EFFECTS OF DIFFERENT FUEL SUPPLY TYPES ON COMBUSTION CHARACTERISTICS BEHIND GROUP OF V-GUTTER FLAME HOLDERS: Experimental and Numerical Study

by

Dias R. UMYSHEV[a*], Abay M. DOSTIYAROV[b], Zhansaya S. DUISENBEK[b], Galya M. TYUTEBAYEVA[c], Ayaulym K. YAMANBEKOVA[b], Balzhan T. BAKHTYAR[b], and Jordan HRISTOV[d]

[a] Satbayev Univeristy, Almaty, Kazakhstan
[b]Almaty University of Power Engineering and Telecommunications, Almaty, Kazakhstan
[c] S. Seifullin Kazakh AgroTechnical University, Astana, Kazakhstan
[d] Department of Chemical Engineering,
University of Chemical Technology and Metallurgy, Sofia, Bulgaria

Original scientific paper
https://doi.org/10.2298/TSCI191115471U

Experiments on fuel effects flame stabilization processes, NO_x generation and temperature at combustion chamber outlet when using a group of three V-gutter flame holders have been reported. Fuel supply directly to the re-circulation zone on the inside of the V-gutter (type A fuel supply), and alternatively in the second type, fuel was supplied to the V-gutter symmetry axis on the outside (type B fuel supply have been carried out.

Key words: *combustion, flame stabilization, bluff body, blow-off, V-gutters, NO_x*

Introduction

State-of-the-art: a brief overview

Technical and economic analyzes worldwide reveal that gas turbine based power-plant units serve as time-peak reserves, intermediate-load-range, as well as standby, and mobile energy sources [1]. Moreover, under certain circumstances such units could be considered as power supplies improving the maintenance of basic units of power systems with effects on their economic efficiencies and reliabilities [1]. During the recent decades intensive developments of both power generation and gas transport (especially fleet and pipeline transport) have been carried out [1].

An important element of gas turbine units is the combustion chamber where which chemically bonded fuel energy converts into heat energy parallel with a considerable amount of harmful substances emitted into the environment with the flue gases. The most hazardous substances are considered to be nitrogen and sulphur oxides [1].

The main scientific and technical challenges address the increases in the operating efficiencies of the gas turbine bases combustion devices inasmuch as decreasing the harmful emissions is a principle task in the new century. Considering technical and economic perspectives it is acceptable to use bluff bodies or their combinations [2-21]. In this context, a considerable advantage of burners based on bluff bodies is that they can operate with various kinds of

* Corresponding author, e-mail: umishev_d@mail.ru, udiazzz@gmail.com

fuels in a broad range of densities and viscosities such as heavy petroleum-based gases or light natural gases or various gas mixtures with hydrogen [6].

Nowadays, various methods mixing air with fuel at low concentrations for premixed combustion are widely used [2-8]. However, when the task is the use of diffusion flames there too many advantages such as high reliabilities and wide range of stable operations [9-13]. In this direction, the possibility of using bluff bodies in cases of large excesses of fuels forms a special interest in development of combustion chambers without separations of air supply into primary and secondary flows. In this context, the experiments of Bikram *et al*. [2, 3] on combustion processes downstream with a disk shaped bluff body (with a diameter of 10 mm) used a preliminarily mixed fuel. These experiments revealed that both turbulence and fuel composition affect significantly the combustion processes downstream of the bluff body: the increase in the turbulence intensity results in narrower reaction zones and consequently reduced flame stabilization characteristics.

Here its it is noteworthy to mention studies [4-8] on combustion processes and toxic substances generation parallel to the heat transfer downstream of bluff bodies performed in micro combustion chamber. The main results of these studies reveals a considerable increase in the flame stability (by up to 2.4 times) when a bluff body is used [4]. Precisely, the flame stabilization is heavily dependent on the heat loss rate [5]. Moreover, the heat loss rate depends on the air-fuel mixture flow turbulence taking into account that semi-spherical bodies (unlike triangular ones) have stronger stabilization effects due to weaker flame *stretching*, and consequently to increase in the heat transfer exchange between the fresh air-fuel mixture and the gaseous combustion products [6].

In addition, the studies on disc-shaped bluff bodies effects on diffusion flame stabilization processes have been performed [9] with main results indicating the strong effect of the bluff body position (location). It is worth noting to refer the extensive studies [10-13] on flame stabilization, ignition, and generation of NO_x in cases with corner-shaped bluff bodies for diffusion revealing the effects of fuel supply along the symmetry axis and optimal variants (in terms of stabilization and generation of toxic substances).

Further, the effect of V-shaped rifles of a cone-shaped bluff body on the combustion characteristics of diffusion flame revealing that the increase in the V-shaped rifles enhances the turbulence intensity have been studied in [14]. As direct consequence of the increased turbulence intensity the combustion zone increases while the NO_x concentrations decrease. In general, these studies demonstrate the On the turbulence intensity is an effect of first order on fuel premixing with air. Precisely, the more effective mixing, the more homogeneous distribution of the temperature field over the bluff body cross-section which leads to reduced NO_x concentrations in the flue gases.

Simulations performed in [15] with a triangular-shaped bluff body (with slits on both sides) and based on experimental data obtained [8] indicate that the increasing in the angle at the corner vertex leads to increased flame stabilization. Similar results have been reported in [16, 17].

There is a large variety of bluff bodies shapes and surface configurations which have been studied experimentally [18-25] or by and using numerical simulation methods [25, 26]. The main task in such studies is to reveal the effect of the cross-section area reduction ratio, the flow structure, and consequently their effects on the fuel mixing process.

The results presented in this articles are motivated by the broad spectrum of results developed in previous experimental reports [16, 17, 27-30]. Precisely, the study focuses on a grid consisting of a group of corner flame holders of the same type and its effect on the combustion process performance. Such a corner arrangement of flame holders has a potential in increasing the operational performances of combustion chambers in gas turbine units, as well as boilers in the post-combustion process heat recovery.

Preceding studies and the new focus of the experimental program

In our previous study [28] we used single V-gutters allowing the blockage ratio to be $B = 0.05$, fig. 1, with different supply types. Further, as it can be seen from figs. 1 and 2, in this preceding study a tube with a diameter of 5 mm for fuel supply was used. As a next step of our research program we focus on the same type of 3 V-gutters but now the blockage ratio equals 0.15. It is worth mentioning, see the analysis of Lefebre [31], that this is the most important parameter of flame stabilization. In addition, the preceding study [28] revealed that the most effective way of fuel supply is at the symmetry axis directly to the recirculation zone (*i. e.* in the inner part of V-gutter). It is important to claim that the further results of this report are related to a rectangular combustion chamber allowing the effect of the boundary layer area to be avoided.

For the sake of the clarity of explanations, we stress the attention that in the preceding studies [15] the effects of the angle β of the V-gutters, see fig. 2, on both the flame stabilization and NO_x emissions were (in these experiments a tube with 5 mm of diameter was used for the fuel supply). In the results commented further in this article remains constant and equals 45°.

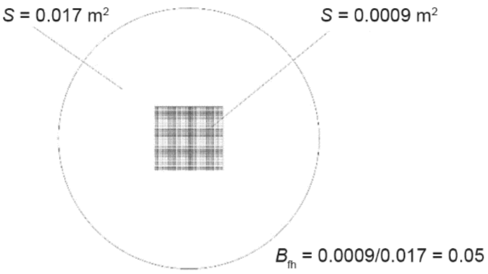

Figure 1. Cross-section of experimental unit [28]; B_{th} – flameholder width, $S = 0.017$ m^2 – empty space area, $S = 0.0009$ m^2 V-gutter area

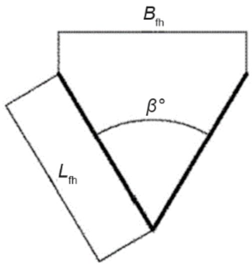

Figure 2. General cross-section of V-gutter used [15]; L_{fh} – length of the flameholder wall

Moreover, two V-gutters (with fuel supplied at the symmetry axes by a nozzle of 5 mm in diameter) and their mutual influence on flame stabilization were studied in [16] with air velocity less than 11 m/s (the same conditions were used in [15, 28], too). Now, the experimental program envisages greater air-flow (16 m/s) which allows significantly to enhance the flame stability, see the analysis in [31], an fuel distribution over the entire gutter height (thus creating conditions for reduced NO_x formation parallel to increased stability of the flame).

The second significant moment in the new experimental program is the use of three V-gutters thus reducing the mutual influences of torches (the preceding studies [15] two V-gutters without possibility to reduce these mutual effects were used).

Experimental

The combustion chamber, shown schematically in fig. 3 [18, 19], has a total length of 900 mm, width of 150 mm and wall thickness is 0.5 mm (a more general view of the corner flame holders is shown in fig. 4). The corner flame holders are installed symmetrically with respect to the combustion chamber axis, and the distance between the nozzle and the corner is equal to 20 mm. The length of corner walls is 30 mm, the angles at the corner vertex are equal to 45°. The section between the fan and the combustion zone consists of a single-piece metal block with drilled tubes (16 mm in diameter) thus ensuring uniformity of the supplied air flow to the combustion zone made by a quartz-made glass tube.

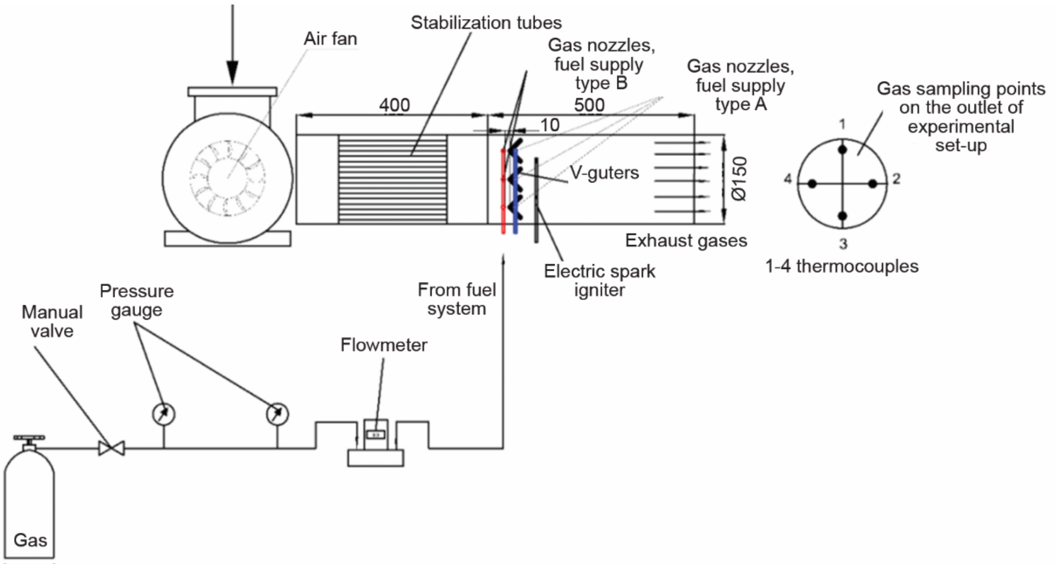

Figure 3. Schematic diagram of the combustor with a bluff bodies

As the non-premixed combustion process (diffusion flame regime) was at issue the fuel and the air were mixed directly in the combustion zone. A spark igniter installed directly at the front of the middle V-gutter flame-holder was used for fuel ignition. Chrome-alumel thermocouples (0.5 mm in diameter) were installed equidistantly along the combustion chamber diameter to recorder process temperature. A fixed-gas analyzer (with error of 5 %) was used to measure the parameters of the exhaust gases. A digital photo camera with high resolution was used for taking images of the flame.

In order to assess the effect of the fuel supply system arrangement under various equivalence ratios on the combustion process the equivalence ratio was adjusted by *increasing* or *decreasing* the velocity of air to be supplied by the fan. In the former case the fuel was supplied from a distance of 10 mm from the V-gutters symmetry axis, while in the second case the fuel was supplied on the inside of V-gutter, directly in the recirculation zone. The fuel was ignited when there was no air supply, that is, at the minimum

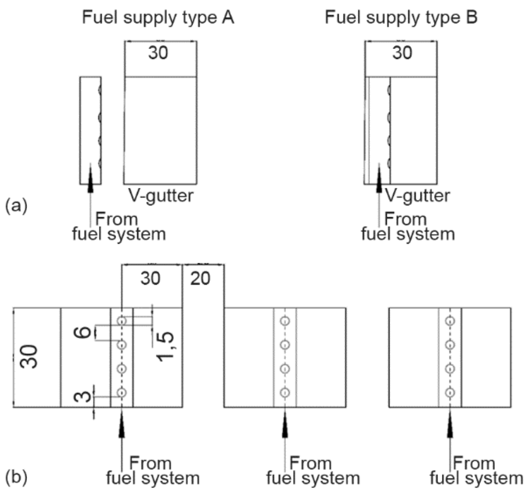

Figure 4. General view of V-gutter flame holders (a) and fuel supply types (b)

fuel mass-flow rate equal to 0.0025 kg/s, then the air supply was adjusted by incrementally increase in the fan speed. When the required air velocity value was able to vary within the range 4-16 m/s (calculated by the cross-section of the chamber), the maximum mass fuel flow rate was set equal to 0.005 kg/s. When the flame attained steady-state regime, the values of NO_x concentrations, exhaust gases temperature were measured. Depending on the air velocity, the Reynolds number varies within the range of Re = 21868-87475.

In order to study the lean blow-off processes, under a fixed air velocity within the range 4-16 m/s and a maximum fuel mass flow rate of 0.005 kg/s, the fuel mass flow rate was gradually reduced (with an increment of 0.0005 kg/s) until the flame was visually extinguished. After this, the fuel mass flow rate was recorded.

Results and discussion

Lean blow-off

The air velocity affects the lean blow-off of various types of fuel supply, see fig. 3. The plots in fig. 5 reveal that under equal operating conditions the lean blow-off in the case of Variant B of fuel supply appears earlier. This can be attributed to the accelerated flow between the corner edges, which actually leads to a sufficiently high velocity of the air-fuel mixture is sufficiently high and the mixture which does not allow the mixture to be sucked into the re-circulation zone generated behind the corner flame holder. With known conditions of flame stabilization, that is, conditions at which the combustion velocity should be fast enough to ignite the newly supplied fresh mixture. Precisely, at high velocities, the burnout velocity is low enough to ignite the fresh mixture. Its amount is rather small due to some *carry-over* of fuel by the high-speed flow.

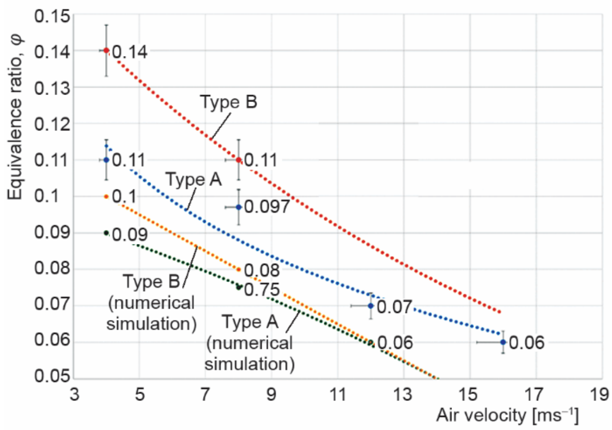

Figure 5. Air velocity effect on the lean blow-off from air velocity at different fuel supply types

Irrespective of the gas temperature at outlet of the test set-up being higher than in the case of Variant A, the flame stabilization is lower. This indicates that the fuel burns out at the combustion chamber *tail*, and therefore the high temperature flame does not contribute to the flame stabilization process taking place in the area of the corner flame holders.

At the same air velocity (4 m/s), the fuel excess coefficients at the lean blow-off varies from 0.11 to 0.14 for both variants of the fuel supply (A and B, respectively). At air velocity of 8 m/s, the fuel excess coefficients are about 0.097 and 0.11 respectively. With air velocity higher than 8 m/s, no steady flame was observed when the fuel supply in accordance with the Variant B was applied. Moreover, the flame blows off from the corner edges and no heat transfer occurs between the burnt gases and the fresh air-fuel mixture.

The high fuel supply stabilization characteristics with the Variant A, in contrast to Variant B, can be attributed to the fact that with Variant B of the fuel supply, directly into the re-circulation zone (generating a downstream of the corner flame holders) the process becomes independent of the air velocity in the intercorner space. Upon such conditions the re-circulation zone is saturated with fuel and consequently relatively high heat transfer process takes place, thus affecting positively the flame stabilization.

Conducted numerical simulation shows a fairly high level of convergence. However, due to a somewhat lower temperature level, see fig. 7, flame stabilization is lower *i.e.* equivalence ratio values are lower. Similar to experiments, combustion during fuel supply to the re-circulation zone leads to flame failure due to a significant excess of fuel and lack of air.

Generation of NO_x

Both the fuel supply type and the air-flow rate affect the NO_x concentrations in the flue gases, see fig. 6. When fuel is supplied directly into the re-circulation zone of the V-gutter (type A), the concentration of NO_x is lower than in the case of Variant B. It is noteworthy, that at low air velocity (4 m/s for instance) the NO_x concentrations for A and B variants are equal to 20 ppm and 25 ppm, respectively.

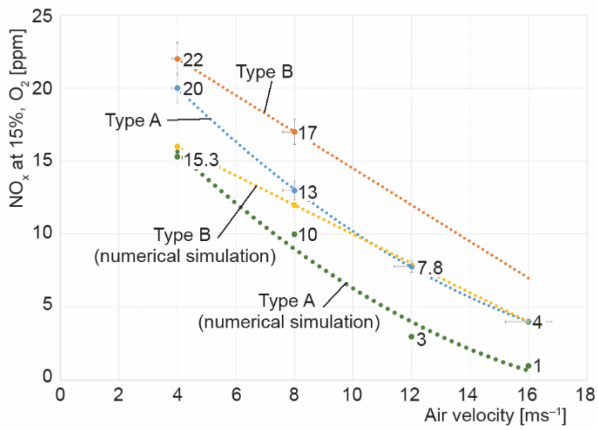

Figure 6. Effect of the air velocity on the NO_x concentrations from air velocity for different types of fuel supply

The NO_x oxides are generated as a result of oxidation of the nitrogen present in the atmospheric air in high temperature zones of combustion chambers in which the temperature is above 1800 K. Therefore, they are mostly generated in the central zones of the chamber [31]. When the fuel is supplied to the re-circulation zone, fuel burns down in the stoichiometric ratio, which can be detected by the blue color of the flame. However, it is well-known that maximal concentrations of NO_x are generated at about $\varphi \approx 0.8$. Since the temperature in the combustion zone has a relatively low value (see further the section devoted to numerical simulations) then the low NO_x concentrations have logical explanations.

With the fuel supply type B, some fuels burn out in the flame *tail*, thus creating a high temperature zone with a temperature exceeding 1800 K where NO_x generation takes place [31].

As it is well-known, chain reactions of NO_x generation begin with oxygen atoms release during dissociations of oxygen molecules [31]. The NO increases with increase in the temperature increases at constant value of φ. The numerical simulations discussed further in the text reveal that under all conditions remaining equal (*i. e.*, air velocity and fuel flow rate) in the combustion zone, the fuel supply in accordance with Variant B creates a high temperature zone where mainly the oxygen molecules disassociate and combine with nitrogen atoms. The competition between the fuel atoms and the nitrogen with respect to the atomic oxygen in the flame zone leads to fuel burning down mainly directly at the V-gutters; in the zone behind the V-gutters there is a sufficiently large amount of atomic oxygen and a low concentration of burning-out fuel. This creates conditions for nitrogen molecules to react with the oxygen and consequently to increase in the NO_x concentrations.

In addition, when the fuel is supplied from the inside of the V-gutter, the generation of NO_x is less than when supplied from the outside. At air velocity of 4 m/s, the concentration of NO_x was equal to 25 ppm and 20 ppm for type A and B, respectively. With increase in the air velocity the oxide concentration decreases irrespective of the fuel supply type. The gas temperature for both types of fuel supplies varies as the air velocity is increased. At air velocity of 4 m/s, for instance, the gas temperature downstream of the combustion chamber are of 740 K and 783 K for type A and B respectively.

It has been identified that at air velocities above 8 m/s, the flame does not burn steadily in case of fuel supply, especially in case of supply B. However, when the supply type A is applied the flame become stable for all air velocities in the range 4-16 m/s. It was observed that at air velocity of 4 m/s, the lean blow-off for type A and B occurred at $\varphi = 0.11$ and $\varphi = 0.14$, respectively.

Similar to the conducted experiments, the maximum concentration of NO_x is observed at the lowest air velocities, in view of the high concentration of fuel and the low concentration of the oxidizing agent – air. Another reason is the low recirculation force appearing in the reverse current zone behind the V-gutter flameholder. The average difference between experimental data and modeling is 22%.

Temperature

The exhaust temperatures for both fuel supply variants at various air velocities are shown in fig. 7. The temperature difference in all air velocity modes was established in the range of 30-40°. The photographs taken reveal that the cause of higher temperatures is the afterburning of some fuel in the flare *tail*, which creates high flame luminosity. In general, the temperature contours indicate good uniformities with the concentrations of NO_x.

The temperature level as previously shown determines the formation of NO_x [1, 14, 16]. As can be seen from fig. 7, in numerical simulation, the temperature at the exit from the simulation region is slightly lower than in the experiment.

Flame structure behind the V-gutter flame holders

The high resolution photographs in fig. 8 show the combustion process behind the V-gutter flame holders. For fuel supply type A, the increase in the air velocity leads to a decrease in the flare luminosity. Maximal value of the luminosity was observed at air velocity of 4 m/s,

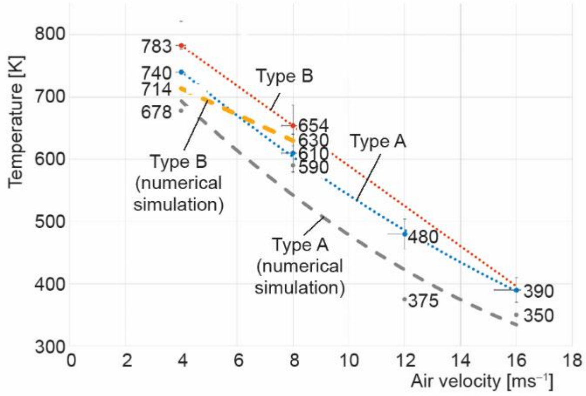

Figure 7. Effect of the air velocities on the exhaust gas temperatures of air velocities for different types of fuel supply

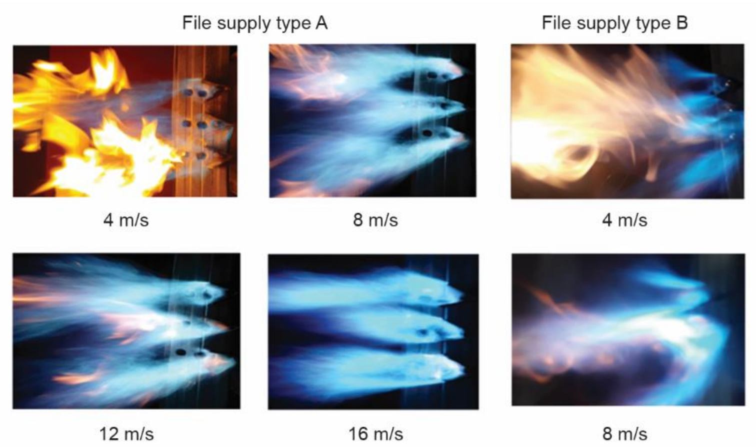

Figure 8. Flame photographs for different fuel supply types and air velocities behind V-gutter flame holders

with yellow flame color and highest temperatures as a result of considerably increased concentration of NO_x. The maximum length of the flare was observed at low velocities which as indicator that that some amount of the fuel burnt out at the flare *tail*. At air velocities of 8 m/s and 12 m/s, the combustion in the flame takes place under stoichiometric conditions but some yellow-colored flame residues were detected. With increase in the air velocity up to 16 m/s, the flame attains a clearly defined shape and the recirculation zones are clearly seen but no flame luminosity was detected.

For the fuel supply type B, the flame has a shorter length when observed from the V-gutter edges which can be attributed to the fuel burnout to some extent in the intercorner space under conditions of high turbulence flow mode. From the photographs reveal a wider reaction zone for fuel supply type B than for supply type A. This can be attributed to the air-fuel mixture combustion taking place in the space between corner flame holders, which allows an additional layer to the wake formed at the V-gutter edges to be created. It is noteworthy the combination of flares in the afterburning zone which is observed with the bot variants of fuel supply (4 and 8). When fuel is supplied from the inside of the V-gutters the flares become more *independent* from each other.

Further, the photographs reveal that the central V-gutter has a shorter flame at all velocity modes when the fuel supply type B is applied. This can be attributed to the mutual interactions of the V-gutters and the air *inflow* in the re-circulation zone. In absence of fluid drag forces at the two outermost corners on one *free* side is assumed, then the adjacent V-gutters could strongly affect the velocity mode near the central V-gutter edges. Due to this arrangement, some part of the air-flow does not enter the re-circulation zone which actually results in reduction in the flame length. The flames observed have relatively symmetric shapes in all modes experimentally studied.

The experiments conducted reveal high degree of flame stabilization when V-gutter flame holders were used. Important aspect of bluff bodies' applications is the self-regulation of the process, that is, the V-gutter flame holders ensure an optimum fuel/air ratio for flame stabilization irrespective of air-flow rate. However, no such self-regulation was observed at high velocities when the fuel supply type B was applied.

Numerical simulation

Physical model

The combustion chamber mode of a rectangular shape (3-D model with dimensions 150 × 150 × 500 mm (height × width × length, respectively) shown schematically in fig. 9 was created by SOLIDWORKS software. The V-gutters arranged symmetrically with respect to the longitudinal axis of the chamber correspond to the experimental situation studied. The fuel supply system arrangements correspond to the situation shown in fig. 2. The simulations used parameters corresponding to the set of variables and parameters used in the experiments. The 0 point of coordinate system was located at the beginning of the modeling area as shown in fig. 9.

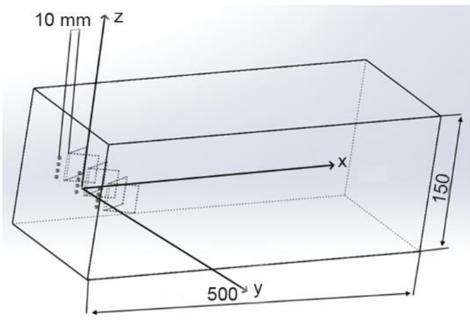

Figure 9. The combustion chamber-schematically (the dimensions are in millimeters)

Mathematical model

The mathematical model developed in [3] was used to validate the experimental results, presented:

– 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 is the total enthalpy of mixture gas, h_j – the enthalpy of component j^{th}, λ_f – the thermal conductivity of the fluid, and q – the heat of reaction [15, 32].

– State of ideal gas

$$p = \rho \mathrm{R} T \sum_{s=1}^{Ng} \frac{Y_s}{M_s}$$

Grid independence study

The current study uses a grid with an element size of 5 mm. To verify the results, additional grids were with a sizes of 2.5 and 7.5 mm were also tested. The reliability of the measurements was determined by the temperature difference between the experimental results and the simulation. The result presented in tab. 1. A comparison of the results, see tab. 1, showed that the temperature difference at the outlet of the experimental set-up and the simulation area for element size of 5 mm is less than 10%. The authors concluded that the error is sufficient for this grid and all subsequent modeling was carried out with a grid with a size of 5 mm.

Table 1. Grid independence study results

Element size/ /elements number	Outlet temperature (simulation) $T_{\mathrm{sim.}}$, [K]	Outlet temperature (experiment) T_{exp}, [K]	Difference, [%] $100\times(T_{\mathrm{exp}} - T_{\mathrm{sim}})/T_{\mathrm{exp}}$
7.5 mm/312551	709	783	9.45
5 mm/450128	714	783	8.81
2.5 mm/1639962	723	783	7.66

Simulations

The simulations performed in 3-D by ANSYS FLUENT software package [33, 34] used air-flow rate in the range 4-16 m/s and a constant fuel mass-flow rate of 0.005 kg/s. The fuel parameters such as density, viscosity, and heat conductivity were taken from [35]. In the previously studies [16] the physical adequacy of the model was confirmed so we will skip here discussions on this problem.

The temperature profiles behind the V-gutter flameholders shown in fig. 10 reveal flames with axisymmetric shapes when the fuel supply A is applied. The temperature contours are presented for the x-y cross-section at $z = 0$, see fig. 9.

The maximum temperature values attained correspond to air velocity of 4 m/s and under such conditions a high temperature zone located directly behind the V-gutter flame holders (where the temperature can reach value of about 1750 K) exists. Further, with increase in the air velocity the length of the high temperature zone decreases that confirm the experimental observations. The increase in the air velocity up to 16 m/s results in reduction of the high temperature zone length but the change in the length of this zone above 12 m/s is insignificant. It is noteworthy that irrespective of the velocity variations the high temperature zone located behind the corner flame holders remains stable. This stability can be attributed to the fact that the high temperature gases ignite the coming fresh air-fuel mixture resulting in high flame stabilization, see fig. 3.

Moreover, the simulations confirm the experimental data obtained to greater extent, especially when the flame structure at the velocity of 4 m/s was simulated.

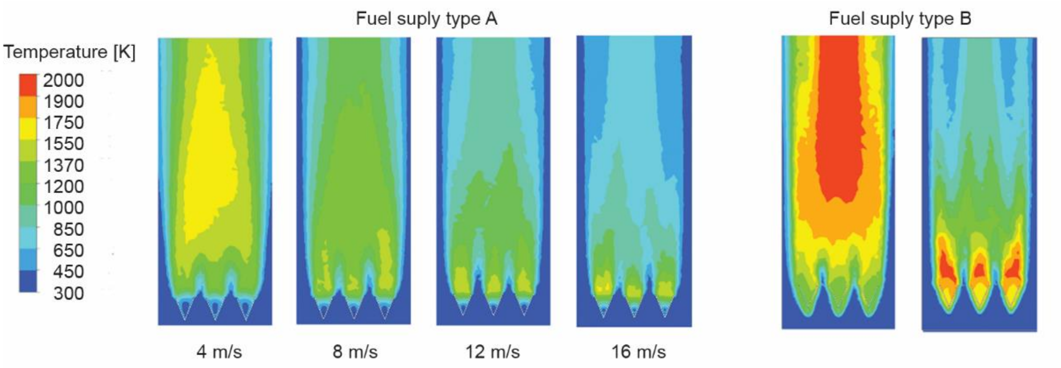

Figure 10. Temperature contours behind V-gutter flameholders on distance *z* = 0

Conclusions

The experimental studies carried out with V-gutter holders reveal that the fuel supply mode affects significantly the flame stability; the exhaust gas temperature and as well as NO_x concentrations at the combustion chamber outlet. The main results can be outlined.

- At velocities higher than 8 m/s, V-gutters with fuel supply to the symmetry axis (type B) does not flame stabilization cannot be attained. However, at velocities of 4 m/s and 8 m/s, with the same mode of fuel supply a narrower stabilization range was obtained (compared to fuel supply type A).
- Fuel supply to the inside of the V-gutters result in optimal NO_x generations. At the velocity of 4 m/s, the concentrations of NO_x were equal to 25 ppm and 20 ppm for types A and B, respectively (the oxide concentration decreases with increase in the air velocity).
- The gas temperature with both variants of fuel simply varies with increase in the air velocity. At a velocity of 4 m/s, the gas temperature downstream of the combustion chamber was equal to 740 and 783 for types A and B, respectively.

The flame stabilization strongly depends on the distance between V-gutters.

The numerical simulation performed allowed much more complete analysis of the results to be obtained.

Nomenclature

B – blockage ratio, [–]

Greek symbols

φ – equivalence ratio [–]
β – angle between walls of V-gutter, [°]

References

[1] Jansohn, P., *Modern Gas Turbine Systems, High Efficiency, Low Emission, Fuel Flexible Power Generation*, Woodhead Publishing Limited, Oxford, UK, 2013

[2] Bikram, R. *et al.,* Experimental Study of the Effects of Free Stream Turbulence on Characteristics and Flame Structure of Bluff-Body Stabilized Conical Lean Premixed Flames, *Combustion and Flame, 178* (2017), 1, pp. 311-328
[3] Bikram, R. *et al.,* Effects of Free Stream Flow Turbulence on Blow-Off Characteristics of Bluff-Body Stabilized Premixed Flames, *Combustion and Flame, 190* (2018), 1, pp. 302-316
[4] Yunfei, Y., *et al.,* Numerical Investigation on Combustion Characteristics of Methane/Air in a Micro-Combustor with a Regular Triangular Pyramid Bluff Body, *International Journal of Hydrogen Energy, 43* (2018), 15, pp. 7581-7590
[5] Fan, A., *et al.,* Numerical Investigation on Flame Blow-Off Limit of a Novel Microscale Swiss-Roll Combustor with a *bluff-body*, *Energy, 123* (2017), 1, pp. 252-259
[6] Fan, A., *et al.,* Effect of Bluff Body Shape on the Blow-Off Limit of Hydrogen/Air Flame in a Planar Micro-Combustor, *Applied Thermal Engineering, 62* (2014), 1, pp. 13-19
[7] Fan, A., *et al.,* Interactions between Heat Transfer, Flow Field and Flame Stabilization in a Micro-Combustor with a Bluff Body, *International Journal of Heat and Mass Transfer, 66* (2013), 1, pp. 72-79
[8] Jianlong, W., *et al*., Experimental and Numerical Investigation on Combustion Characteristics of Premixed Hydrogen/Air Flame in a Micro-Combustor with a Bluff Body, *International Journal of Hydrogen Energy, 37* (2012), 24, pp. 19190-19197
[9] Yiheng, T., *et al*., Effects of the Position of a Bluff-Body on the Diffusion Flames: A Combined Experimental and Numerical Study, *Applied Thermal Engineering, 131* (2018), 1, pp. 507-521
[10] Khristich, V. A., Litoshenko, V. N., Investigation of the Counter Flow Zone Dimensions behind the System of corner Flameholders. Herald of KPI (in Russian), *Thermal Engineering Series, 5* (1968), 1, pp. 10-15
[11] Butovskiy, L. S., Khristich, V.A., The Structure of Mixing Zone and Particular Qualities of Burning Behind Triangle Flameholder, in: *Theory and Practice of Gas Burning* (in Russian), Nedra, Leningrad, Russia, 1972, 1, pp. 76-82
[12] Khristich, V. A., Lyubchik, G. N., About the Stability of Diffusional Combustion behind Flameholders, in: *Theory and Practice of Gas Burning* (in Russian), Nedra, Leningrad, Russia, 1972, 1, pp. 82-85
[13] Khristich, V. A., Lyubchik, G. N., The Influence of Gas Fuel Type of Combustion Process of Jet-Stabilizer Burners, in: *Theory and Practice of Gas Burning* (in Russian), Nedra, Leningrad, Russia, 1972, 1, pp. 12-132
[14] Shun-Chang, Y., *et al*., Non-Premixed Flame Characteristics and Exhaust Gas Concentrations behind Rifled Bluff-Body Cones, *Journal of the Energy Institute, 91* (2018), 4, pp. 489-501
[15] Yunfei, Y., *et al*. 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* (2019), 3, pp. 1998-2012
[16] Umyshev, D. R., *et al*., Experimental Investigation of V-Gutter Flameholders, *Thermal Science, 21* (2017), 2, pp. 1011-1019
[17] Umyshev, D. R., *et al*., Experimental Investigation of Distance between V-Gutters on Flame Stabilization and NO_x Emissions, *Thermal Science, 23* (2019), 5B, pp. 2971-2981
[18] Schefer, R., *et al*., Effect of Confinement on Bluff-Body Burner Recirculation Zone Characteristics and Flame Stability, *Combust. Sci. Technol., 120* (1996), 6, pp. 185-211
[19] Yang, J.-T., *et al*., Flow Structures and Mixing Mechanisms behind a Disc Stabilizer with a Central Fuel Jet, *Combust. Sci. Technol., 174* (2002), 3, pp. 93-124
[20] Schefer, R., *et al*., Velocity Measurements in Turbulent Bluff Body Stabilized Flows, *AIAA J, 32* (1994) 9, pp. 1844-1851
[21] Huang, R., Lin, C., Velocity Fields of Non-Premixed Bluff-Body Stabilized Flames, *J. Energy Resour. Technol., 122* (2000) 2, pp. 88-93
[22] Bakić, V., Experimental Investigation of a Flow Around a Sphere, *Thermal Science, 8* (2004), 1, pp. 63-81
[23] Wesfreid, J. E., *et al*., Global Mode Behavior of the Streamwise Velocity in Wakes (in French), *Journal de Physique, 6* (1996), 10, pp. 1343-1357
[24] Bosch, G., *et al*., Experiments on the Flow Past a Square Cylinder Placed Near a Wall, *Exp. Thermal Fluid Sci., 13* (1996), 3, pp. 292-305
[25] Nakagawa, S., *et al*., Heat Transfer in Channel Flow Around a Rectangular Cylinder, *Heat Transfer-Japanese Reseach, 27* (1998), 1, pp. 84-94

[26] Taymaz, I., *et al*. Numerical Investigation of Incompressible Fluid Flow and Heat Transfer across a Bluff Body in a Channel Flow, *Thermal Science, 19* (2015), 2, pp. 537-547
[27] Umyshev, D. R., *et al*., Application of Semi Perforated V-Gutter Flameholders in Heat-Generating Systems for Autonomous Building Heating, *International Journal of Mechanics and Mechanotronics, 16* (2016), 6, pp. 63-69
[28] Umyshev, D. R., *et al.,* Experimental Investigation of Recirculation Zones behind V-Gutter Type Flameholders, *International Journal of Pharmacy and Technology, 8* (2016), 4, pp. 27369-27380
[29] Umyshev D. R., *et al*., Experimental Investigation of the Management of NO_x Emissions and Their Dependence on Different Types of Fuel Supply, *Revista Espacios, 38* (2017), 24, pp. 17-23
[30] Dostiyarov, A. M., *et al*., Results of Investigation of the GTE Combustion Chamber with a Two-Stage Burner, *Revista Espacios, 39* (2018), 24, pp. 33-35
[31] Lefebre, A., *Gas Turbine Combustion* (in Russian), Mir Publ., Moscow, 1986
[32] Kirchhartz, R., *et al*., Effect of Boundary Layer Thickness and Entropy Layer on Boundary Layer Combustion, *Proceedings,* 16th Australasian Fluid Mechanics Conference, Gold Coast, Australia, 2007, Vol. 1, pp. 491-496
[33] ***, ANSYS FLUENT 13.0 Theory Guide
[34] ***, ANSYS FLUENT 13.0 User's Guide
[35] Mikheev, M. A., Mikheeva I. M., *Heat Transfer Fundamentals* (in Russian), Energya, Moscow, 1977

Paper submitted: November 11, 2019
Paper revised: December 12, 2019
Paper accepted: December 15, 2019