EXPERIMENTAL INVESTIGATION OF V-GUTTER FLAMEHOLDERS

by

Dias R. UMYSHEV[a,*], Abay M. DOSTIYAROV[a], Musagul Y. TUMANOV[a], and Qiuwang WANG[b]

[a] Almaty University of Power Engineering and Communication, Almaty, Kazakhstan

[b] Xian Jiatong Universty, Xi'an, Shaanxi, China

Original scientific paper
https://doi.org/10.2298/TSCI151209072U

Combustion characteristics and NO_x emissions of propane and air mixture in a channel with a bluff body were investigated experimentally. Effects of the angle and type of the flameholder on the NO_x emissions, blow-off limit, combustion efficiency, and exhaust gas temperature were examined. The results show that the NO_x emissions are dependent on flameholder type and angle. Also it was observed that the perforated V-gutters considerably increases the blow-off performance. Moreover, the blow-off limit decreases as the geometrical size of flameholder is increased. In addition, the combustion efficiency increase first and then decrease with the increase of the angle. The physics of the combustion process behind V-gutter flameholdes has been discussed. On the basis of experiment authors presented a modified version of the formula for calculation of lean blow-off limits when using bluff bodies, such as V-gutter flameholders.

Key words: *V-gutter, flameholder, NO_x, combustion, exhaust gases, combustion efficiency, temperature, computational fluid dynamics*

Introduction

The current worldwide emphasis on environmental issues has resulted in more stringent NO_x emission regulations for gas turbines. Fundamentally, NO_x emissions depend on the flame temperature, residence time of gases and mixing efficiency [1]. One of the most attractive methods of NO_x reduction is using bluff body as flameholders. In such cases, it is possible to reduce the size of the combustion chambers, lower the concentration of nitrogen oxides, and ensure high combustion efficiency [1-16].

The V-gutter flameholders are classified as one of components for micro-flame devices [2-8]. The flame tube head of the micro-flame combustion chambers consists of micro-flame devices. Since fuel air mixture (FAM) stabilizing and burning procedures are determined by the re-circulation zone outside V-gutters, then the NO_x formation is defined by FAM quality, temperature in the combustion zone and combustion gases residence time in the high temperature area. The optimum selection of expansion angle and wall length as well as possible perforations may provide an optimum value of the re-circulation zone. The value of the re-circulation zone provides a relatively low average temperature in the combustion zone, short time of residence of the burnout gases exposure, and sufficient mixing.

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

Aiwu Fan *et al.* [17-20] conducted profound study of the effect of bluff body shape, inlet velocities and equivalence ratios on the blow-off limits, combustion processes, flame stabilizations and heat transfer. It was shown that flame stabilization is significantly dependent on re-circulation zone and flame stretching behind flameholder. Also, it was shown that material of flameholder is significantly affects stabilization, due to the heat transfer between re-circulation zone and fresh air-fuel mixture. Also, it was shown that the combustion efficiency and exhaust gas temperature increase first, and then decrease with the increase in the inlet velocity. The influence of different types of flameholders, fuel injection [2-6] showed that V-gutter flameholders show good blow-off performance due to the developed re-circulation zone.

The influence of approach stream velocity and the V-gutter size on blow-off performance was investigated in [21]. The results showed that when the V-gutter size is large, there are two flame bases which are located immediately after the V-gutter's trailing edge, on both sides of the shear layers. The influence of fuel supply on the combustion process with bluff body, in the shape of a triangle, was investigated in [22]. The results showed that for a given velocity, the increased fuel profile asymmetry caused an increase in the blow-off equivalence ratio.

A study of the formation of hazardous substances when using various bluff bodies [9, 23] has proven that bluff bodies in a form of V-gutters allow for a significant reduction in the formation of hazardous substances and a drastic increase in combustion stability due to a well-developed re-circulation zone. It is known [10-14] that NO_x are generated either in re-circulation zones or downstream. That means that air and fuel quantity, *i. e.* φ in the re-circulation zone plays a significant role in NO_x formation.

On the basis of the conducted analysis, authors conducted an experimental investigation of the V-gutter flameholders, with special emphasis on the NO_x emissions.

In addition, the authors have conducted a simple numerical simulation of the combustion process outside V-gutters to receive auxiliary information for theoretical analysis and illustration of the research test.

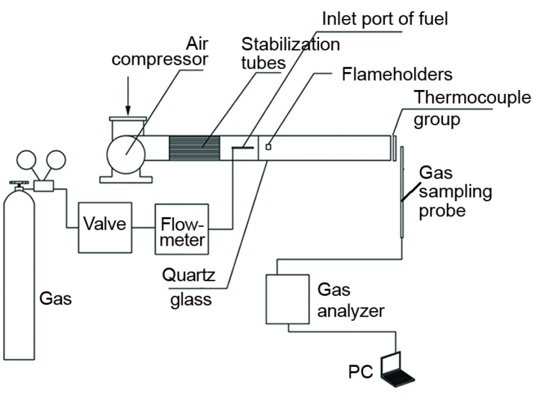

Figure 1. Schematic diagram of the experimental set-up

Experimental set-up and method

Schematic diagram of the experimental set-up is presented in fig. 1.

The main elements of the experimental set-up are:

– air compressor,
– section for equalization of the velocity field, which consists of stabilization tubes with a diameter of 16 mm,
– gas supply system, which consists of a gas cylinder, valve and connected flowmeter,
– section with flameholder,
– quartz tube,
– thermocouple group, and
– gas analyzer connected with PC.

Figure 2 shows the fuel supply circuit in the test device. The fuel in the form of pure propane is supplied directly to V-gutter, in which the distance between the nozzle and the V-gutter is 30 mm. The air-flow whilst measuring NO_x concentration, temperature and taking

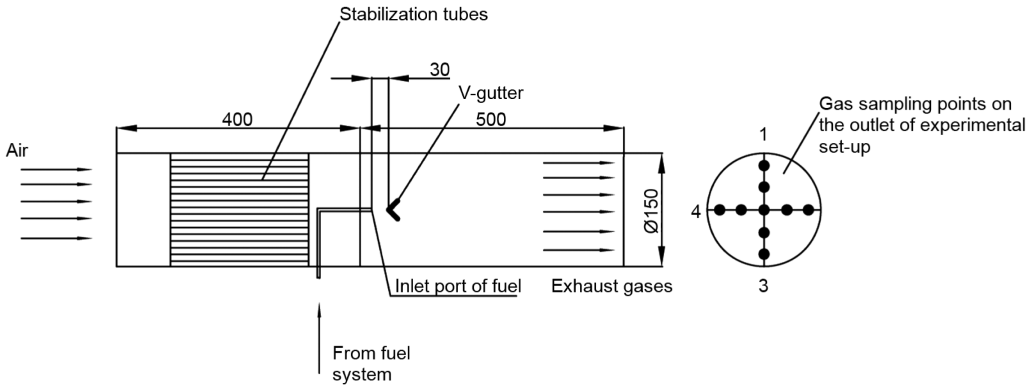

Figure 2. Diagram of fuel supply system and measuring points

photos was constant, 127 kg/h, and fuel flow was 1 kg/h. To calculate blow-off limits, the air-flow rate was constant and the fuel flow was gradually decreased till visual flame attenuation; flowmeter data was recorded, then φ_{LBO} was calculated using eq. (2). Air and fuel temperature were equal to 300 K, atmospheric pressure was assumed. Reynolds number is 19,300.

The V-gutters of various types were used in this test as shown in fig. 3 and tab. 1, with different expansion angles (15, 45, and 90°). In the first two cases, FAM was supplied to the combustion zone after it flowed around the V-gutter, drastically influenced by the blockage ratio [1]. In case of perforated V-gutters, FAM could be supplied to the re-circulation zone through V-gutter perforations.

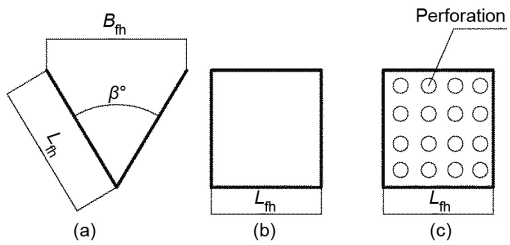

Figure 3. General view of flameholders; (a) top view, (b) standard flameholder, (c) perforated flameholder

Table 1. Flameholders characteristics

Type of V-gutter	Length	Features
1	30 mm	
2	50 mm	
3	30 mm	perforated

Figure 2 also shows the NO_x concentration and temperature measurement diagram. According to the procedure [15, 16] to receive reliable measurements for pipes less than 1 m in diameter, one should take measurements in nine points around the outlet circumference. To measure temperature values, except for gas analyzer, the group used the Cr/Al thermocouples installed in the diagram shown in fig. 2. Additionally, random NO_x measures were tested by chemiluminescence analysis.

Results and discussion

The NO_x formation

The dependence of NO_x emissions from angles of V-gutters is presented in fig. 4. Evidently, the highest capture rate of air flow when comparing re-circulation zones behind the V-gutter flameholders is observed at 90°; therefore φ decreases, and this leads to a decrease in

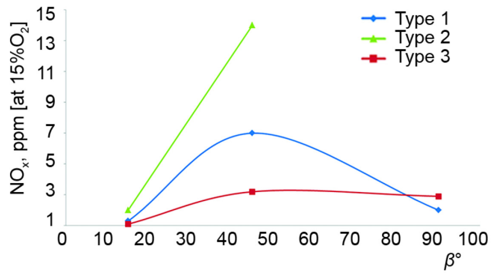

Figure 4. The NO_x emissions dependence from type and angles of flameholders

average burning temperature, thus leading to a decrease in C_{NO_x}. An angle of 15° leads to weak development of the re-circulation zone, which can be seen from the results of numerical simulation; the burning process occurs with low combustion efficiency, and the low average burning temperature leads to a decrease in NO_x. An angle of 45° creates the optimal re-circulation zone, which intensifies the process of combustion. In this case, the process takes place at a higher temperature; therefore, a certain increase in NO_x was observed.

In the case of perforated V-gutter, at a narrow angle of 15° the effect of perforation is the lowest, as the existing depression behind the flameholder is insufficient to draw the air-fuel mixture into the flameholder. At an angle of 45° there is more intensive mixing, but overall C_{NO_x} decreases due to suction and an overall decrease of φ in the combustion zone. Also, the force of the existing re-circulation zone is not high enough, so the flow of air-fuel mixture through the perforations destroy it, thus reducing the residence time of gases in the combustion area. This leads to a high level of fuel combustion efficiency. An increase of the angle to 90° increases the volume of air-fuel mixture coming through perforations and destroys the re-circulation zone, which increases the air-fuel ratio, thus increasing the temperature.

As in the aforementioned cases, an increase in admixing leads to an increase in average temperature. An increase in angle length leads to a proportional increase in flameholder width (blockage ratio). According to [1], a higher blockage ratio leads to higher intensity of burning due to higher air-fuel mixture suction, which leads to increased temperature, and, consequently, higher concentrations of NO_x.

Combustion efficiency

Combustion efficiency is calculated by the following equation:

$$\eta_c = \frac{\left(1+\dfrac{L_0}{\varphi_{out}}\right)(C_{pg}T_g - C_{pg}T_0) - \dfrac{L_0}{\varphi_{out}}(C_{pa}T_g - C_{pa}T_0) - (C_{pg}T_g - C_{pg}T_0)}{Q_1^w} \tag{1}$$

As can be seen from the equation, the combustion efficiency for a homogeneous air-fuel mixture is determined by how well the air and fuel are mixed. In our case, fig. 5 shows that mixing is better in perforated flameholders. This can be seen from numerical simulation and from photographs of the combustion process behind the flameholders.

The highest value of combustion efficiency is observed at 45° for all types of flameholders. This can be explained by a well-developed re-circulation zone and better mixing of fuel and air, especially when there are perforations. The decrease of combustion efficiency at 90° occurs due to rapid displacement of incomplete combustion products from the re-circulation zone by the air-fuel mixture being drawn in, which can be seen from the photographs of the combustion.

This displacement is insignificant at 15° with perforation due to very low amount of air being drawn in. This makes it possible to achieve complete burn-out of the fuel by the end of the experimental set-up. Lower combustion efficiency in the case of the standard flameholder can be explained by an insufficient amount of oxygen in the re-circulation zone.

An increase of flameholders length leads to lower combustion efficiency, at angles lower than 45° due to a poorly-developed re-circulation zone, and at higher angles due to low temperatures resulting from a higher air capture rate.

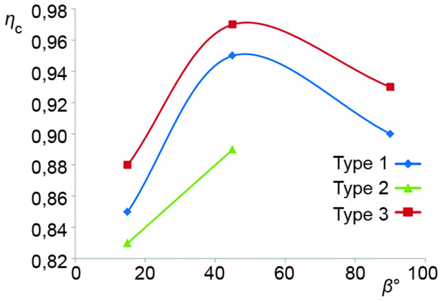

Figure 5. Dependence of combustion efficiency from type and angles of flameholders

Temperature

Increasing angle $\beta°$ for all three types of flameholders increases the temperature, which is natural in the case of re-circulation zone intensification, fig. 6. Numerical simulation shows that intensification of combustion is observed at a higher angle $\beta°$, which leads to an increase in temperature. Perforated angles show certain advantages, since the higher velocity of air-fuel mixture in the holes of the flameholder walls, in conjunction with thin border layers, leads to higher intensity of combustion.

Increased flameholder wall length leads to a negative effect, which can be seen from numerical simulation.

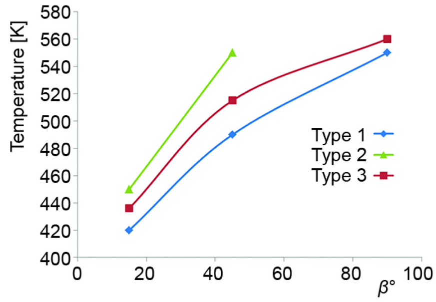

Figure 6. Dependence of temperature from type and angles of flameholders

Structure of the flame

Figure 7 shows photographs of the flame behind the flameholders. Analysis of the flame structure based on the photographs shows incomplete combustion for standart flameholder with the angle of 15°. Perforated V-gutters show good mixing, but they also show low combustion efficiency, which can be seen from the flame structure. Greater length at the same angle leads (type 2) to significant elongation of the flame with incomplete combustion at the flame end due to underdevelopment of the re-circulation area, which naturally affects combustion intensity.

An angle of 90° gives a well-developed re-circulation area, which is also shown by numerical simulation, but the combustion process, with and without perforations, leads to incomplete combustion, which can be seen from the flame structure. This is explained by the fact that when there are perforations there is a displacement of large amounts of unburnt combustion products from the re-circulation zone. In the case of a regular flameholder, there is still a shortage of air or dominance of gas mixture, which leads to an increase in incomplete combustion.

The most favorable angle in terms of efficiency is 45°, but the numerical simulations show that when stabilizer length is greater (type 2) the efficiency of the re-circulation area is insignificant, which naturally affects combustion and leads to significant incompleteness of combustion behind the flameholder.

The flame structure in the case of a regular flameholder indicates good combustion, but there is also a high luminosity in the central area, albeit lower than in case of long flame-

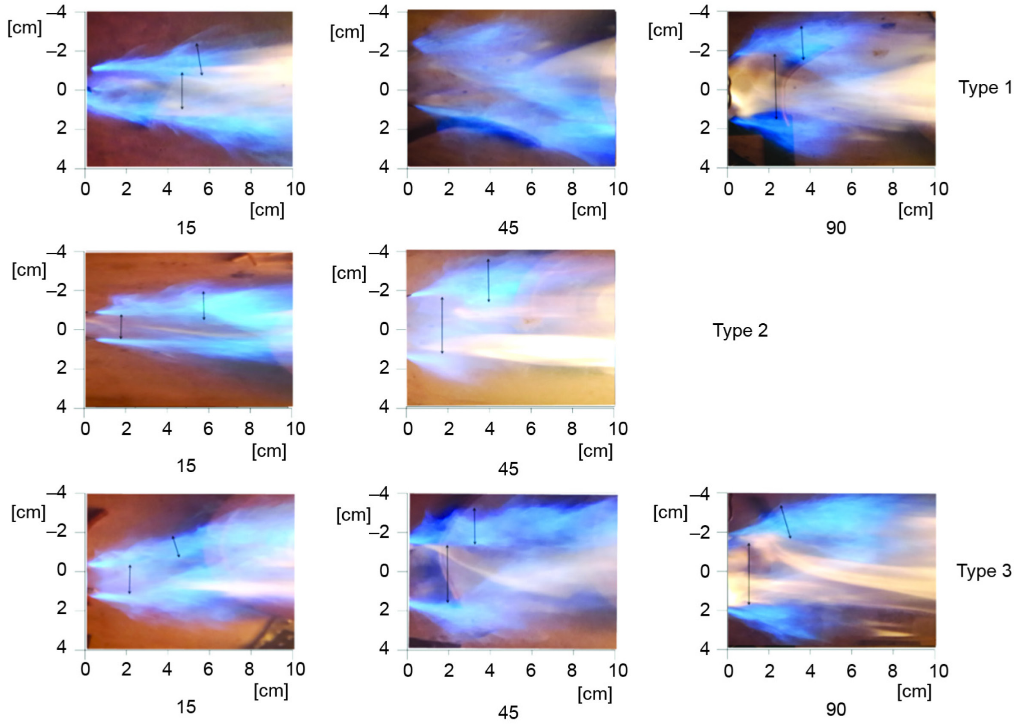

Figure 7. Photographs of the flame behind the flameholders
(*for color image see journal web site*)

holders. The most efficient flameholder in terms of combustion efficiency and flame length is a perforated V-gutter at 45°. In our opinion, it shows very good mixing, since in comparison with a 90° angle, the force of air-fuel mixture displacement through the perforations has little effect, although there is some air shortage in the central area, which gives a certain luminosity.

Lean blow-off limits

The lean blow-off (LBO) limits were calculated by formula [2-6], according to which only the part of the air corresponding to the geometrical dimensions of the flameholders (area $S = B\,H$) is involved in combustion:

$$\varphi_{\mathrm{LBO}} = \frac{m_{\mathrm{fuel}}}{m_{\mathrm{air}}\left(\dfrac{m_{\mathrm{fuel}}}{m_{\mathrm{air}}}\right)_{\mathrm{st}}} = \frac{m_{\mathrm{fuel}}}{\rho_{\mathrm{a}}\omega_{\mathrm{a}}B_{\mathrm{fh}}H_{\mathrm{fh}}0.2} \tag{2}$$

Figure 8 shows actual and calculated LBO limits. The highest value of φ is observed at 15°. Since this angle has little effect on the flow of air-fuel mixture, there is no significantly developed re-circulation zone behind the flameholder. This means that downstream burnt gases do not have sufficient time to ignite the fresh reactant coming into the re-circulation zone. The minimum φ, *i. e.*, high stabilization performance, is observed at 45°. It is known [1] that the highest stabilization is achieved by ensuring sufficient contact time between fresh reagents and burnout gases. As mentioned before, the 45° angle shows optimal re--circulation zone size, which makes it possible to effectively ignite the fresh mixture and broadens the range of stable combustion.

A perforated angle at 90° shows a slight increase. This occurs due to higher depression behind the flameholder, which, in turn, leads to high air-fuel mixture flow through the perforations. High air-fuel mixture flow displaces the re-circulation zone downstream, which decreases the contact and mixing time of reactants and burnout gases. Using standard flameholders shows some improvement of stabilization values. This occurs due to greater flameholder widths [1], which increases the residence time of reagents in the re-circulation zone. Standard flameholders at an 90° show similar values to those of perforated at an 45°. This indicates that high values of stabilization can be achieved without high blockage ratio of the cross-section (which would lead to large pressure losses) through perforation of flameholders.

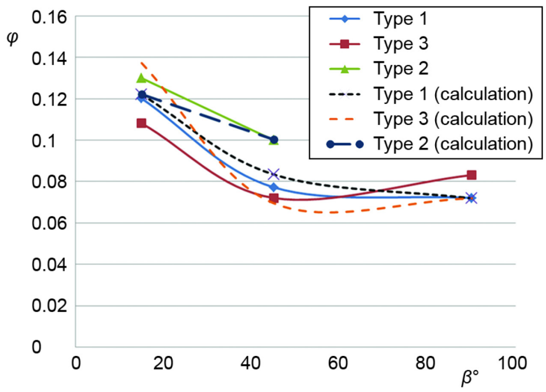

Figure 8. Dependence of LBO limits from type and angles of flameholders

Based on the experimental data, a modified version of the formula mentioned in [3, 4] is presented for calculation of LBO limits when using bluff bodies, such as V-gutter flameholders. The formula accounts for the surface structure, width of the flameholder, as well as the efficiency of fuel mixing in the re-circulation zone. Calculated data is shown in fig. 8 by dashed lines.

$$\varphi_{\mathrm{LBO}} = k_{\mathrm{FH}} \left[6 \left(\frac{B}{d} \right)^{1.2} \left(\frac{\rho_{\mathrm{a}} \omega_{\mathrm{a}}}{\rho_{\mathrm{g}} \omega_{\mathrm{g\,min}}} \right)^{0.5} \right] \tag{3}$$

where k_{FH} is the empirical coefficient, which varies in the range of 0.017-0.45 for different types and width of flameholders.

The CFD analysis

To investigate how a flameholder angle affects flow velocity, a simple CFD analysis was carried out for all cases. For computation, a commercial CFD package, FLUENT Ver. 13 [24, 25], was used with appropriate assumptions. A total of 800,000 tetra mesh elements were generated within the calculation domain. For turbulent modeling, realizable k-ε model with enhanced wall treatment was chosen. Non-premixed combustion model was chosen for combustion modeling. The air-flow was 127 kg/s and the fuel flow was equal to 1 kg/s. The cross--section of the numerical model is schematically shown in fig. 9.

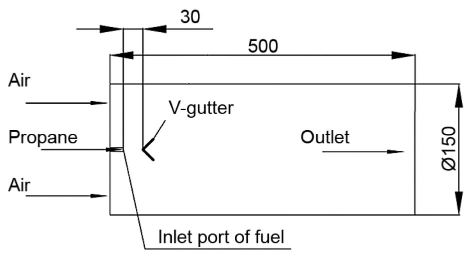

Figure 9. Cross-section of the numerical model

Figure 10 shows velocity contours of three types of V-gutter flameholders under consideration. Re-circulation zone development outside V-gutters can be inferred by it. A less developed re-circulation zone is available at 15°. An expanded re-circulation zone is available at 90° and optimally effective zones – at 45°.

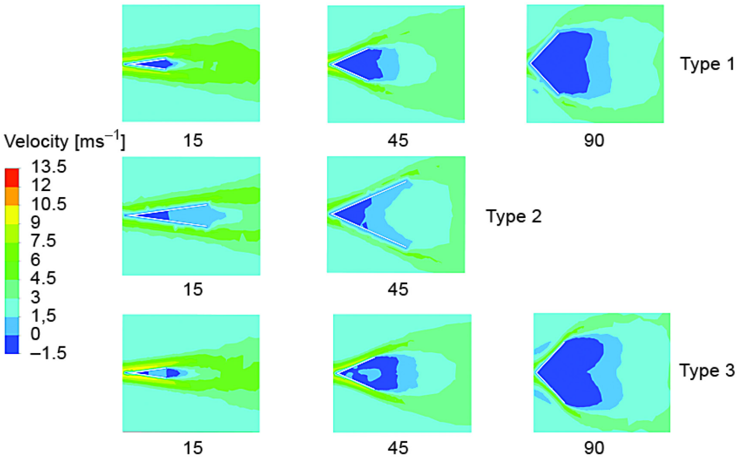

Figure 10. Velocity contours of three types of V-gutter flameholders with different angles *β*°
(*for color image see journal web site*)

When considering a V-gutter flameholder at 90° with perforations there is an upstream gas emission from re-circulation zone. A V-gutter at 45° with perforations is the most rational.

Conclusions

To perform a micro-flame combustion (*i. e.* dispersed gas combustion) in the combustion chamber, it is necessary to complete one component (micro-flame device) that provides consistent burning, minimum emission of C_{NO_x}, maximum combustion efficiency and minimum pressure loss.

We experimentally selected V-gutter micro-flame devices at 45° with perforations and short walls that provide effective performances in the new combustion chamber.

It is apparent that a V-gutter with perforation and angle 45° provides low NO_x emission and full combustion efficiency.

Nomenclature

B_{fh} – width of flameholder, [m]
C_{pa} – heat capacity of air at constant pressure, [kJkg^{-1}K^{-1}]
C_{pg} – heat capacity of gas at constant pressure, [kJkg^{-1}K^{-1}]
d – nozzle diameter, [m]
H_{fh} – height of flameholder, [m]
L_0 – stoichiometric coefficient (= $10\cdot10^{-3}\cdot0{,}266\ Q^w{}_1$), [–]
m – mas flow rate, [kgs^{-1}]
Q_1^w – lower heating value of fuel, [kJm^{-3}]
T_0 – ambient temperature, [K]
T_g – gas temperature, [K]

Greek symbols

$\beta°$ – angle of flameholder, [°]
η_c – combustion efficiency, [–]
ρ_a – density of air, [kgm^{-3}]
ρ_g – density of gas, [kgm^{-3}]
φ – equivalence ratio, [–]
ω_a – air speed, [ms^{-1}]
ω_g – gas speed, [ms^{-1}]

Acronyms

FAM – fuel air mixture
LBO – lean blow off

References

[1] Lefebre, A., *Gas Turbine Combustion* (in Russian), Mir, Moscow, USSR, 1986
[2] Khristich, V. A., Litoshenko, V. N., Investigation of the Counter Flow Zone Dimensions behind the System of Corner Flameholders (in Russian), *Herald of KPI, Thermal engineering series*, *5* (1968), pp.10-15
[3] Butovskiy, L. S., Khristich, V. A., The Structure of Mixing Zone and Particular Qualities of Burning behind Triangle Flameholder (in Russian), in: *Theory and Practice of Gas Burning*, Leningrad, Russia, 1972, pp. 76-82
[4] Khristich, V. A., Lyubchik, G. N., About the Stability of Diffusional Combustion behind Flameholders (in Russian), in: *Theory and Practice of Gas Burning*, Leningrad, Russia, 1972, pp. 82-85
[5] Khristich, V. A., Lyubchik, G. N., The Influence of Gas Fuel Type of Combustion Process of Jet-Stabilizer Burners (in Russian), in: *Theory and Practice of Gas Burning*, Leningrad, Russia, 1972, pp. 122-132
[6] Khristich, V. A., Tumanovskiy, G. B., *Gas Turbine Engines and Environmental Protection* (in Russian), Kiev, Ukraina SSR, 1983
[7] Khristich, V. A., Annular Combustion Chamber for Gas Turbine (in Russian), Patent SU169948
[8] Dostiyarov, A. M., Development of Fuel-Burning Arrangement with Microflame Burning and Method of Calculation (in Russian), Ph. D. thesis, Almaty, Kazakhstan, 2000
[9] Lovett, J. A., Abuaf, N., Emissions and Stability Characteristics of Flameholders for Lean-Premixed Combustion, ASME paper 92-GT-120, 1998
[10] Dally, B. B., *et al.,* Measurements of NO in Turbulent Non-Premixed Flames Stabilized on a Bluff Body. *Symposium (International) on Combustion*, *26* (1996), 2, pp. 2191-2197
[11] Maughan, J. R., *et al.,* Effect of Initial Fuel Distribution and Subsequent Mixing on Emissions from Lean, Premixed Flames, ASME paper 92-GT-121, 1992
[12] Gough, A. J., *et al.,* Measurements and Predictions in a Confined Bluff-Body Burner Modeled as an Imperfectly Stirred Reactor, *Symposium (International) on Combustion, 27* (1998), 2, pp. 31813188
[13] Dostiyarov, A. M., *et al.,* Opredelenie Kriteriev Stabilizatsii pri Mikrofakel'nom Szhiganii Topliva (The Determination of Flame Stabilization with Microflame Burning – in Russian), *South-Kazakhstan Univer-sity, Herald of KazNTU*, Shymkent, Kazakhstan*,* 2000, pp. 67-69
[14] Umyshev, D. R., *et al*., Klassifikatsiya Metodov Snizheniya Oksidov Azota i Uluchsheniya Peremeshivaniya TVS (Classification Methods for the Suppression of NO_x Emissions and Mitigation through Improved of Mixture Formation of Air-Fuel Mixture – in Russian), *Herald of KazNTU,* Almaty, Kazakhstan, (2015), pp. 35-40
[15] Trembovlya, V. I., *et al.,* Teplo-Tekhnicheskie Ispytaniya Kotel'nykh Ustanovok (*Thermo-Technical Test of Boilers* – in Russian), Moscow, 1991
[16] Pchelkin, Yu. M., *et al.,* Kharakteristiki Raboty Gazovykh Turbin i Ustanovok (The Work Characteristics of Gas Turbines and Units – in Russian), Moscow, 1989
[17] Aiwu, F., *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
[18] Aiwu, F., *et al.,* Interactions between Heat Transfer, Flow Field and Flame Stabilization in a Micro-Combustor with a Bluff Body, *Int. Journal of Heat and Mass Transfer, 66* (2013), Nov., pp. 72-79
[19] 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
[20] Aiwu, F., *et al.*, The Effect of the Blockage Ratio on the Blow-off Limit of a Hydrogen/Air Flame in a Planar Micro-Combustor with a Bluff Body, *Int. J. of Hydrogen Energy*, *38* (2013), 26, pp. 11438-11445
[21] Gong, F., *et al.,* Size Effect on the Flame Base Locations after V-Gutters for Premixed Flames, *International Journal of Heat and Mass Transfer*, *82* (2015), Mar., pp. 406-418
[22] Tuttle, S. G., *et al.,* Lean Blow-off behavior of Asymmetrically-Fueled Bluff Body-Stabilized Flames, *Combustion and Flame*, *160* (2013), 9, pp. 1677-1692
[23] Song, J. *et al.,* An Experimental Study on the Flame Dynamics with V-Gutter Type Flameholder in the Model Combustor, *Proceedings*, 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 2011, San Diego, Cal., USA
[24] ***, ANSYS FLUENT 13.0 Theory Guide
[25] ***, ANSYS FLUENT 13.0 User's Guide

Paper submitted: December 9, 2015
Paper revised: March 11, 2016
Paper accepted: March 17, 2016