combustion efficiency at the exit of the combustion chambers with a two-stage "air" nozzle can be achieved at $\beta_{ex.out}=25^0\div30^0$, and for the inner tier – at $\beta_{ex.in}=45^0\div60^0$. At the same time, the larger the value of $\Delta\beta_{ex}$, the wider is the range of operation of the combustion chamber with high combustion efficiency η_{fuel}.

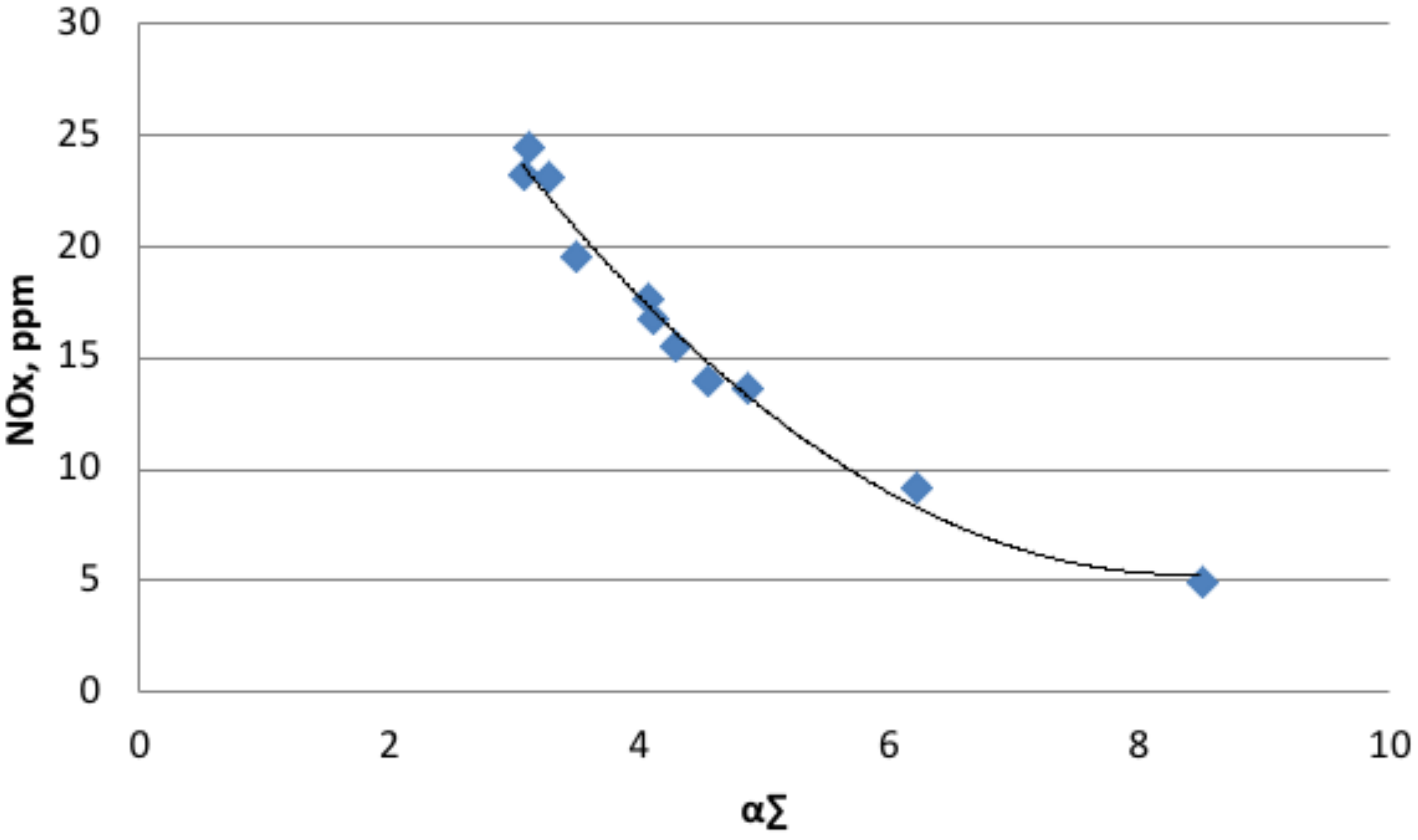
3.3. Formation of hazardous substances

Much attention was paid to the issues of toxicity of combustion products, in particular, emissions of nitrogen oxides as the most toxic components.

As shown by the experiments, the microflame principles of fuel combustion, applied in the development of a multi-tier "air" nozzle and providing for the dispersion of the combustion zone along the combustion chamber section and the burning of the "poor" fuel-air mixture, ensured the reduction of NOx emission in the combustion chamber of the transport GTE.

Figure 4 shows the dependence of $NOx=f(\alpha_{\Sigma})$ for a two-stage "air" nozzle. As can be seen, NOx emission is highly dependent on the composition of the fuel-air mixture ($\alpha_{ex.in.}$ and $\alpha_{ex.out.}$), formed by the nozzle. Moreover, this dependence increases with decreasing α_{Σ}.

Figure 7
Dependence of NOx formation on αΣ



The minimal toxicity of combustion products was achieved at $\alpha_{ex.in.}$=1,31÷1,6, $\alpha_{ex.out.}$=1,58÷1,7. In this case, in the design conditions ($\alpha_{\Sigma}\approx 4$), nitrogen oxides in combustion products when burning kerosene TS-1 do not exceed 20 ppm.

The highest NOx emission was obtained when operating on a fuel-air mixture with $\alpha_{ex.in}$=1,1÷1,12, $\alpha_{ex.out.}$=2,2.

A further decrease in the excess air factor of the inner tier of the nozzle ($\alpha_{ex.in}$=0.8) leads to the fact that the total amount of nitrogen oxides decreases. At the same time, the volume of zones with the mixture composition of α_{batch}=1.1, (which is known to be the ratio at which the maximum amount of nitrogen oxides is formed) is also significant. However, the time interval is required for the air-fuel mixture in the zones of the combustion chamber with *greater* values of the excess air factors in the primary zone, than in the previous case. The interaction of these two competing processes determines the numerical value of NOx concentrations and the different intensity of its decrease with increasing α_{Σ}.

Thus, the lowest concentration of NOx in combustion products is achieved with the following air-fuel mixture in the nozzle:

$\alpha_{ex.in.}$=1,3÷1,6, $\alpha_{ex.out.}$=1,58÷1,7.

3.4. Temperature field at the exit of the combustion chamber

One of the tasks set in the development of a two-stage "air" nozzle was the creation of a burner device that makes it possible to obtain a controlled, regulated temperature field at the exit of the combustion chamber with a low degree of unevenness.

The temperature field at the exit of the combustion chamber is determined not only by the nature of the combustion process, heat exchange and mixing in the corresponding zones of the flame tube, but also by the specific design of the combustion chamber, its front device: the structure of the formed flame, the fuel atomization characteristic, the angle and range of the fuel flame.

A cardinal way to significantly improve the temperature field is the realization of the microflame fuel combustion method, which makes it possible to avoid the separation of air into primary and diluent, i.e. to supply all air through the front of the combustion chamber. In this case, the processes of dilution and mixing of combustion products and excess air flow inside the entire length of the flame tube and are determined by the length and diameter of the flame tube as well as by pressure drops on its walls. Therefore, to generalize the experimental data on the degree of unevenness of the transport field at the exit of the combustion chamber of the multilevel "air" nozzle, the following dependence was chosen:

$$\frac{T^*_{gmax}\text{-}T^*_g}{T^*_g\text{-}T^*_{air}} = f\left(\frac{L_{f.t..}}{D_{f.t.}}\cdot\frac{\Delta P_{f.t}}{q}\right)$$

where $\theta = \frac{T^*_{gmax}\text{-}T^*_g}{T^*_g\text{-}T^*_{air}}$ is the degree of unevenness of the temperature field of gases;

The degree of unevenness of the temperature field was investigated under different operating conditions of the nozzle.

The analysis of the experimental data showed that the most significant effect on the degree of unevenness of the temperature field is made by the distribution of fuel between the tiers of nozzles, i.e. the values and the ratio of the excess air factor $\alpha_{ex.in.}$=1 and $\alpha_{ex.out.}$, while the dependence on the angles $\beta_{ex.in}$ and $\beta_{ex.out.}$ was negligible for this mode.

Two areas can be distinguished, differing in the character of the dependence of θ on the dimensionless parameter of the air-fuel mixture composition: $m=\alpha_{ex.in.}/\alpha_{ex.out.}=0.1\div1.0$ and $m>1.0$. In this case, the excess air factor in the inner tier $\alpha_{ex.in}$ varies within the range of 0.61÷1.6.

As shown by the measurements of the temperature field at the exit of the combustion chamber when testing different nozzle variants, the values of θ when burning both diesel fuel and kerosene TS-1 had a weak dependence on α_Σ.

The last circumstance is very typical for microflame tube heads, especially for those designed for diffusion fuel combustion. Such combustion chamber flame tube heads allow the fuel burn-out process to be carried out at a shorter length of the combustion chamber. In addition, the rest of the length of the flame tube is used to equalize the temperature field of combustion products and achieved by a given unevenness of θ.

For a straight-through cylindrical combustion chamber with a two-stage "air" nozzle, the following interrogating dependences of the degree of unevenness of the temperature field at the exit of the combustion chamber were obtained: for the range of compositions m=0.1 ÷ 1.0:

$$\theta = 1\text{-exp }(\text{-}0{,}54\frac{L_{f.t}}{D_{f.t}}\cdot\frac{\Delta P_{f.t}}{q}\left(\frac{\alpha_{ex.in}}{\alpha_{ex.out.}}\right)^{0{,}59})^{-1}$$

for m>1.0:

$$\theta = 1\text{-exp }(\text{-}0{,}54\frac{L_{f.t}}{D_{f.t}}\cdot\frac{\Delta P_{f.t}}{q}\left(\frac{\alpha_{ex.in}}{\alpha_{ex.out.}}\right)^{-2{,}27})^{-1}$$

To determine the value of the air-fuel mixture composition parameter providing the required temperature field unevenness and used in the design of a two-stage nozzle, the ratios given above were converted:

$$m = \ (0{,}54\frac{L_{f.t}}{D_{f.t}}\cdot\frac{\Delta P_{f.t}}{q}\,ln\left(\frac{1}{1-\theta}\right)^{0{,}59})^{\frac{1}{b}}$$

where $m=\alpha_{ex.in.}/\alpha_{ex.out}$ is the dimensionless composition parameter;

θ is a given degree of unevenness of the temperature field;

b = f(m) is the exponent.

This two-stage "air" nozzle made it possible to obtain θ within 5÷6.2%.

Thus, the two-stage "air" nozzle meets the most stringent requirements for the parameter θ and makes it possible to obtain a controlled and regulated temperature gas field at the exit of the combustion chamber.

3.5. Results of CFD analysis

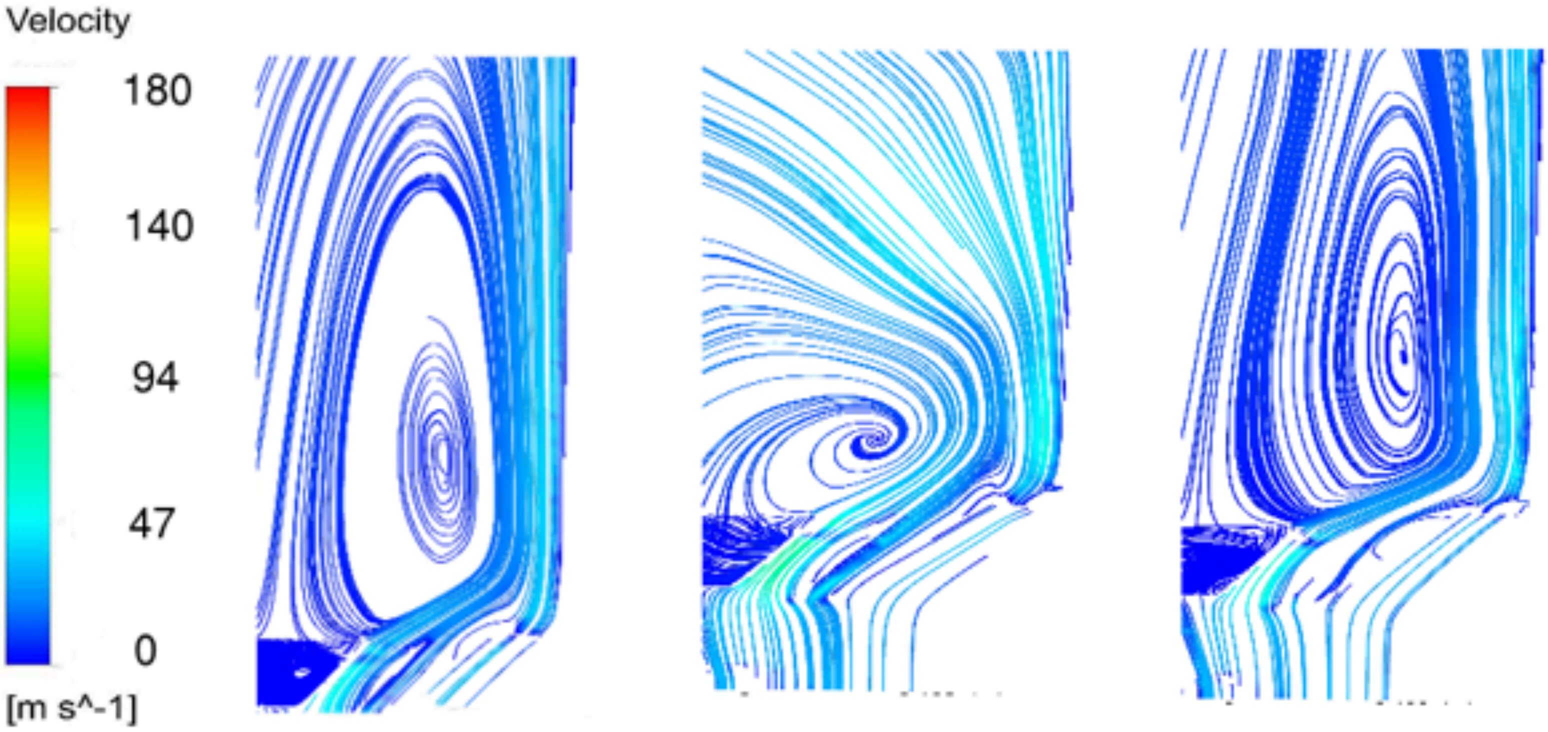
To study the influence of the swirler stagger angles on the burner tiers on high-speed currents, a non-reaction (isothermal) CFD analysis was performed in the program FLUENT 16.0 for five variants of blade setting: $\beta_{ex.in}=30^0$, $\beta_{ex.out}=25^0$; $\beta_{ex.in}=45^0$, $\beta_{ex.out}=30^0$; $\beta_{ex.in}=60^0$, $\beta_{ex.out}=45^0$, $\beta_{ex.in}=60^0$, $\beta_{ex.out}=25^0$, $\beta_{ex.in}=45^0$, $\beta_{ex.out}=25^0$. In the program FLUENT 16.0. The frame consisted of 421,000 tetrahedrons. To simulate the turbulent flow, a k-ε realizable model was used with a standard wall function.

Figure 7 shows the current contours for the five variants. As can be seen, the location of the corner swirls appreciably changes the speed contours. At the angle of $\beta_{ex.in}$=300, $\beta_{ex.out}$=250 a circulation movement has the largest size. It is seen that the recirculation zone is in the center at the angle of $\beta_{ex.in}$=450, $\beta_{ex.out}$=300. At the angles of $\beta_{ex.in}$=600, $\beta_{ex.out}$=450, the recirculation zone is extended in the longitudinal size. At the angles of $\beta_{ex.in}$=600, $\beta_{ex.out}$=250, the recirculation zone is very short, but very intense, which explains the very effective mixing of fuel with air and proves the calculated coefficient of unmixedness. The most complex contour of recirculation zones in the structure has $\beta_{ex.in}$=450, $\beta_{ex.out}$=250. The reason for this structure is the insufficient swirling of the flow at the inlet and a sufficiently high level of swirling at the outlet.

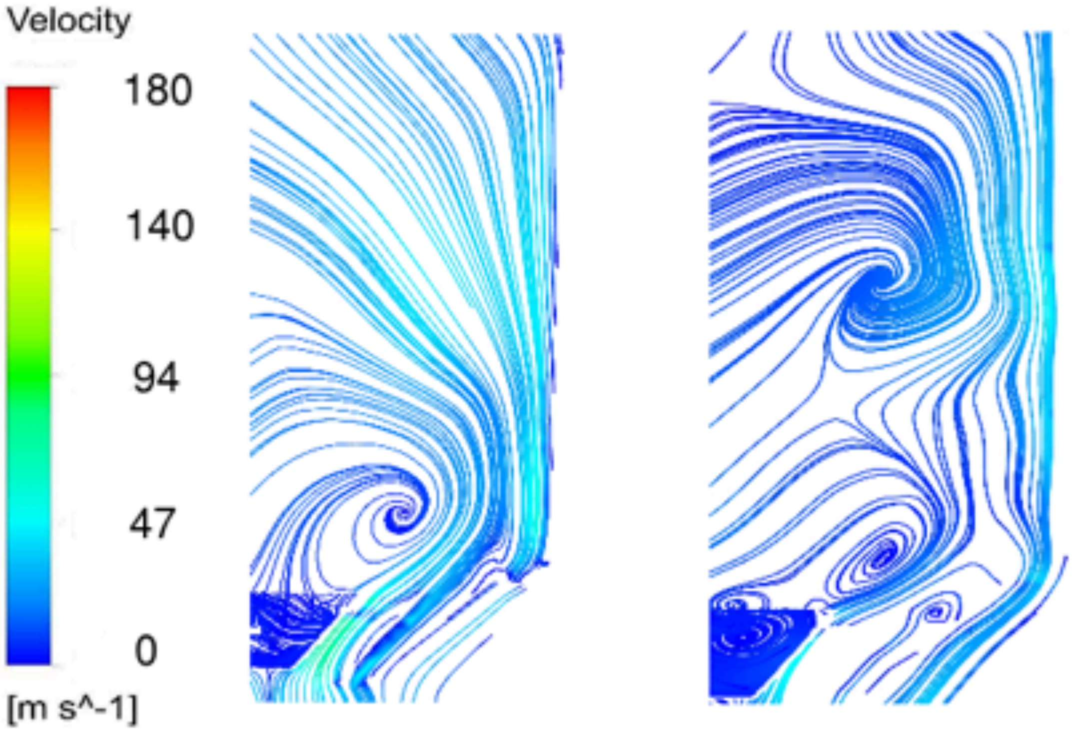
It is also seen that in the zone of the stabilizing cone there is a circulation current, which depends on the size and strength of the main recirculation zone.

Figure 7

Flow recirculation contours



Inner/outer=30/25 Inner/outer=45/30 Inner/outer=60/45



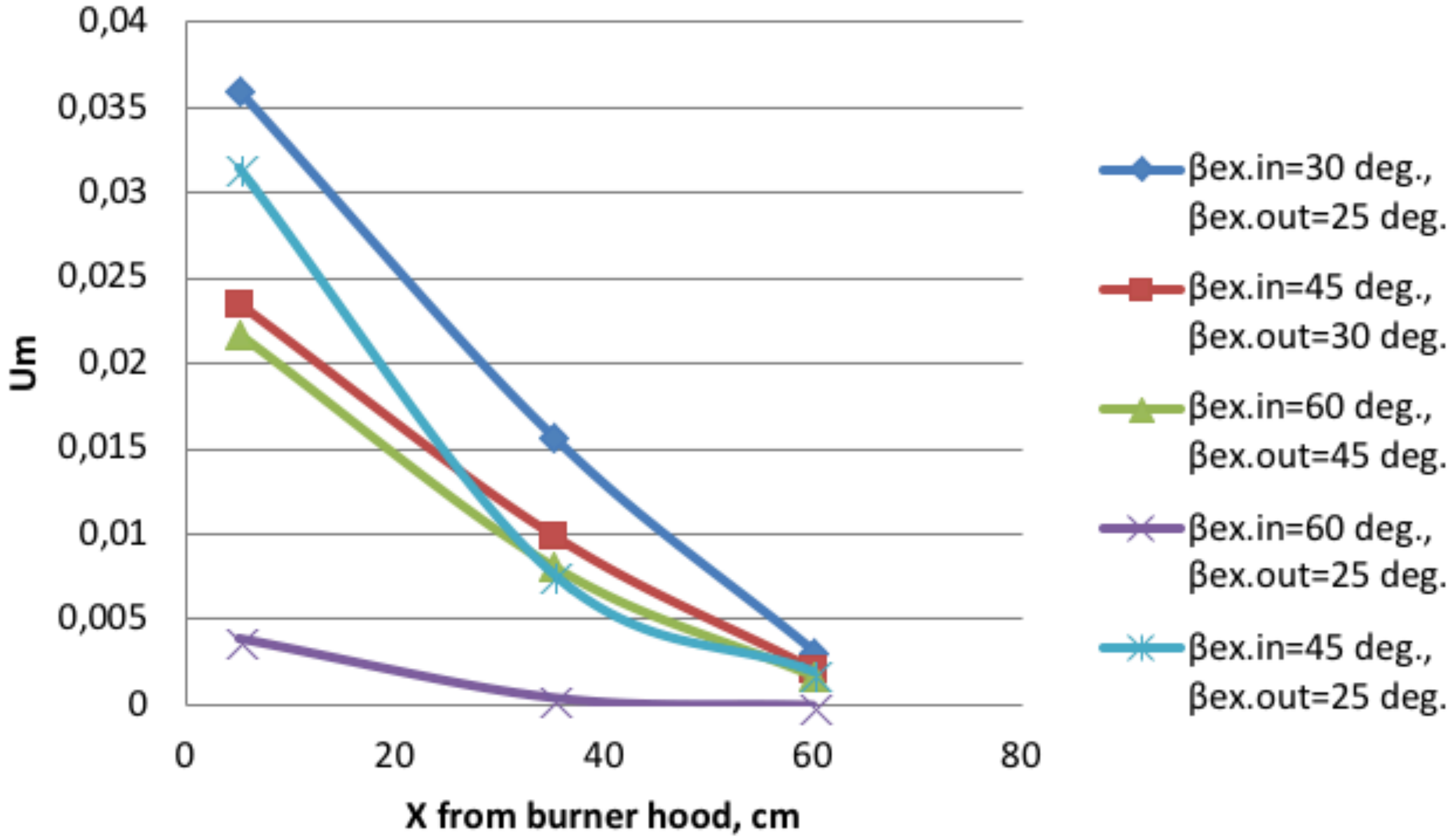
Inner/outer=60/25 Inner/outer=45/25

The coefficient of unmixedness was presented in the article (Fernando and Felic, 2007). The authors modified this equation, which is based not on temporal parameters, but on the parameters of the investigated sites. The equation is represented in the form (lvl 1):

$$U_m = \frac{(f\text{-}f_{aver})^2}{f_{aver}(1 - f_{aver})} \qquad (1)$$

According to Eq. 1, the smaller the value of U_m, the higher the mixing level. The results of calculating the coefficient of unmixedness are shown in Figure 8. It can be seen that the maximum mixing is achieved at the installation angles $\beta_{ex.in}=60^0$, $\beta_{ex.out}=45^0$. A good level of mixing is also achieved at the angles $\beta_{ex.in}=45^0$, $\beta_{ex.out}=30^0$. The minimum value of the coefficient of unmixedness was obtained at $\beta_{ex.in}=60^0$, $\beta_{ex.out}=25^0$.

Figure 8
Indicator of modified unmixedness at the burner axis



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4. Conclusions

The experimental studies of a two-stage burner in the combustion chamber of the transport GTE confirmed the possibility of achieving high combustion efficiency η_{fuel}, a low degree of unevenness of the temperature field and a decrease in NOx emissions.

The high main combustion chambers are reached at the stagger angles of the outlet swirlers $\beta_{ex.in}=45^0 \div 60^0$, $\beta_{ex.out}=25^0 \div 30^0$ and the excess air factors in the nozzle tier at the design mode $\alpha_{ex.in}=1.05 \div 1.55$, $\alpha_{ex.out}=1.5 \div 2.05$. Temperatures at the exit of the burner were measured and the approximate dependence of the degree of unevenness of the temperature field at the exit of the combustion chamber was obtained.

A numerical simulation of the flow in a two-stage burner is carried out. The contours of recirculation zones and the calculation of the coefficient of unmixedness are presented. The findings of the numerical simulation correspond to the obtained experimental data.

For the optimal version of the "air" nozzle in the calculated mode, the following indicators were obtained:

- combustion efficiency η_{fuel} =0,98-0,995;
- wall temperature Tw=320 ^{0}C;
- degree of irregularity of the temperature field θ=6.5%;
- NOx concentration $C_{NOx}<20$ ppm.

The numerical simulation has shown that blade profiles can be used as output swirlers, which will ensure low hydraulic losses and NOx emissions. In particular, in order to provide improved performance for off-design modes, the thickness of the trailing edge of profiles can be made adjustable.

Nomenclature

$\alpha_{ex.in.}$	Excess air factor in the inner tier of the burner
$\alpha_{ex.out}$	Excess air factor in the outer tier of the burner
α_{Σ}	Total excess air factor of two tiers
$\beta_{ex.in}$	Stagger angle of the inner tier
$\beta_{ex.out}$	Stagger angle of the outer tier
$\Delta\ \beta_{ex.}$	$\beta_{ex.in}-\beta_{ex.out}$
η_{fuel}	Fuel combustion efficiency
m	Air excess ratio of inner and outer tiers, $\alpha_{ex.in.}/\alpha_{ex.out.}$
T^*_{gmax}	Local maximum gas temperature
T^*_{max}	Average assumed gas temperature
T^*_{in}	Air temperature at combustor inlet
$L_{f.t.}$	Flame tube length
$D_{f.t.}$	Flame tube diameter
$\Delta P_{f.t.}$	Pressure differential across a flame tube wall
q	Typical velocity head

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