Bulgarian Chemical Communications, Volume 52, Special Issue C (pp. 12-19) 2020 DOI: 10.34049/bcc.52.C.0018

Numerical investigation of combustion process behind bluff bodies during separation

A. M. Dostiyarov[1], D. R. Umyshev[2*], Zh. S. Duissenbek[1], I. K. Iliev[3], H. I. Beloev[3], S. Ph. Ozhikenova[1]

[1]*Almaty University of Power Engineering and Telecommunications, Almaty, Kazakhstan*
[2*]*Kazakh National Research Technical University, 22a Satpaev str, Almaty, Kazakhstan*
[3]*University of Ruse, Department of Thermotechnics, Hydraulics and Environmental Engineering 7017 Ruse, 8 Studentska Str., Bulgaria*

The article presents the results of numerical simulation of combustion process methane mixture from the group of corner stabilizers, and the corners arranged in two rows, in first row three area, two in the second area. The influence of the distance between the rows of corners on the formation of toxic substances and the formation of swirling currents was studied. The study showed that from the point of view of reducing nitrogen oxides, the optimal distance is 120 mm. The results of modeling the emission of nitrogen oxides showed that the highest concentrations of nitrogen oxides are formed at a distance of 140 mm and a fuel consumption of 0.1 kg/s. for the variants L=80 mm, L=120 mm, L=140 mm, the oxide concentrations at a flow rate of 0.1 kg/s were equal to 10, 60, 109 ppm respectively.

Keywords: v-gutter flameholders, mixing efficiency, recirculation zone, combustion efficiency

INTRODUCTION

In the combustion chamber and the afterburning chambers of gas turbine engines (GTE) of fuel combustion mainly occurs in turbulent trace behind poor-streamlined body stabilizers flame. The process of turbulent combustion depends on the physic-chemical and hydrodynamic parameters of the flow of hot mixture. The influence of these factors, at least, qualitatively manifests itself in the same way as in the case of combustion in a stream with homogeneous and isotropic turbulence, and when burning in a direct-flow combustion chamber.

Specific features of combustion in the trace of poor-streamlined bodies are as follows. As the measurements showed, the turbulence intensity in the isothermal flow changes dramatically along the length of the stabilizer and in the cross sections of the track, reaching 30% or more on the axis near the stabilizer and decreasing to the intensity of turbulence in the incoming flow as it moves away from the stabilizer and at the borders of the track.

In combustion chambers of jet engines and afterburner chambers of gas turbine engines, the combustion process takes place over lattice (group) stabilizers. In this case, the size and configuration of the flares behind each stabilizer depends on the number of stabilizers and their relative positions in the combustion chamber. When the stabilizers are evenly positioned in the same plane (when the distance S between the edges of adjacent stabilizers is the same, and the distance between the wall and the edge of the adjacent stabilizer is S/2), the torch axes are parallel to the pipe axis and the torches have the same measures behind each stabilizer of the same size and geometric shape.

The study of combustion processes for bluff bodies devoted quite a lot of work. For example, in [1, 2], the influence of installing bluff bodies in a niche on the completeness of hydrogen fuel combustion is considered. The results showed that a bluff body is an anchor for the torch, thereby increasing the completeness of combustion. In [3], methods for measuring the combustion of fuel behind bluff bodies were investigated. Famous works [5, 6] for the study of hydrogen combustion for different types of poor-streamlined bodies. The results showed that the application increased the poor breakdown limit by 2.4 times when using a pyramidal body. Study of the process of detonation gas using [7] showed that poor-streamlined body is the source of the increase in the rate of combustion. Studies are being conducted on the effect of bluff bodies on the flow of liquid in separators [8]. Study of the effect of poor-streamlined bodies on the border of poor failures [9-11, 14] showed that poor-streamlined ones largely significantly expand the boundaries of stable combustion.

The analysis of modern methods and structures of the recirculation zones makes it possible to analyze and put the basic requirements for them. According to [15, 16], modern combustion chambers of gas turbines must meet the following

* To whom all correspondence should be sent:
umishev_d@mail.ru

criteria:

• high coefficient of completeness of fuel combustion; modern combustion chambers should have $\eta c = 98 \div 99\%$;

• small hydraulic pressure losses;

• high heat intensity of the working volume;

• small temperature non-uniformity of temperatures at the outlet of the compressor station, to ensure reliable operation of the turbine;

• fast and reliable start. Stable operation over the entire load range;

• durability of structures, high reliability;

• absence of smoke, carbon deposits and toxic substances.

The analysis of different methods and principles of burning microflare devices showed the features of microflame burning, which can be as close as possible to the requirements for the combustion chambers presented above. Microflare burning is a type of zone combustion [27].

An analysis of the main causes of the formation of nitrogen oxides in various devices and the prospects for the development of energy showed that traditional methods of burning fuel do not provide the required parameters. Improving the efficiency of fuel combustion can be obtained by using microflare burning [28].

Despite the limited amount of experimental data on the use of microflare burning in combustion chambers, various authors [1-10] noted the following positive qualities of this method: low pressure losses of gas, reduced structural dimensions, reduced unevenness of the temperature field at the outlet of the combustion chambers, low yield of nitrogen oxides with products combustion, reduced radiation loss [26-27].

Still known from the mid-twentieth century [16], microflare burning technology began to attract the attention of scientists relatively recently. Currently, there are several main directions of microflare burning, but all have one thing in common - this is the “spreading" of the torch along the front and volume of combustion [17].

According to [18], reduction of NOx emissions can be achieved by conducting a combustion process with an excess of primary air $\alpha I > 1.6\ 1.8$, while ensuring intensification of mixture formation in the front of the combustion chambers. The fulfillment of such requirements makes it possible to reduce the local maximum temperatures in the combustion zone and bring them closer to the average flame temperature and significantly reduce the burnup time of the fuel.

Such principles were implemented on gas turbine units GT-25-700-II, GT-700-12M, GT-50-800. The studies were carried out both with the original combustion chambers and with the modified ones, which makes it possible to visually see the results.

Alstom combustion chambers are known that use multi-burner devices. The company uses burners under the brand name EV and AEV. Emissions of gas turbine NOx using these burners do not exceed 15 ppm. If in the gas turbine engine ABB GT10 (23 MW) there were only 18 burners, then ABB GT13E (> 150 MW) has 72 burners installed in two circular rows.

General Electric LM6000 is a known gas turbine burner. The combustion chambers produced by this company is made in the form of two rings. In the outer two rings there are 60 nozzles, in the inner ring 15. This arrangement of the rings facilitates operation under partial load. 75 nozzles are connected by 30 stems with pre-mixing devices. LM6000-PD turbines have NOx emissions close to 25 ppm, at a power of 50 MW.

Widely known is the DLE technology. In the DLE system, a “premixed lean mixture” of fuel and air is burned, which produces little NOx and CO. In the system of “pre-mixing the lean mixture”, the formation of CO remains relatively low until approaching the conditions of flame failure due to the “lean” mixture. In this system, NOx and CO concentrations are controlled by maintaining the gas-to-air ratio and flame temperature in a narrow range where stable combustion is maintained at low emission levels.

Interesting NASA work on the study of multi-burner devices is presented in [19]. Conventionally, the 120-modular annular combustion chambers designed for Pratt-Whitney engines can conditionally be classified as microflare. Each module consists of a mixer, swirl and stabilizer. Tests of this combustion chamber showed that the small length of flares provided by a sufficiently high degree of preliminary and secondary mixing reduces the formation of nitrogen oxides. When testing the chamber, the NOx concentration was two times lower than conventional chambers.

At the Kiev Polytechnic Institute on the proposal of V.A. Khristich created the original design of a gas burner with separate gas and air supply, which ensures high intensity of the processes of mixture formation and combustion and has the property of self-regulation of the composition of the burning mixture with variable excesses of air [19-24].

The peculiarity of such a burner is that it, with a separate supply of gas and air, provides the same short and transparent torch as the preliminary burners.

Front-end devices operating on the principle of a "perforated front" have one significant drawback - perforations of the front-end device lead to an increase in pressure loss. There are also a number of questions about front cooling and the use of expensive heat-resistant materials and metals.

A known method of burning fuels in the fuel-air mixture, which applied the principle of perforated front [24]. The authors propose using a bulk matrix in the combustion chambers, but mix fuel assemblies in relative proportions before it.

At the exit from the matrix, a flame is maintained in the surface combustion mode with a laminar flow of fuel assemblies and at temperatures in the range of 1200–1500 K. The front-mounted device itself consists of a housing with a fuel supply system and an outlet for combustion products. Inside the combustion chambers case there is a matrix made of heat-resistant material permeable to fuel assemblies. The volumetric matrix is made with cavities that are connected to the outlet for the output of combustion products. This design is aimed at lowering the combustion temperature, as well as at reducing temperature unevenness at the outlet of the compressor station.

The relative low temperature of the flame burning near the matrix allows one to reduce the formation of a significant part of thermal nitrogen, as well as solve the problem of cooling. The design of the chamber itself is also simplified due to the absence of a flame tube and a cooling and dilution system. The decrease in metal consumption leads to an increase in the service life of the structure.

Another closest analogue to the "perforated front" can be a multi-chamber tube-type gas burner [25]. The tubular type gas burner consists of an outer and inner case, which are isolated from each other, nozzles for supplying gas and air. Also, gas burners consists air and gas chambers, end inner and outer walls, between which there are air tubes with gas holes on the side walls, the last of which made in the form of a distribution plate with holes for supplying gas.

There are known developments of multi-burner front devices for combustion chambers of gas turbines [25-26] which contain a front conical wall in which there is a burner section consisting of a central conical sleeve and a peripheral honeycomb frame, which are connected to the ends of the holes on the front conical wall, and seven burners, one of which is mounted in the central conical sleeve, and the rest, consisting of a gas pipe, two flat perforated walls, air tubes and end plates between them, are installed in the honeycombs of the frame. The use of this burner improves the reliability and simplification of the manufacturing technology of the front-end compressor unit, reduces the emission of toxic nitrogen oxides (NO_x) and carbon monoxide (CO), ensures high efficiency of the compressor unit in a gas turbine in a wide range of oxidant excess changes.

This front-mounted device allows you to work in a wide range of changes in the excess of oxidizing agent, and provides a minimum level of thermal shocks when starting a gas turbine, a homogeneous aerodynamic and thermal structure of the duct at the entrance to the turbine blade apparatus, and minimal aerodynamic and thermal resistance of a gas turbine compressor unit.

The operation of the front-end device based on turbine profiles is as follows. The air flow in cooperation with a system of fan-shaped fuel jets formed by the atomizer is supplied to the combustion zone together with the fuel, resulting in a well-mixed combustible mixture. Drops of fuel, in contact with the hot walls of the pipe, evaporate and enter the internal cavities of the profiled blades of the register in a mixture with air [6].

Analyzing in general the results of an experimental study of the combustion process behind a system of profiles, it should be noted that the operating conditions of the profile grating in some cases turned out to be close to the operating conditions of a real combustion chambers transport gas turbine engine, primarily in terms of temperature and speed conditions of the incoming air. In addition, a number of the most developed profile options demonstrated reliable operation in a wide range of changes in the coefficient of excess air -1.5 ÷ 25 and higher [23].

The material of the blades used in the microflames is a heat-resistant high-alloy alloy. Naturally, the choice of material for microflame blades for fuel combustion should be determined.

Numerical methods are known for studying various bluff bodies [31-33]. In [31-33], a numerical simulation of the combustion of hydrogen and traditional fuel behind corner stabilizers and other non-streamlined ones was carried out. Studies have shown that they are optimal from the point of view of flame stabilization, and also that numerical simulation can effectively simulate combustion processes behind them.

In previous works of the authors, the following have been studied:

• angle of v-gutters [27];
• length of v-gutter walls [28];
• presence of wall perforations [29];
• fuel supply method [29].

At present, power units with HRSG installations with fuel afterburning are rapidly developing. Accodring to [19, 20]. For this, v-gutter flameholders are the most optimal. However, to date, no studies have been conducted on the effect of different locations of v-gutter, in particular, separation (echeloning) [12]. Based on this, the authors conducted studies of the effect of separation on the formation of toxic substances.

GENERAL DATA ABOUT THE MODELING PROCESS

Fig.1 shows General views of the simulated v-gutter stabilizers.

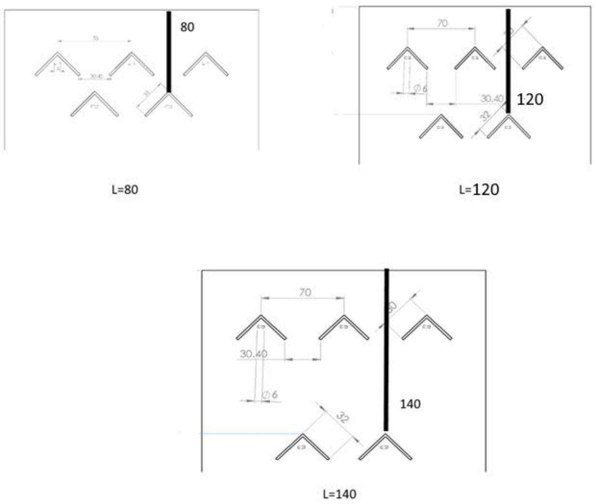

Fig.1. Options for installing v-gutter stabilizers

Tab.1 shows the initial modeling conditions. In the simulation, the airflow was constant and equal to 10 m/s.

Table 1. Iinitial modeling conditions

Airflow through the nozzles	Air speed (taken according to the experi-mental setup)	Initial temperature of the oxidizer (air)/fuel,	Number of elements in the simulated area
kg/h	m/s	K	-
36	10	300	1 135 456

Fig.2 shows a simulated area consisting of an air source 1, corner stabilizers 2 with a fuel distribution system-nozzles 3, and an output area 4.

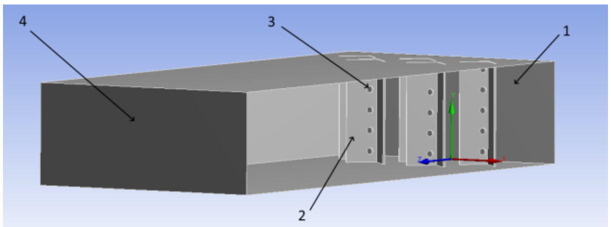

Fig.2. Isometric view of the modeling area.

Fig.3 shows a model grid in which the top part is made with a large number of elements compared to the rest of the parts. This is due to the fact that the flow and reactions have a strict z-axis orientation.

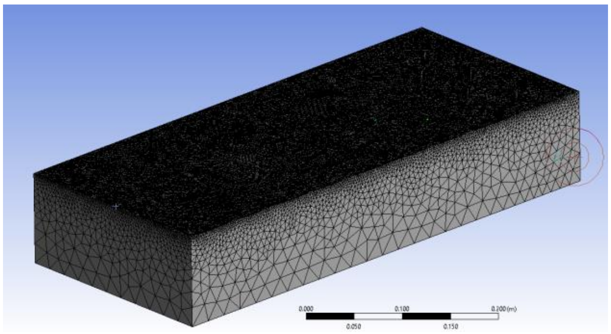

Fig.3. Mesh of the model

The simulation used the k-ε realizable turbulence model, which according to [12] is the most optimal solution. The grid consisted of 1,135,456 elements. Elements with dimensions of 7 mm were used for the mesh. The main part of the grid was on a plane parallel to the combustion process. Fuel was supplied through holes 3, through a flat wall.

The mathematical model developed in [30] was used to validate the experimental results, presented as follows

Continuity equation:

$$\frac{\partial p}{\partial t} + \frac{\partial (pu_i)}{\partial x_i} = 0$$

Momentum equation:

$$\frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial(p)}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}$$

Energy equation:

$$\frac{\partial(\rho u_i h)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\lambda_f \frac{\partial T}{\partial x_i}\right) + \sum_j \left[\frac{\partial}{x_i}(D_{j,m}\rho h_j \frac{\partial Y_j}{\partial x_j})\right] + q$$

Where h the total enthalpy of mixture gas is, h_i is the enthalpy of component j^{th} , λ_f is the thermal conductivity of the fluid, and q is heat of reaction.

State of ideal gas:

$$p = \rho RT \sum_{s=1}^{Ng} \frac{Y_s}{M_s}$$

Model validation

To check the validity of the simulation, the authors compared the results obtained with previous works [27-29] in which this model was used. The model was validated in the following way: for the current model used in this study, v-gutter flamehoderls were placed as in the article [29]. The comparison results are shown in Tab.2. The difference between model and experimental results are 6%, which we consider as sufficient.

Table 2. Model validation

Experimental results [29]	Numerical results results [29]	Numerical results results (current)
Outlet temperature, T_{out}, K	Outlet temperature, T_{out}, K	Outlet temperature, T_{out}, K
783	723	735

RESULTS AND DISCUSSION

The temperature contours. Fig.4 shows temperature contours for different fuel consumption.

As can be seen from the figure, the combustion starts in the region between the v-gutter stabilizers. Moreover, the reduced fuel consumption leads to more complete combustion due to the optimum ratio of fuel/air in the combustion zone. Despite the fact that burning is taking place in the area of maximum turbulence between the v-gutter fins, the maximum temperature achieved in the tail of the torch, it features significantly in the fuel consumption of 0.03 kg/s.

The minimum distance between the v-gutters of 80 mm, provides a uniform flame, due to the" throwing " of the torch to the nearest. In other options, especially at L=140 mm, it is noticeable that combustion occurs independently, and the reverse part of the area is subjected to thermal stress from the hot gases burning in the corners of the first row.

With a significant increase in fuel consumption, it is noticeable that the flame does not burn up, due to the high concentration of fuel and high flow rate from the fuel distribution nozzles. This is obviously undesirable, in view of the large underburning of fuel and according its much more consumption.

It is also noticeable that in the inner part of the area the temperature is not so high, compared to the tailed part, however with increasing distance the combustion starts in the region between the corners, that on the one hand indicates a high completeness of combustion gases, because gases will burn in the zone of recirculation, on the other hand, it imposes certain requirements to heat resistance of materials from which to make the corners.

If to consider the scheme of the combustion chamber, inside of which is installed in the same plane stabilizers of the same shape and size, it will become apparent that regardless of the diameter of the chamber and the number of installed stabilizers in it, the whole process of fuel combustion is essentially determined only by the laws of burnout in the plane of symmetry between two adjacent fins and between the wall and the adjacent stabilizer. Therefore, the two stabilizers can be considered as the main element of the combustion chamber and the combustion between these stabilizers can be extended to the combustion chamber of any size with any number of stabilizers.

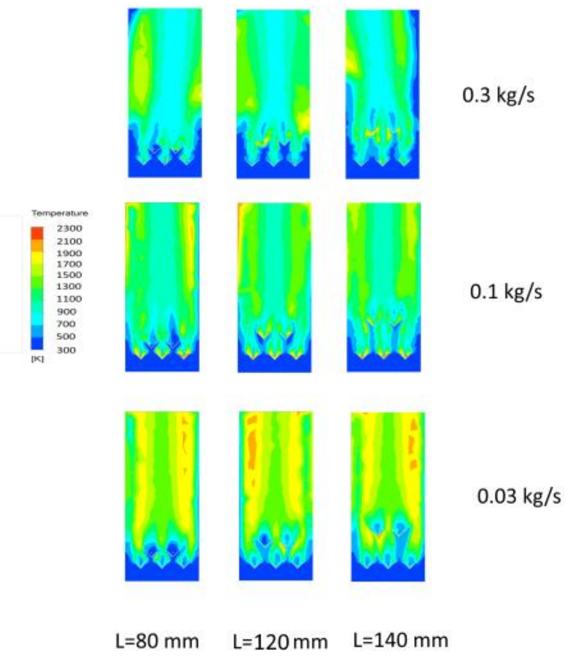

Fig.4. Temperature Contours at different distances

The swirling flow in Fig.5 shows the contours of swirling currents depending on the distance and fuel consumption. As can be seen from the figure, an increase in fuel consumption leads to significant swirls around the corner stabilizers. However, taking into account the NO_x and temperature dependencies (Figs.6, 7), we can say that despite the high swirling flows, the concentration of nitrogen oxides is small due to the large underburning of the fuel, which occurs due to insufficient mixing of the fuel with air.

The highest concentrations of nitrogen oxides are observed at a fuel consumption of 0.03 kg/s, which is explained by the fuel / air ratio close to stoichiometric. It is known that the formation of nitrogen oxides is mainly influenced by the temperature in the combustion zone, the efficiency of mixing fuel with air and the residence time of gases in the zone of high temperatures. Given that most of the time spent gases have on the fuel consumption of 0.3 kg/s, then we can conclude that the most influential factor is the temperature in the combustion zone. And as you know, it is the maximum in the stoichiometric ratio of fuel/air.

The mutual influence of flares affects not only that the conditions of thermal expansion change and their shape is deformed by the flow, but also that the turbulent characteristics of the flow along the length and cross sections of the combustion chamber change. Obviously, the smaller the distance between the stabilizers, the same length will be above the common level of intensity of turbulence in the gap between the stabilizers and the higher bodyscroll combustion of the fuel in this interval. During combustion behind a grid of stabilizers increases the flow rate gradients along the cross sections of the pipe, which cause additional turbulence of the flow, and this also leads to an increase in the combustion rate.

Suggested, of course, true only in the case that the combustion in the interval between the two adjacent stabilizers do not depend on the total number of stabilizers installed in the camera, or the mutual influence they are small and can be ignored. The characteristic change in the intensity of turbulence of each stabilizer with the maximum intensity on the track axis seems to create two barriers that prevent the penetration of speed pulsations generated behind other stabilizers into the space between the two adjacent stabilizers under consideration and, therefore, the influence of other stabilizers in this respect should be negligible.

But an increase in the number of stabilizers will lead to an increase in heat generation and at the same air flow rate the average flow rate along the length of the combustion chamber will increase; in addition, the thermal expansion conditions will change.

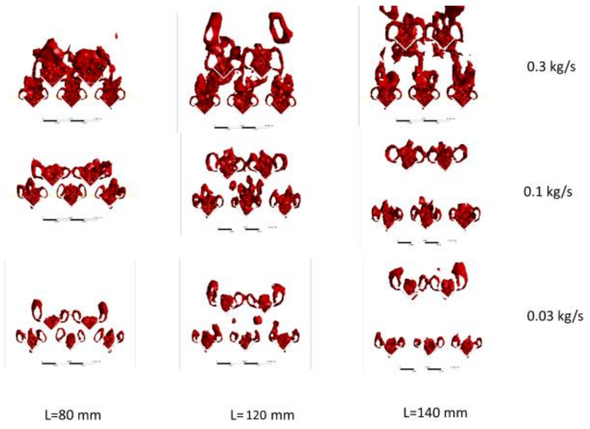

Fig.5. Spin of the flow depending on the distance and fuel consumption

NOX CONCENTRATIONS AND TEMPERATURES

Fig.6 shows the dependence of the concentration of nitrogen oxides on fuel consumption at different distances. As can be seen from the figure, the maximum concentrations are reached at a fuel consumption of 0.03 kg/s, as already noted above, since the fuel/air ratio is close to the stoichiometric one. The minimum concentrations are reached at a fuel consumption of 0.3 kg/s, due to the large amount of underburning fuel [13].

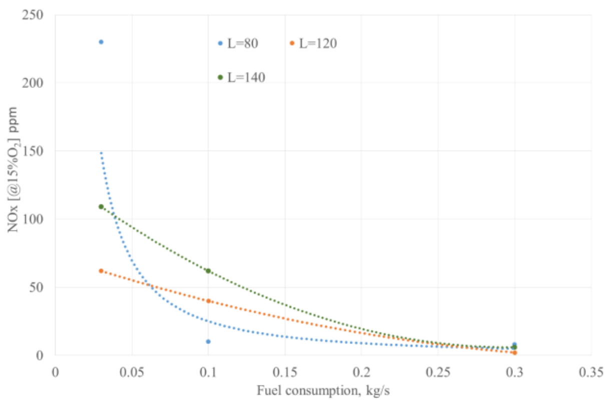

Fig.6. Concentrations of nitrogen oxides at the exit from the simulation zone

Fig.7 shows the dependence of the temperature at the output section of the simulation area on the fuel consumption and the distance between the corners. The temperature data corresponds to the nitrogen oxide data, and the maximum temperature corresponds to the minimum fuel consumption.

As can be seen from the figure, the temperature levels are approximately equal, but there is a significant difference in nitrogen oxides, this is due to the time spent by high-temperature gases in the combustion zone.

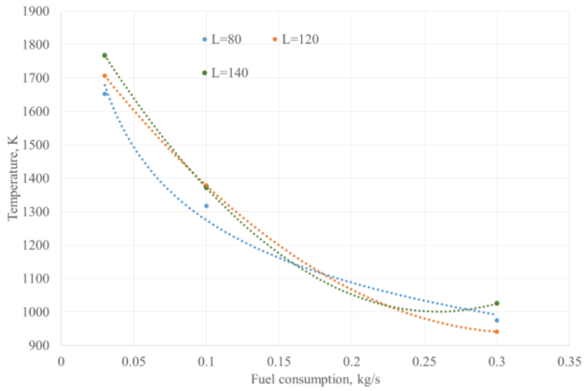

Fig.7. Temperature of exhaust gases at the exit from the simulation zone

CONCLUSIONS

The study shows that the angle of the v-gutter stabilizers are an effective way of stabilizing the combustion at relatively low concentrations of harmful substances. From the simulation, we can conclude that from the point of view of harmful substances and flame stabilization, it is best to use rows of corners with a distance of 100 mm. The highest concentrations of nitrogen oxides are formed at a distance of 140 mm and a fuel consumption of 0.1 kg/s. For variants L=80 mm, L=120 mm, and L=140 mm, the oxide concentrations at a flow rate of 0.1 kg/s were equal to 10, 60, and 109 ppm respectively.

REFERENCES

[1] Zheng Zhang, Kun Wu, Richard Yuen, Wei Yao, Jian Wang. Numerical investigation on the performance of bluff body augmented micro cavity-combustor. *International Journal of Hydrogen Energy*, (2020), in press.

[2] Zheng Zhang, Kun Wu, Wei Yao, Richard Yuen, Jian Wang. Enhancement of combustion performance in a microchannel: Synergistic effects of bluff-body and cavity. *Fuel*, **265** (2020)

[3] Jianfeng Pan, Chenxin Zhang, Zhenhua Pan, Di Wu, Yuejin Zhu, Qingbo Lu, Yi Zhang. Investigation on the effect of bluff body ball on the combustion characteristics for methane/oxygen in micro combustor. *Energy*, **190** (2020)

[4] Yunfei Yan, Ziqiang He, Qingyun Xu, Li Zhang, Lixian Li, Zhongqing Yang, Jingyu Ran. Numerical study on premixed hydrogen/air combustion characteristics in micro–combustor with slits on both sides of the bluff body. *International Journal of Hydrogen Energy*, **44** (**3)**, 1998-2012 (2019).

[5] Yunfei Yan, Hongyu Yan, Li Zhang, Lixian Li, Junchen Zhu, Zhien Zhang. Numerical investigation on combustion characteristics of methane/air in a micro-combustor with a regular triangular pyramid bluff body. *International Journal of Hydrogen Energy*, Volume **43**, (15), 7581-7590 (2018).

[6] Lu-Qing Wang, Hong-Hao Ma, Zhao-Wu Shen, Jun Pan. Effects of bluff bodies on the propagation behaviours of gaseous detonation. *Combustion and Flame*, **201**, 118-128 (2019).

[7] Nabil Kharoua, Lyes Khezzar, Mohamed Alshehhi. The interaction of confined swirling flow with a conical bluff body: Numerical simulation. *Chemical Engineering Research and Design*, **136,** 207-218 (2018).

[8] Anthony J. Morales, Ian M. Lasky, Marissa K. Geikie, Christian A. Engelmann, Kareem A. Ahmed,Mechanisms of flame extinction and lean blowout of bluff body stabilized flames. *Combustion and Flame*, Volume **203**, 31-45 (2019).

[9] Juntian Niu, Jingyu Ran, Liya Li, Xuesen Du, Ruirui Wang, Mingchu Ran. Effects of trapezoidal bluff bodies on blow out limit of methane/air combustion in a micro-channel. *Applied Thermal Engineering*, **95**, 454-461 (2016).

[10] Harun Yilmaz. Investigation of combustion and emission performance of a micro combustor: Effects of bluff body insertion and oxygen enriched combustion conditions. *International Journal of Hydrogen Energy*, **44 (**47), 25985-25999 (2019).

[11] S.V. Tsanev, V.D. Burov, A.N. Remezov. Gas-turbine and combined-cycle plants of thermal power plants. - M.: Publishing House of MPEI, (2002) (in Russian)

[12] ANSYS FLUENT 12.0 Theory Guide: «ANSYS» http://ansys.com (2009).

[13] B. Ongar, I. K. Iliev, V. Nikolić and A. Milašinović. The study and the mechanism of nitrogen oxides' formation in combustion of fossil fuels. *Facta Universitatis, Series: Mechanical Engineering* **16 (**2), 273–283 (2018).

[14] Pchelkin Yu.M. Combustion chambers of gas turbine engines, Engineering Publishing House, 1984, (in Russian).

[15] A. M. Dostiyarov, A.G. Userov, T.B. Maysutov. Analysis of studies on emissions of toxic components of gas compressor units of type GTK-10-4 under operating conditions at the Makat compressor station at Atyrau UMG. *International Scientific and Practical Conference Energy, Telecommunications and Higher Education in Modern Conditions*, Almaty (2006).

[16] A. G. Tumanovsky. Some ways to reduce the concentration of nitrogen oxides in the combustion chambers of gas turbines. *Thermal Engineering*, **6,** 30-33 (1973).

[17] L. B. Davis, S. H. Black. GE Power Systems Schenectady, *General Electric Development Brochure. GER-3568G. New York; USA* (2008).

[18] A. S. Isserlin, Gas-burners, Nedra Publishing House, 1966.

[19] V. A. Khristich. About ways to reduce NOx emissions during the combustion of fuels with high and variable excess air, in: The formation of nitrogen oxides in combustion processes and ways to reduce their emission into the atmosphere, Naukova Dumka Publishing house, 33-37 (1979).

[20] V. A. Khristich, G. N. Lyubchik, L. S. Butovsky. On the discharge characteristics of the recirculation zone behind the corner stabilizer, *Bulletin of the KPI, ser. Heat power engineering* **8**, 27-30 (1971).

[21] P. M. Canilo. Numerical modeling of the formation of toxic substances in a gas turbine combustion chamber. *Institute of Mechanical Engineering of the Academy of Sciences of the Ukrainian SSR* **194**, 43 (1984).

[22] A. G. Tumanovsky, A. V. Sudarev, V. A. Mayev. Combustion of liquid fuel in counter-swirling jets of the GTU annular combustion chamber. *Thermal Engineering* **3**, 37-42, (1986).

[23] A. G. Tumanovsky, M. N. Gutnik, K. Yu. Sokolov. Reducing emissions of carbon monoxide and hydrocarbons at starting and variable modes of energy gas turbines when burning liquid and gaseous fuels. *Electric stations* **6**, 2-6, (1991).

[24] A. G. Tumanovsky, M. N. Gutnik, K. Yu. Sokolov. Low-toxic combustion chambers for energy gas turbines. *Thermal Engineering* **3**, 48-52 (1997).

[25] A. V. Sudarev. Development, research of optimal ways to intensify the working process and their implementation in the design of combustion chambers of stationary gas turbines. Doctoral thesis, USSR: MTU, 1980.

[26] M. M. Brevdo, Yu. I. Zakharov, V. A. Maev, A. M. Ponkratov, A. V. Sudarev. Operation results of microtorch annular combustion chambers of gas turbine units with a capacity of 25 MW at compressor stations of gas pipelines *Abstracts of the All-Union Scientific Conference, Moscow*, (1987).

[27] D. R. Umyshev, A. M. Dostiyarov, M. E. Tumanov, Qiuwang Wang. Experimental investigation of v-gutter flameholders. *Thermal science*, **21,** 1011-1019 (2017).

[28] D. R. Umyshev, A. M. Dostiyarov, G. M. Tuytebayeva. Experimental investigation of the management of NOx emissions and their dependence on different types of fuel supply. *Espacios*, **38,** 17 (2017).

[29] D. R. Umyshev, A. M. Dostiyarov, G. M. Tyutebayeva, A. K. Yamanbekova, B. T. Bakhtyar, Jordan Hristov. Effects of different fuel supply types on flame stabilization and nox emissions behind group of v-gutter flame holders: experimental and numerical study. *Thermal science*, **24,** 1A, 379-391 (2020).

[30] Bikram, R. et al.. Effects of Free Stream Flow Turbulence on Blow-Off Characteristics of Bluff-Body Stabilized Premixed Flames. *Combustion and Flame*, **190**, 302-316 (2018).

[31] Linhong Li, Aiwu Fan. A numerical study on non-premixed H2/air flame stability in a micro-combustor with a slotted bluff-body. *International Journal of Hydrogen Energy*, In press, 2020.

[32] Fulei Xu, Yunfei Yan, Ziqiang He, Zhongqing Yang, Li Zhang. Numerical study on the influence of controllable flow ratio on combustion characteristics of a controllable central slotted bluff body and cavity combined micro combustor. *International Journal of Hydrogen Energy*, In press, (2020).

[33] Sudhir Chandra Murmu, Suvanjan Bhattacharyya, Himadri Chattopadhyay, Ranjib Biswas. Analysis of heat transfer around bluff bodies with variable inlet turbulent intensity: A numerical simulation. *International Communications in Heat and Mass Transfer*, **117**, 104779, (2020).