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Research Article

EXPERIMENTAL INVESTIGATION OF RECIRCULATION ZONES BEHIND V-GUTTER FLAMEHOLDERS

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Abstract

The experimental investigation of the recirculation zones behind v-gutter flameholders has been conducted. The blowout limits, flame length, inlet and outlet pressures, and velocities were duly measured, using the laboratory equipment. It was observed that the perforated v-gutters considerably increase the blowout performance. Also, it was determined that there is a strong dependence of the blowout limits on the absolute air flow into the recirculation zone. The conducted experiment shows the correlations between the blowout limits and the absolute air flow into the recirculation zone. On the basis of the conducted experiment, the authors offered an equation for the calculation of the lean blowout limits.

The conducted experiment and CFD modelling revealed a strong influence of the v-gutter type on the blowout performance and the velocity contours in the recirculation zones.

Keywords: v-gutter flameholder, recirculation zone, combustion, blowout

Introduction

One of the principles of microflame combustion is to provide the entire amount of air in the primary zone, without using the dilution zone. 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. The combustion chambers, with v-gutter flameholders, could be considered as such. Ballal and Lefebvre [1,2,3] investigated the effects of inlet air temperature, pressure, velocity, and turbulence on the lean blowout performance of the flameholders. The experiment showed that blowout is strongly influenced by the processes taking place inside the recirculation zones, such as time of residence of gases in the recirculation zone and their combustion. The influence of approach stream, Mach number, and the angles of flameholders on blowout performance was investigated in [4]. The minimal equivalence ratio has been obtained by increasing the angle up to 90 degrees, and at a relatively lower Mach number. Generally, the stability limits are extended by [1] a reduction in the approach stream velocity, turbulence intensity, and an increase in flameholder size. Investigation of the combustion process of lean hydrogen/air mixture with a bluff body [5-7] showed that the blowout limits are extended by their increase in equivalence ratio. Also, the combustion efficiency and exhaust gas temperature increase first, and then decrease with the increase in the inlet velocity. Under the comprehensive effect of the V-gutter vortex and the swirl flow vortex, the stability of combustion is benefited, and there is a subsequent reduction of the drag [8]. The investigation of lean blowout process [9] showed that during the blowout event, the overall blowout occurred with the gradual elimination of the flame fragments behind the recirculation zone. Similar results were obtained [10] for premixed fuel. The processes of stabilization of the flame, with bluff body in laminar flow for various materials, were studied in [11]. It is shown that the premixed flame anchors at an immediate downstream location near the bluff-body, where the favorable ignition conditions are established. Such location has high temperature, due to the intensified heat and mass transfer between the bluff body and reactants. The influence of approach stream velocity and the v-gutter size on blowout performance was investigated in [12]. 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 [13]. The results showed that for a given velocity, the increased fuel profile asymmetry caused an increase in the blowout equivalence ratio. Great contribution to the study of combustion processes with bluff bodies was done by the Soviet authors [14-19]. The influence of different types of bluff bodies and types of fuel introduction was investigated. On the basis of the presented materials, it can be concluded, that by using bluff bodies as flameholders, it is significant to know the quantity of air entering the recirculation zone, as it affects the amount of fuel that can be burned efficiently. As the approach speed increases to the limits of the blowout, the shape and flame length changes. The blowout with bluff body flameholders occur due to the decrease in the contact time between a combustible mixture and gases from reverse flow. Intensification of the flow, including in the area of reverse flows (recirculation zone), leads to the intense heat extraction from the flame to the recirculation zone, before the combustion can spread to the whole flow [14-19]. On the basis of the conducted analysis, authors conducted an experimental investigation of the v-gutter flameholders, with special emphasis on the processes of air entrainment into the recirculation zone.

Experimental setup and method

The main diagram of the experimental setup is shown in fig.1.

The main elements of experimental setup:

- Air compressor;
- Section for equalization of the velocity field, which consists stabilization tubes with diameter ø16 mm.
- Gas supply system which consists gas cylinder,connected flowmeter and gas inlet;
- Section with v-gutter flame holder (combustion chamber);
- Metering devices: anemometer and manometer;

Fuel – pure propane. As an ignition device we used electric ignition system consisting of a block of ignition, rectifier and spark. The diameter of experimental tube ø0,15 m, length – 0,9 m. The air flow of compressor was controlled by transformer connected to 220 V line.

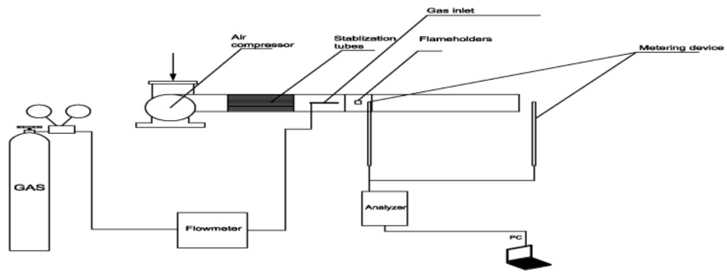

Fig. 1. The main diagram of the experimental setup.

For all experimental cases, the air flow speed was fixed to12m/s and fuel rate changed from 0.5-1.13 kg/h to simulate different equivalence ratios. The experimental setup is working as following: gas under high pressure is supplied in a fixed rate to v-gutter through ø5mm copper tube. The air is supplied through compressor and velocity field of air is equalized in stabilization tube.

Schematic diagram of v-gutter flameholderis presented in fig. 2. During the experiment we used four types of v-gutter. The paper defines that small v-gutters should be considered as standard flameholders (type 1,2).

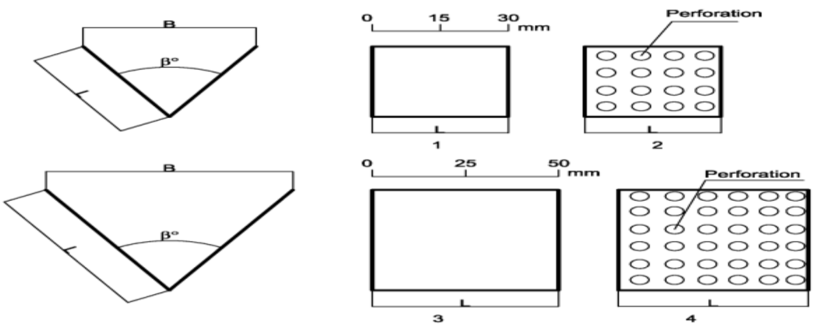

Fig. 2. Schematic diagrams of v-gutter flameholder: 1,2,3,4 – the types of flameholder investigated in experiment.

Results and discussion

Absolute air flow into the recirculation zone

The following equation was used for determining the absolute air flow into the recirculation zone:

$$G_{rec} = \frac{G_{min}^{fuel} L_0 V_{rec}}{\varphi_{LBO} V_{flame} \omega_{air} F \gamma} \quad (1)$$

The dependence of the absolute air flow into the recirculation zone behind the v-gutter flameholders on the flameholder width is shown in Figure 3. The maximum value of the absolute air flow into the recirculation zone is achieved using a standard v-gutter (type 1) at 30-mm width. The extension of the width, up to 35 mm, leads to a sharp reduction in the air involvement at the recirculation zone.

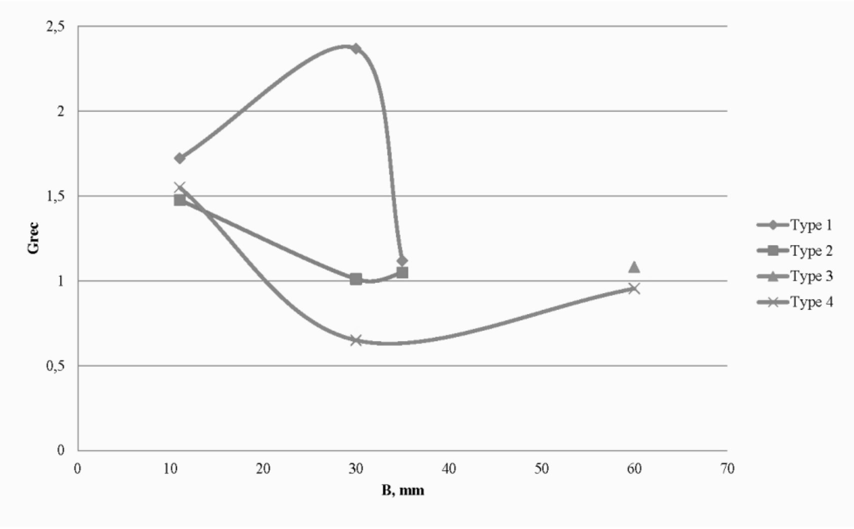

Fig. 3. Influence of flameholder size on the absolute air flow into the recirculation zone.

Perforated v-gutters have lower values of absolute air flow in the recirculation zone.However, there is some visible growth at a width of 35 mm, which is equal to the angle of 90°. This is caused by the increase in the resistance generated by the flameholder, due to the increase in the congestion. This fact leads to a stronger air swirl at the edges of the flameholder, which increases the air volume inside the recirculation zone. It should be noted that when using a large v-gutter (type 3), the flame blowout occurred after a few seconds in all the variants, except for the width of 60 mm. The lowest values of the air flow were obtained when using large perforated v-gutters (type 4). As the Figure shows, the minimum value is achieved at a width of 30 mm, and there is some growth, with further increase in the width, up to 60 mm.

Air flow depends considerably on the v-gutter width, however, this dependence is complicated, and there is a certain value, after which, a sharp change occurs: the decrease in case of a standard v-gutter, or increase in case of a large perforated v-gutter.

Flame length

The dependence of the L/B complex on the flameholder width is shown in Figure 4. When using perforated v-gutters (type 2), the flame length at a width of 11 mm reaches the maximum size. When the width increases up to 30 mm, the flame becomes much shorter, and the value of the L/B complex reaches ≈5.

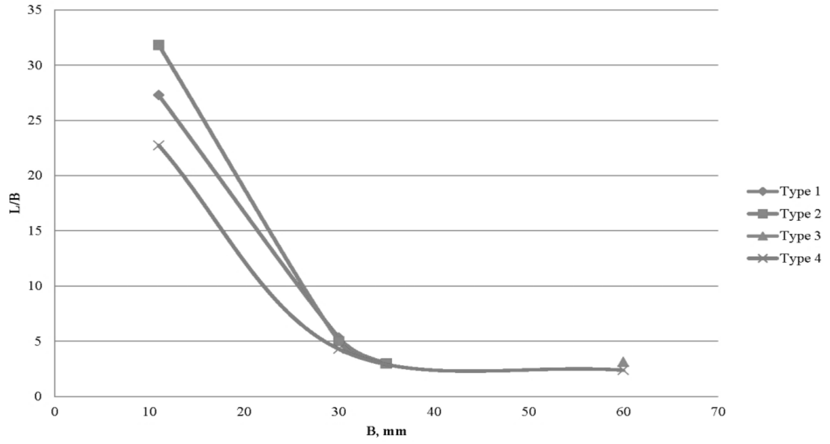

Fig. 4. Influence of flameholder size on the length of the flame.

Such dependence is typical for all the three variants of v-gutters. However, the smallest size had a large perforated v-gutter (type 4). The diagram indicates that the L/B ratio depends on the v-gutter width, and is very weakly dependent on the type of v-gutter. It is also apparent that regardless of the type of the v-gutter, as the flameholder width increases, the value of the L/B complex tends to become a single value ≈3.

Lean blowout

The dependence of the equivalence ratio values at lean blowout on the flameholder width is shown in Figure 5. As an incomplete amount of air volume was involved in the combustion process, the equivalence ratio was calculated, using the following formula [20]:

$$\varphi = \frac{m_{fuel}}{m_{air} \cdot 0.2} = \frac{4 \cdot m_{fuel}}{1.2 \cdot \omega \cdot \pi \cdot 3.14 \cdot F^2 \cdot 0.2} \quad (2)$$

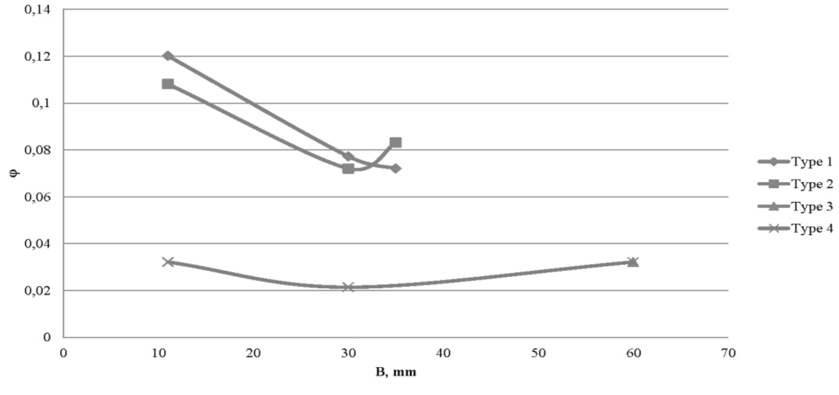

Fig. 5. Influence of flameholder size on lean blowout limits.

It is apparent that using a standard v-gutter (type 1) expansion of the flameholder width leads to the extension of the blowout limit. A perforated v-gutter (type 2) within the whole range, except for B=35 mm, has better performance indicators, as compared to a standard v-gutter. However, when the width is B = 35 mm, the blowout limit decreases. It also apparent that the use of large perforated v-gutters (type 4) lead to a considerable increase in thestabilization of the flame. The fuel concentration value, with the use of such v-gutters, is several times lower when compared to the standard v-gutters (type 1, 2). It was also noticed that a large non-perforated v-gutter (type 3) had very poor characteristics, as the flame combustion was stable at the width of 60 mm only. All theories relating to flame stabilization indicate [1] that the expansion of the flameholder width increases the limits of stable combustion. However, the walls in the channel system restrict the air flow around the flameholder, which results in the air speed becoming higher than it would be in the open space. Such circumstances lead to the reduction in the width of the recirculation zone. It can be concluded that an increase in the geometric blockage - by way of increasing the size of flameholders or narrowing the channel - reduces the size of the recirculation zone, which, in turn, leads to a reduction in stability. This was noticed when the width of the perforated flameholders increased up to 60 mm. The dependence of lean blowout limits on the absolute air flow into the recirculation zone is shown in Figure 6. It is apparent that with the use of standard v-gutters (type 1), there is an air flow, at which, the maximum blowout value is achieved, Grec≈1.7. With an increase in the air flow, the blowout limits reduce slightly. The type of dependence for the perforated v-gutter (type 2) is practically identical. The maximum φ blowout value is achieved at Grec ≈1.5. It is apparent than when using large v-gutters (types 3,4) the blowout limits, at similar Grec values, are much lower.

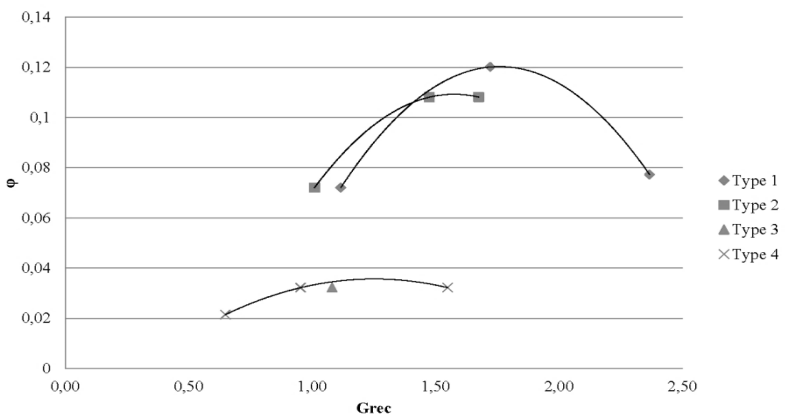

Fig. 6. Influence of absolute air flow on lean blowout performance.

It may be concluded from the data presented that there is a significant dependence of blowout limits on the air flow into the recirculation zone. When using large perforated v-gutters (type 4), the blowout limits depend much less on the absolute air flow, into the recirculation zone.

Pressure losses

The dependence of pressure losses on the type and width of v-gutters is shown in Figure 7. The following formula [19] was used for the calculation of pressure losses:

$$\sigma = \frac{P_{in}-P_{out}}{P_{in}} \cdot 100\% \quad (3)$$

Obviously, the expansion of the v-gutter width leads to increasing air losses. At the v-gutter width of 11 mm, all of them have similar loss values, which is associated with the fact that such width of the v-gutter has a minor impact on the flow. When the width increases up to 35 mm, pressure losses of the standard v-gutters (type 1) amount to 25%. Losses of similar perforated v-gutters (type 2) are equal to 22%. An expansion of the width up to 60 mm while using perforated v-gutters (type 4), leads to an increase in losses up to 25-26%. Losses of non-perforated v-gutters, at the same width, are equal to 27-28%. It may be concluded from these results that the pressure losses depend insignificantly on the type of v-gutters, but depend greatly on their width.

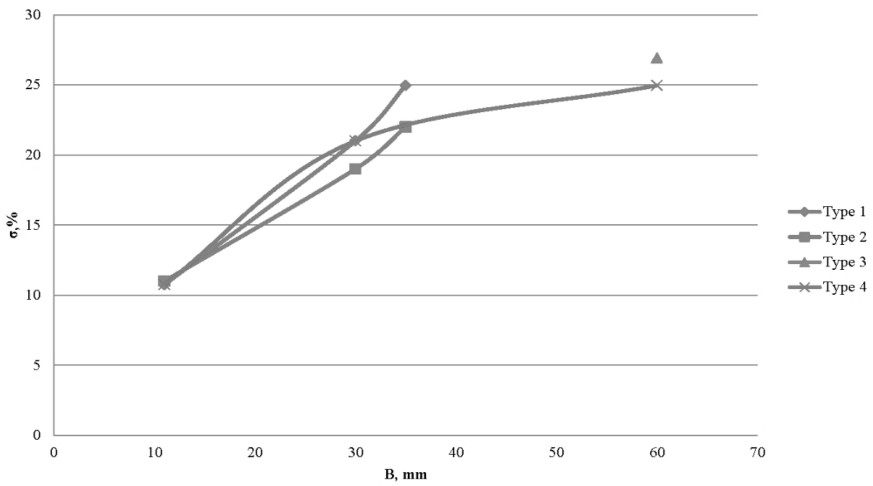

Fig 7. Influence of flameholder size pressure loss.

Combustion intensity of the combustion zone

The equation given in [17] was used to determine the combustion intensity:

$$q_v = \frac{Q_w^l\sqrt{\rho_g\omega_g}\sqrt{\rho_{air}\omega_{air}}}{(L_0+1)\cdot P\cdot L}\left(\frac{d}{B}\right)^{1.2} \quad (4)$$

The dependence of the combustion intensity on the v-gutter flameholder width is shown in Figure 8. When using v-gutters of 1 and 2 types, the combustion intensity does not depend strongly on the flameholder width, and is within the range of 17000-14000 W/m^3. However, the large size of the v-gutter flameholders lead to a considerable increase in the combustion intensity. At the width of 11 mm, the q_v value is equal to 33000; expansion of the width, up to 60mm, leads to thedecreaseof the combustion intensity to 24000-25000 W/m^3.

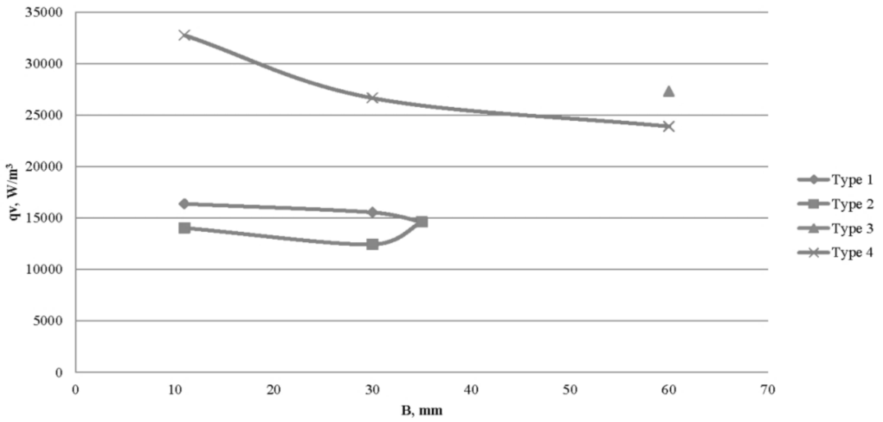

Fig 8. Influence of flameholder size on combustion intensity.

Formula for determining blowout limits

A modified variant of formula [15] was presented on the basis of the obtained experimental data for lean blowout limits calculation, using bluff bodies in the form of v-gutter flameholders. The formula takes into account the v-gutter surface structure and the efficiency of fuel mixing in the recirculation zone.

$$\lambda_{LBO} = kk_{mix}\left[6\left(\frac{B}{d}\right)^{1.2}\frac{\rho_{air}\omega_{air}}{\rho_{g}\omega_{gmin}}^{0.5}\right] \quad (5)$$

Flame structure

Photos of the flame behind the v-gutter flame holders, at various widths, are shown in Figure 9. As noted, the increase in the v-gutter width leads to the expansion of the recirculation zone. At the width of 35 mm, the flame has two recirculation zones. It is also apparent that there is a thin blue line, breaking away from the v-gutter edge. It should be noted that its size increases as the distance grows. Reduction in the v-gutter width leads to the narrowing of the recirculation zone, and elongation of the flame. When using perforated v-gutters, the flame structure is similar. However, in contrast to the standard v-gutters (type 1), there is a high-temperature bright yellow zone "inside" the perforated v-gutters.

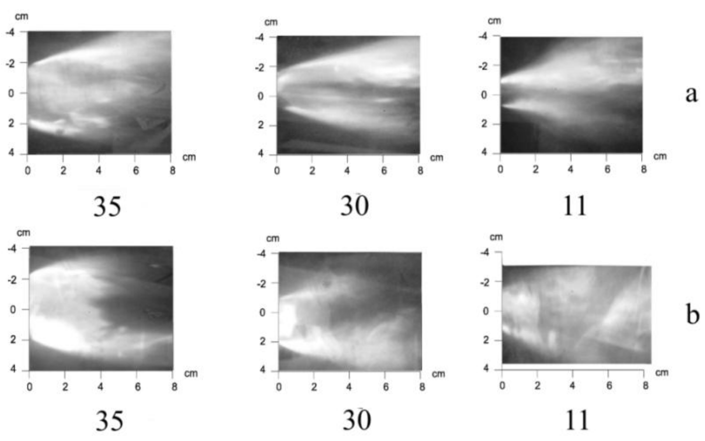

Fig 9. Influence of flameholder size on flame structure. a-type 1, b – type 2.

CFD analysis

CFD analysis of the combustion process behind the v-gutter flameholders was carried out, with the aim to confirm the obtained results. Longitudinal velocity profiles were obtained, as seen in Figure 10. The article defines that the velocities lower than or equal to zero are considered to be the recirculation zones. As the figures show, the expansion of the flameholder width leads to an increase in the recirculation zone. It should be noted that at the minimum width, a flow is practically undisturbed. Expansion of the width leads to the appearance of negative v behind the flameholders, and an increase of the velocities at v-gutter edges. As the figures show, the maximum speed values reaches 20 m/s.

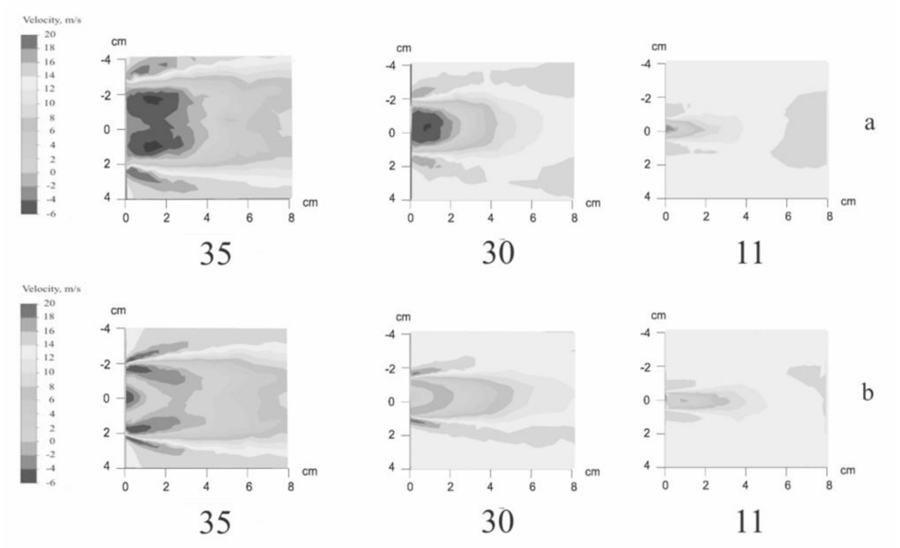

Fig 10. The longitudinal velocity profiles behind flameholders. a-type 1, b – type 2.

As mentioned above, a flow in the channel results in the velocities around the flameholdersto have higher values, which leads to a certain narrowing of the recirculation zone. There are also significant differences noticed between the recirculation zone of a standard v-gutter (type 1) and a perforated one (type 2). When using a perforated v-gutter, there are zones of positive and negative speeds which may appear within the v-gutters, allowing the mixing of fuel and air in a more efficient manner. It is also obvious that at the width of 35 mm, the velocity profiles around the v-gutters have lower values, due to the fact that a part of the air enters the recirculation zone through the perforations. According to [1], the speed reduction around the v-gutter leads to an increase in the limit of stable operation, proved by the experiment conducted.

Conclusions

The dependence of absolute air flow into the recirculation zone onthe width and type of flameholders was investigated. When using perforated flameholders, the air flow into the recirculation zone was less than that with standard flameholder. However, at the same values of air flow, the perforated flameholders showed a better blowout performance.

It is shown that the flame length is mostly dependent on the width of theflameholder. The perforated and standardflameholders had a few differences. Also, it showed that the big perforated flameholders can increase the combustion intensity by 1.5-2 times, compared to the standard flameholders.

On the basis of the conducted experiment, the authors offered an equation for the calculation of the lean blowout limits. Conducted CFD modelling revealed the strong influence of the v-gutter type on the blowout performance, and the velocity contours in the recirculation zones.

Nomenclature

B – width of flameholder [mm]

d – nozzle diameter [mm]

F – area of the flameholder [m^2]

G_{min}^{fuel} – fuel flow on the blowout [kg/s]

L_0 – stoichiometric coefficient(=$10\cdot10^{-3}\cdot0{,}266\cdot Q^{w}_{l}$)[-]

L – flame length [m]

P – pressure, [kPa]

Q^{l}_{w} – lower heating value [kJm^{-3}]

q_v – combustion intensity [Wm^{-3}]

V_{rec} – volume of recirculation zone [m^3]

V_{flame} – volume of the flame [m^3]

Greek symbols

ρ_{air} – density of air [kgm^{-3}]

ρ_{gas} – density of gas [kgm^{-3}]

γ – specific density of air [m^3kg]

ω_{air} – air velocity [ms^{-1}]

ω_g – gas velocity [ms^{-1}]

φ_{LBO}– lean blowout equivalence ratio [-]

φ – equivalence ratio [-]

References

1. Lefebre. A. *Gas turbine combustion*, Moscow,USSR (in Russian) 1986.
2. D. R.Ballal , and A. H. Lefebvre, Weak Extinction Limits of Turbulent Flowing Mixtures, *Journal of Engineering for Power*, 1979, Vol 101, No. 3, pp343–348.
3. Ballal, D. R. and A. H. Lefebvre, Some Fundamental Aspects of Flame Stabilization,*Fifth International Symposium on Air Breathing Engines,* AIAA, Washington, DC, 1981, *Vol 8*, pp48.1–48.
4. M.Barrère, and A.Mestre, Stabilisation des Flammes par des Obstacles, *Selected Combustion Problems: Fundamentals and Aeronautical Applications*,Butterworth, London, UK,1954, pp426–46.
5. Aiwu Fan, *et.al.*, Effect of bluff body shape on the blow-off limit of hydrogen/air flame in a planar micro-combustor,*Applied Thermal Engineering*, 2014, *Vol* 62, pp13-19.
6. Aiwu Fan, *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*, 2013,Vol 66,pp72–79.
7. Jianlong Wana, 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*,2012, *Vol 37*, pp.19190-19197.
8. Gan Dong, *et.al*, Study on the Vortex Shedding Mechanism of Coupling Combustion Stabilizer with V-gutter and Strong Swirl Flow,*Asia-Pacific International Symposium on Aerospace Technology*, 2014, APISAT2014, Shanghai, China.
9. J.R. Dawsona*et.al*, Visualization of blow-off events in bluff-body stabilized turbulent premixed flames, *Proceedings of the Combustion Institute*, 2011, *Vol 33*, pp.1559–1566.
10. KariukiJames, et.al, Measurements in turbulent premixed bluff body flames close to blow-off, *Combustion and Flame*, 2012, *Vol 159(8)*, pp2589–2607.
11. S. K. Kushal, A. F. Ghoniem, The anchoring mechanism of a bluff-body stabilized laminar premixed flame, *Combustion and Flame*,2014, *Vol 161*, pp2327–2339.
12. Fan Gong, *et.al*, Size effect on the flame base locations after V-gutters for premixed flames, *International Journal of Heat and Mass Transfer*2015, Vol 82,pp406–418.
13. S. G. Tuttle, M. W. Renfro, J. M. Cohen, Lean blowoff behavior of asymmetrically-fueled bluff body-stabilized flames. *Combustion and Flame*2013, *Vol 160*,pp1677–1692.

14. V.A. Khristich, V.N. Litoshenko. Investigation of the counter flow zone dimensions behind the system of corner flameholders. *HeraldofKPI. Thermalengineeringseries*, 1968, *Vol 5*, pp10-15
15. ButovskiyL.S., KhristichV.A., The structure of mixing zone and particular qualities ofburning behind triangle flameholder, in: *Theory and practice of gasburning*, Leningrad 1972, pp76-82
16. KhristichV.A., LyubchikG.N., About the stability of diffusional combustion behind flameholders, in: *Theory and practice of gasburning*, Leningrad 1972, pp82-85
17. KhristichV.A., LyubchikG.N., The influence of gas fuel type of combustion process of jet-stabilizerburners, in:*Theoryandpracticeofgasburning*, Leningrad 1972, pp12-132
18. Turns S.R., An Introduction to Combustion, second ed.,McGraw-Hill 2005, p567.
19. Pchelkin Y.M. Combustion chambers of gas turbines, Moscow 1984.