EXPRERIMENTAL INVESTIGATION OF DISTANCE BETWEEN V-GUTTERS ON FLAME STABILIZATION AND NO_X EMISSIONS

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Blow-off performance and NOx emissions of the propane and air mixture in a rectangular combustion chamber with bluff bodies were investigated experimentally and numerically. The effects of distance between bluff bodies on NOx emissions, the blow-off limit, and exhaust gas temperature were examined. It was observed that NOx emissions are highly dependent on distance between v-gutters.

The recirculation zone behind the bluff body expands in width based on the decrease of distance between v-gutters, and expands in length with the increase of inlet velocity. The temperature fields behind the bluff body show a similar change, the temperature behind the bluff body reaches its highest when the distance between v-gutters reaches 20 mm, meaning it has better flame stability.

The blow-off limit is significantly improved with the decrease of distance between v-gutters. The blow-off limit is greatly improved by reducing the distance between the v-gutters. Maximum blow-off limit of 0.11 is reached in the case of 20 mm, compared with 0.16 at 50 mm at a speed of 10 m/s.

Keywords: *combustion, flame stabilization, bluff body, blow off, v-gutter,* NO_x

Introduction

Ballal and Lefebvre [1-3] investigated the effects of inlet air temperature, pressure, velocity, and turbulence on the lean blow-off performance of flame holders supplied with homogeneous mixtures of gaseous propane and air. They discovered that flame stabilization can be achieved by a highly developed recirculation zone and high temperature behind bluff bodies. Barrère, M., and Mestre A. [4] investigated the influence of the Mach number on flame stabilization. The minimal equivalence ratio is achieved by increasing the angle up to 90 degrees, and at a relatively low Mach number. In general, stability limits are extended by [1] a reduction in the approach stream velocity, turbulence intensity, and an increase in flame holder size.

Aiwu Fan *et al*. [5-7, 20] conducted an in-depth study of combustion, stabilization, and heat exchange using bluff bodies with hydrogen mixed fuels. The influence of different types of stabilizers, as well as various options for fuel injection, the arrangement of bluff bodies and the installation of flame bridges [14-17] showed that v-gutter flame holders have a wide range for stabilization. The results indicate that the blow-off limit of flame can be extended in a combustor with a bluff body with an increase of the fuel supply, and that the temperature of the gases first increases, and then decreases.

Study of the vortex shedding mechanism of the coupling combustion stabilizer with a v-gutter and strong swirl flow [8,9] showed that the vortex shedding mechanism of the flameholder is controlled by the swirling flow and the flow around the flameholder can increase the length of the recirculation zone. Similar results were achieved for lean premixed fuel [10]. The anchoring mechanism of a bluff-body stabilized laminar premixed flame [11] showed that premixed flame anchors are at an immediate downstream location near the bluff-body where favorable ignition conditions are established.

Size effect on flame base locations after V-gutters for premixed flames [12] showed that as the inlet velocity increases, the flame bases move upstream, while the recirculation zone extends downstream.

Steven G. Tuttle *et al.*, studied the lean blow-off behavior of asymmetrically-fueled bluff body-stabilized flames [13]. He discovered that for a given velocity, increased fuel profile asymmetry caused an increase in the blow-off equivalence ratio. Soviet authors also conducted experiments with v-gutters [14-19]. They demonstrated that lean blow-off behavior is highly dependent on the amount of fuel in the recirculation zones and shape of the bluff body.

The study of the formation of harmful substances in the use of various bluff bodies [21-28] showed that bluff bodies can be an inexpensive solution for the construction of modern combustion chambers with low emissions of toxic substances.

The experimental investigation of [29] regarding steady laminar premixed flames on a square bluff body in a channel showed that the flame stabilizes in such a location that balances the flame’s ability to sustain stretch and the impact of the stretch on heat release. Experimental investigations of the combustion process behind bluff bodies [30] proved that the flame front structure was observed to be strongly dependent on the mean velocity, as well as the free stream turbulence level of the incoming fuel/air mixture. Increasing the mean velocity changes the position of the flame with respect to the shear layer, and consequently modifies interactions with the roll-up of vortices in the shear layer. An experimental study of the effect of different levels of free stream turbulence on the blow-off dynamics of a bluff-body stabilized flame [31] showed that the length of the recirculation zone was observed to decrease significantly with increasing turbulence levels, which indicates a need to study the effect of velocity on stabilization using two v-gutters. Various authors have numerically investigated the influence of bluff body shape on flame stability and combustion efficiency via CFD simulations [32-34]. The results were then used in CFD modeling conducted by the authors.

A combined experimental and numerical study of the effects of the position of a bluff-body on diffusion flames [35] showed that mounting the bluff-body 10 mm above the annular channel exit could better stabilize the flame, which more generally means that the position of the bluff body has a significant effect on combustion and emissions.

Many authors have also focused on the study of stabilization processes with bluff bodies [36-48]. In this area, particular attention must be paid to the air supply (oxidizer) velocity, and the shape, size and material of the bluff body. Regarding previous studies [49-53], it was shown that recirculation behind v-gutter bluff bodies is affected by many parameters. Given that an increase in speed leads to a narrowing of the recirculation zone on one side, and an increase in the dimensions of v-gutters leads to an increase in the size of the recirculation zone, the most pertinent issue is the study of the interaction of recirculation zones and the determination of the optimal distance between v-gutters.

Single v-gutter flameholders of different sizes, angles on the vertex and methods of fuel supply were investigated in previous studies [49-53]. The studies have demonstrted that the most effective bluff body stabilizers are v-gutters with an angle of 45^0 on the vertex and a wall length of 30 mm. They allow sufficiently high stabilization characteristics and low concentrations of nitrogen oxides at the output of the experimental rig. The study of fuel supply methods showed that diffusion combustion produced by fuel supply to the v-gutter's axis of symmetry has a fairly good combustion performance. Based on previous experiments, the authors decided to study the interaction of combustion behind two v-gutter flameholders and the corresponding distance between them. In this experiment, v-gutters with an angle of 45º on the vertex, a length of 30 mm and a separate fuel supply to the v-gutter’s axis of symmetry were used.

1. Experimental apparatus and experiment methodology

The scheme of the combustor with v-gutter flame holders is depicted in Fig. 1. The total length of the combustor is 900 mm, the width and height of the combustor is 150 mm, and wall thickness of the combustion chamber is 0.5 mm. The distance from nozzle to vertex of the v-gutters is 30 mm. The general view of the v-gutters is presented in Fig.3. The v-gutters were placed symmetrically to the cross section of the combustor. The length of the v-gutter walls is 30 mm, height 30 mm. The angle on the vertex is 45º.

The experimental setup is presented in Fig. 2. The main elements of the experimental setup are: the air fan, section for equalization of the velocity field consisting of stabilization tubes with a diameter of 16 mm; gas supply system consisting of a gas cylinder, valve and connected flowmeter; combustor with v-gutter flameholders, quartz tube, the thermocouple group on the outlet of the combustor, and gas analyzer connected to the PC. Propane of high pressure is stored in the gas tank. The gas tank’s pressure was reduced to atmospheric pressure using pressure reducing valves, while the mass flow rate was adjusted and controlled by electric mass flow meter with an accuracy of 1% over the full range. The fuel and air streams mixed in the combustion zone. The propane was divided in two parts before entering the combustion chamber to supply both v-gutters. An electric spark igniter was used to ignite the fresh gaseous mixture.

The vertical distance between the v-gutters at the trailing edge in order to be more independent to the width of the v-gutter was set, as shown in Figure 3. The flame was ignited without an air supply, with a minimum fuel consumption of 0.0005 kg/s, then the fan speed gradually increased, in steps of 1 m/s. After reaching the required velocity from 2 to 10 m/s, the maximum fuel consumption is set at 1 kg/h. After that, the fuel consumption was reduced in steps of 0.0005 kg/s, to determine the lean blow-off.

To calculate blow-off limits, the airflow rate was constant and the fuel flow was gradually decreased till visual flame attenuation. Flow meter data was recorded, then φ_{LBO} was calculated using eq. (1). Air and fuel temperature were equal to 300 K, and atmospheric pressure was assumed. Reynolds number is 19,300 [47].

The equivalence ratio is defined by (1):

$$\varphi = \frac{F/A}{F_0/A_0} \qquad (1)$$

where, F/A is the actual ratio of fuel/air in the inlet, and F_0/A_0 is the stoichiometric fuel/air ratio.

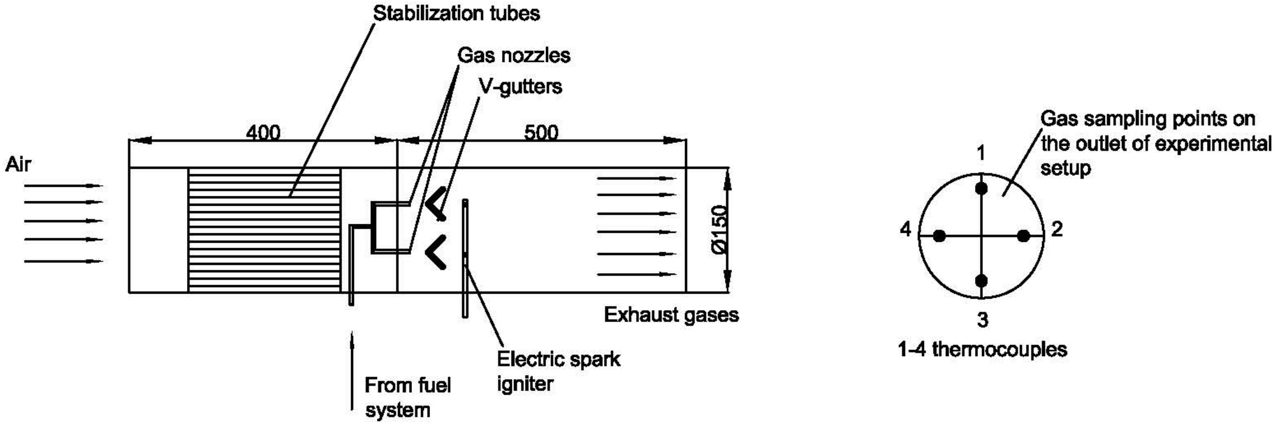

Figure 1. Schematic diagram of the combustor with a bluff body (top view)

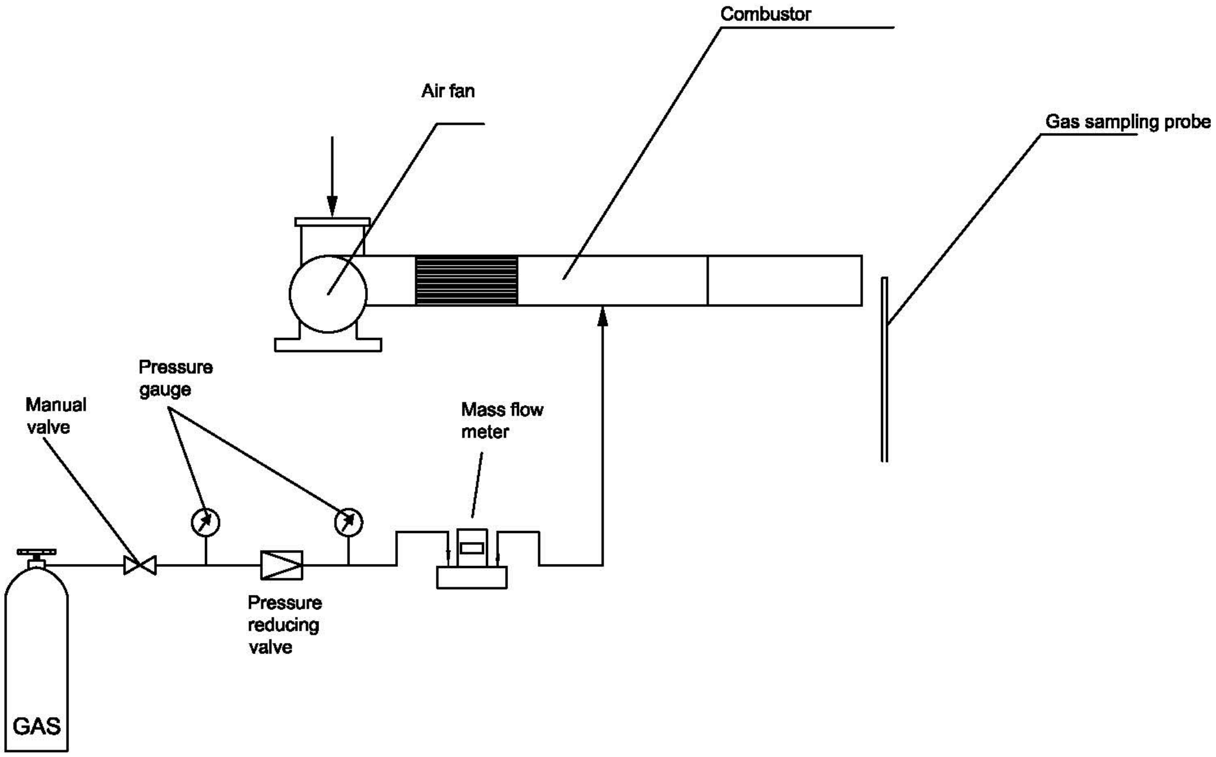

Figure 2. Schematic diagram of the experimental system (rear view)

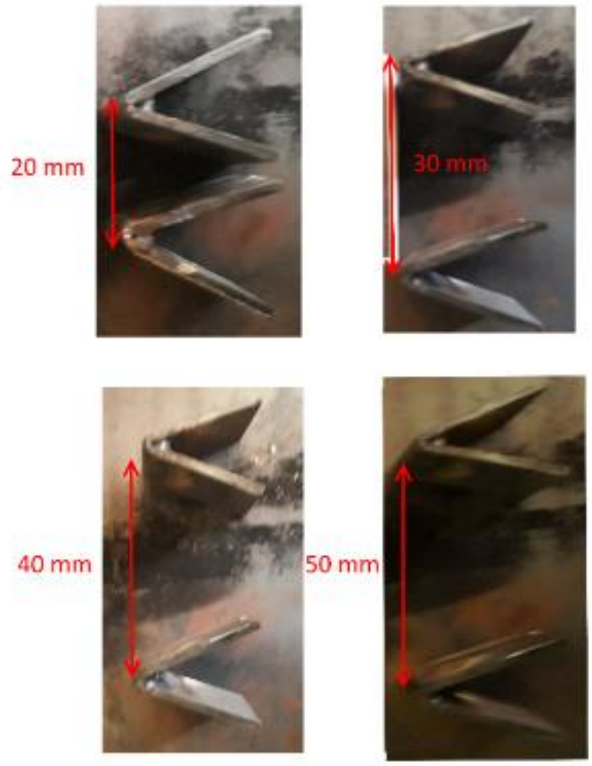

Figure 3. General view of v-gutter flame holders and the distances between them

2. Results and discussion

2.1 Lean blow off

The experimental results of blow-off limits under different velocities obtained through experimental investigations are shown in Fig. 4. It is seen from Fig. 4 that the blow-off limit decreases with an increase of velocity. This is mainly because the velocity increase leads to an increase of oxygen concentrations in the recirculation zone, which leads to a decrease of the leaning of the fuel air mixture in the recirculation zone.

The improvement in stability with an increase in flame holder diameter is attributed to the longer residence time of the reactants in the recirculation zone [1]. According to [1], the characteristic dimension of a bluff-body flame holder should not be its geometric width, but rather the maximum aerodynamic width of the wake created behind it. The increase of the flame holder diameter by decreasing the distance between v-gutters leads to the formation of a larger wake. Thus explains the increase in flame stability.

By increasing the distance between v-gutters, we have two separate v-gutters, burning almost independently from each other, which narrows the range stability. At a distance of 50 mm, lean blow-off occurs much earlier than at a distance of 20 mm. For example, at 10 m/s, the highest stabilization values for v-gutters with a distance 20 mm is equal to $\varphi = 0.11$, for a distance of 50 mm: $\varphi = 0.16$.

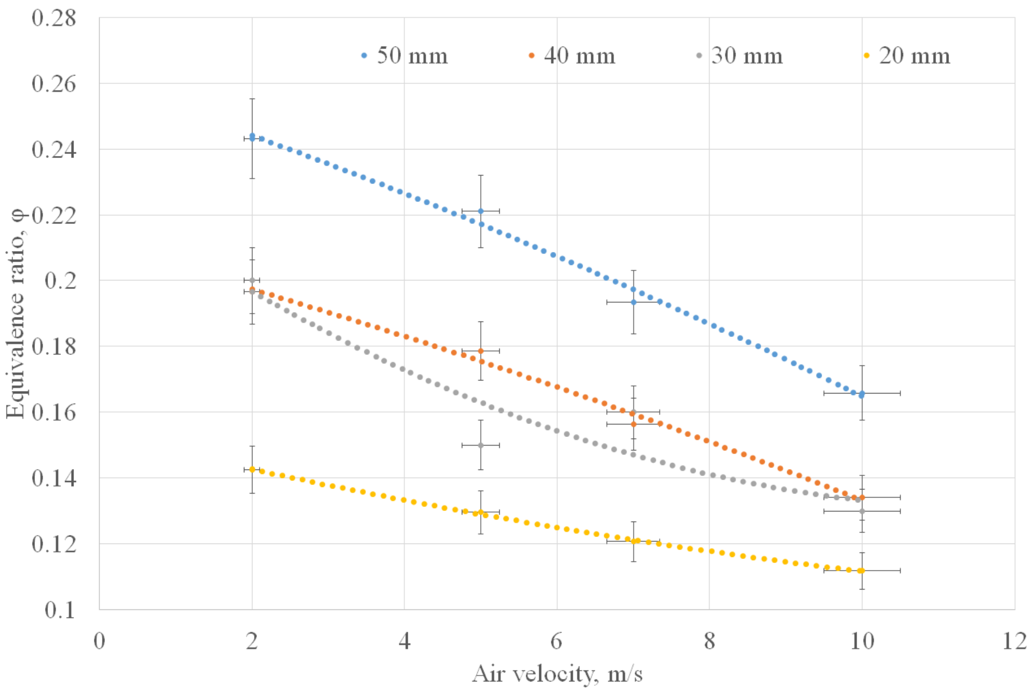

Figure 4. Influence of velocity on lean blow-off limits

2.2. The NOx formation

As is known from [1], NO emissions are highly dependent on flame temperature, residence time of the reactants in the high temperature zone, and the efficiency of the mixing process.

Nitrogen oxides are produced by the oxidation of atmospheric nitrogen in high-temperature regions, and in the post combustion parts of the combustion chamber. The process is endothermic, and proceeds at a significant rate only at temperatures above around 1850 K. Therefore, it is known that the temperature in the combustion zone depends on the excess fuel (air). A reduction of excess air, in our case of velocity, increases competition between fuel and nitrogen molecules for free oxygen, therefore the maximum concentrations of nitrogen oxides are reached from the "poor" side of stoichiometry. Another explanation is the "dilution" of the concentration of nitrogen oxides by increasing excess air in the combustion zone.

Figure 5 shows the dependence of NO_x on the equivalence ratio. When the equivalence ratio is reduced, the combustion temperature drop is so great that it overpowers the effect of increasing the free oxygen content, thus correspondingly reduces the concentration level of the formed nitrogen oxides.

It was observed that the distance between v-gutters also plays a significant role. At a minimum distance of 20 mm, the maximum amount of nitrogen oxides is formed. This is explained by the existence of a well-developed recirculation region, which increases the gas residence time in the high-temperature zone. It is known that NOx emissions increase with an increase in residence time, except for in very lean mixtures ($\phi \cong 0.4$), for which the rate of formation is so low that it becomes relatively insensitive to time. In our case, the minimal value of the equivalence ratio was equal to 0.5, which means that residence time plays a significant role in NOx production.

The increase in size leads to the capture of a large amount of oxygen, which subsequently combines with nitrogen molecules, thereby increasing the emission of nitrogen oxides. A well-developed recirculation zone also provides high temperatures in the combustion zone, which directly increases the concentration of nitrogen oxides at the outlet of the combustor. The maximum concentration of nitrogen oxides is observed at φ = 2.6, and is equal to 50 ppm, at a distance of 20 mm, which is 36% greater with the same φ for a distance of 30 mm.

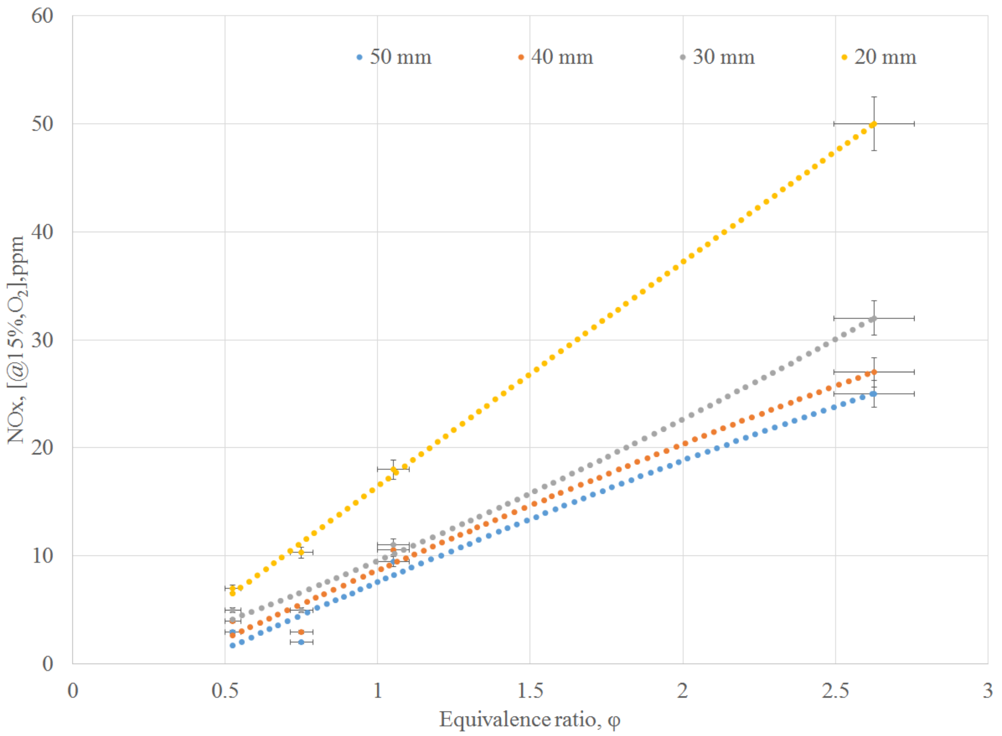

Figure 5. Influence of the equivalence ratio on NO_x emissions

2.3 Temperature

Figure 6 shows the dependence of exhaust gas temperatures from air velocity. It has been proven that temperature plays the dominant role in the formation of NO_x. The experimental data presented in Figure 6 show that the minimum distance between v-gutter increases the average temperature to 50-70 K. An increase in velocity decreases the temperature on the outlet of the combustor. The maximal temperature is achieved when there is 20 mm of distance between v-gutters, equal to 800 K. An increase in velocity leads to a decrease in the difference between outlet temperatures due to the domination of the proportion of air in the exhaust gases. The minimum temperatures are reached at 10 m/s, equal to 450-500 K.

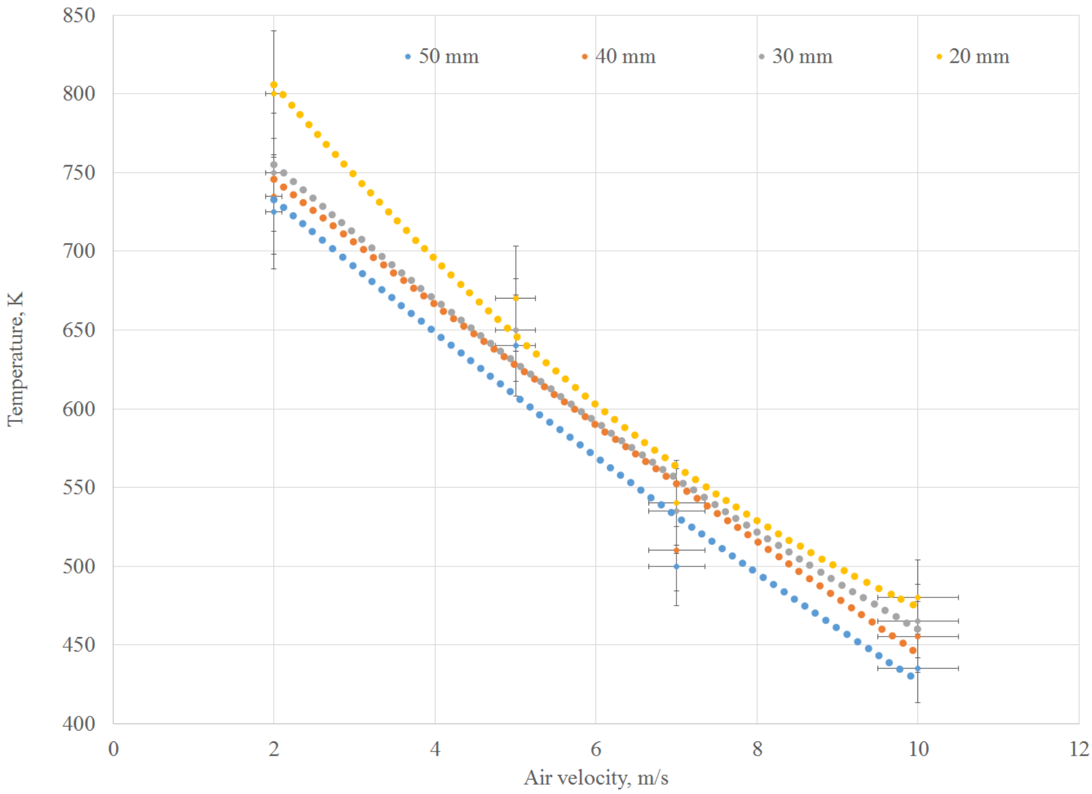

Figure 6. Influence of distance between v-gutters on exhaust gas temperature

2.4 Flame observation

Flame pictures were taken with digital high resolution camera from the top viewpoint at 5 m/s, as shown in Fig. 7.

It can be seen from Fig. 7 that a reduction of distance between v-gutters to 20 mm results in a “uniting” of the flame, which explains the increase in temperature and the formation of nitrogen oxides. It is also noticeable that, at a minimum distance, the flame has a minimum luminosity in conjunction with a short torch. This occurs because of the well-developed recirculation zone, which ensures a high temperature in the combustion zone and good mixing of the fuel-air mixture.

On the other hand, creating a well-developed recirculation zone by raising the temperature and increasing the residence time of gases in the combustion zone leads to an increase in the formation of nitrogen oxides. A well-developed recirculation zone draws in a large amount of oxygen (with air), which leads to the fact that nitrogen molecules “easily” find oxygen molecules.

The increase of distance between v-gutters leads to “independent” combustion behind each bluff body. It was noted that at a distance of 50 mm, there is practically no luminosity of the torches. At 30 mm, it is seen that the flame length and luminosity are higher compared to 50 mm. On the one hand, this reduces the temperature in the combustion zone and residence time of gases in the high-temperature zone, but on the other, this leads to the underburning of fuel, which can be seen from the increased luminosity.

The length of 40 mm is the moderate between absolutely “independent” flames and one flame observed at a distance of 20 mm.

In the figure 7 it can be seen that the flames burning behind the v-gutter flameholders have an asymmetrical shape. This is especially noticeable when the distance between the v-gutters is 50 mm.

The authors assume that the asymmetry is affected by the boundary layer formed on the walls of the quartz tube. Increasing the distance between the v-gutter flameholders leads to the v-gutters becoming closer to the near-wall region where a turbulent boundary layer is formed (given that Re>4,000).

Another cause may be the presence of fuel supply tubes, which are a kind of flow turbulizers at high velocities. The fuel supply tubes disturb the gas flow before the v-gutter flameholders which influences the symmetry of flame after them due to an uneven supply of fuel-air mixture along the walls of the corner. The symmetry of the flame can also be slightly affected by the surface roughness of the stabilizers.

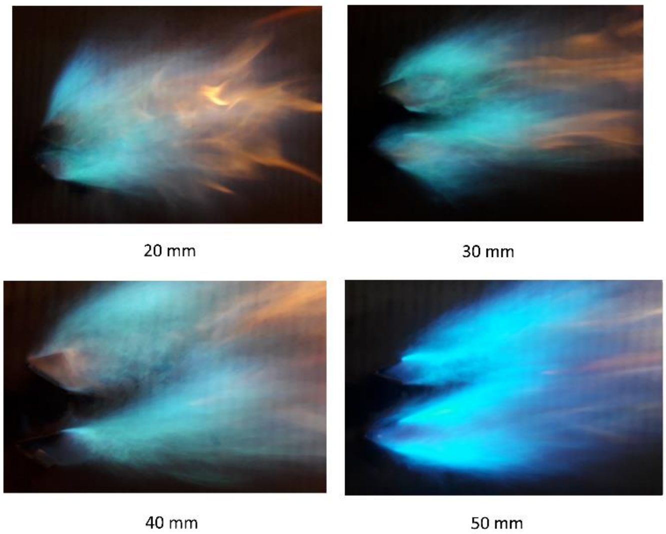

Figure 7. Flame photos for different distances between v-gutters at the same velocity of 5m/s

4. Numerical modeling

Physical model

The model of a quadrangular combustion chamber with v-gutter flameholders is given in Figure 8. The model has been made using SolidWorks software. The LWH of the simulated area is 500x150x150 mm. The distance between the v-gutters and nozzles is 30 mm. The v-gutter flameholders are 30 mm wide, just as in the experiment. The angle at the top of the v-gutters is 45º. V-gutters are arranged symmetrically in relation to the center of the combustion chamber. All other parameters, such as temperature, air velocity, fuel pressure and consumption are the same as in the experiment.

Mathematical model

ANSYS [51] software was used for simulation. The gas to air ratio was calculated according to formula (1). Density, viscosity and heat conduction were defined as piecewise-linear, the data was taken from the book [54], heat capacity is according to kinetic theory. The results were confirmed to be adequate by comparing gas temperatures at the combustion chamber outlet.

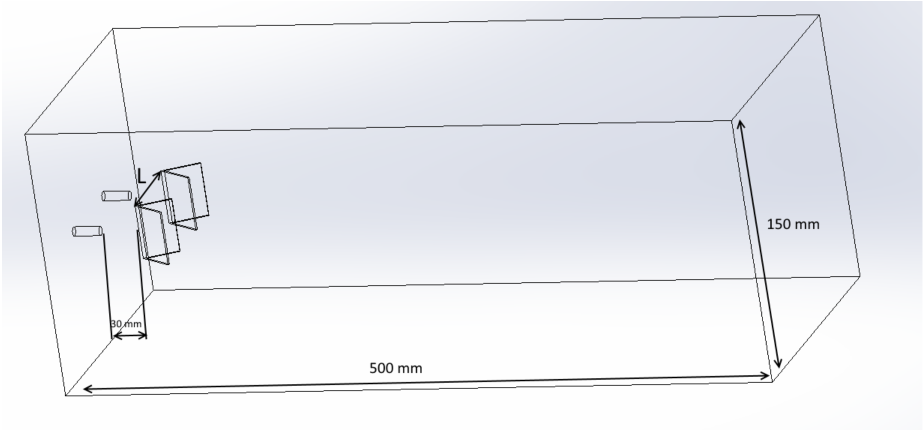

Figure 8. Schematic diagram of the combustor presented in SolidWorks

The results of numerical simulation for different distances between v-gutter flameholders, with gas-air ratio φ=1 is presented in Figure 9. As seen in the image, the v-gutter flameholder size influences blow-off performance significantly. Longer distances between v-gutters lead to decrease in the temperature within the recirculation zone, which never exceeds 1600 K. This occurs as a result of the reduced resistance drag created by the v-gutter flameholders. When closing the distance to 30 mm, the temperature in the recirculation zone will rise to 1780–1800 K. This factor will lead to increased stabilization. The rise of gas temperatures within the recirculation zone will lead to an increase in stabilization parameters, as high-temperature gases need less time to ignite fresh air-fuel mixture. However, the temperature rise will lead to higher nitrogen oxide formations due to their exponential dependency on temperature.

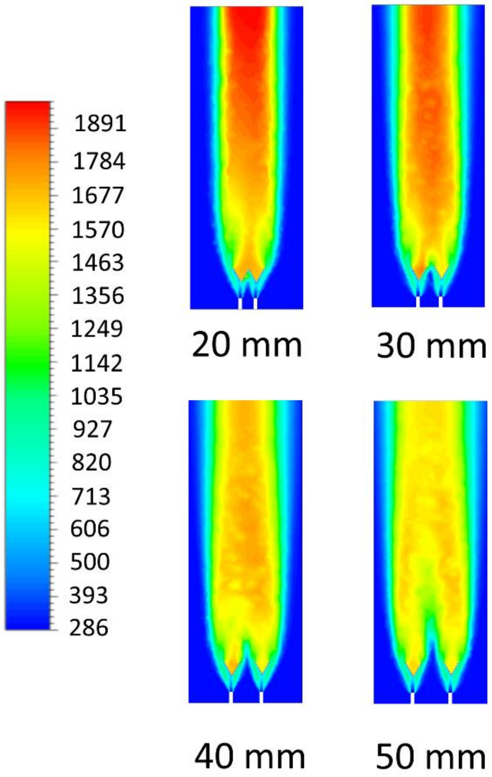

Figure 9. Numerical results of temperature fields for different distances between v-gutters at an inlet velocity of 5 m/s

Maximum temperatures are achieved when the distance between the v-gutters is 20 mm. Under these conditions, the temperature within the recirculation zone will reach 1891 K, and this will similarly lead to, on the one hand, an increase in stabilization parameters, and on the other hand, higher nitrogen oxide concentrations in the exhaust gases. The results of the simulation are to be aligned with the results of the experiment.

Figure 10 shows the longitudinal velocity in the combustion chamber. As you can be seen, the recirculation zone (marked blue, negative velocity) is intensified when the distance between the v-gutters is shortened. Notably, at distance of 20 mm, one developed recirculation zone can be detected. The results show that development of the recirculation zone will increase gas flow to the recirculation zone beyond the v-gutters. Gases combust in the recirculation zone and thus increase the temperature. This fact shows that an increase in longitudinal size will clearly result in better stabilization parameters and higher combustion efficiency.

20 mm shows the narrowest high velocity field. This is achieved by creating one bluff body by combining two v-gutters, and explains the high stability of the flame achieved in experimental measurements.

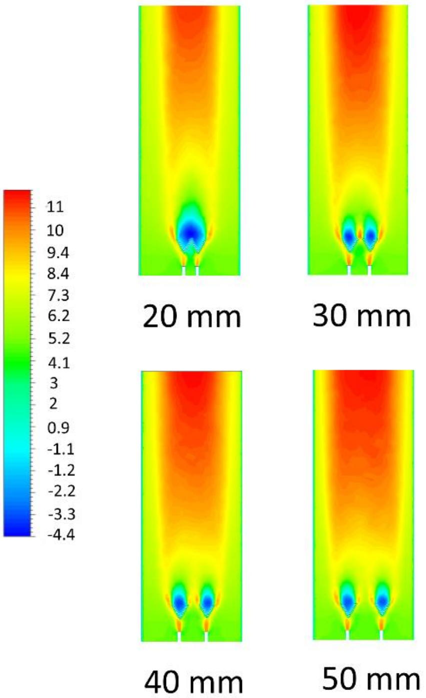

Figure 10. Numerical results of temperature fields for different distances between v-gutters at the inlet velocity of 5 m/s

5. Conclusions

At velocities of 10 m/s, lean blow-off for v-gutter flameholders with a distance of 20 mm is equal to 0.111, and for a distance of 50 mm it is 0.165. The difference is 32%, which indicates a significant affect of the distance between the v-gutters on flame stabilization. The experiments have demonstrated that increasing the distance between the v-gutters reduces the temperature of the gases at the exhaust of the experimental rig. This is due to a reduction of the recirculation zone formed behind the v-gutter flameholders by reducing the "dimensions" of the v-gutters due to the separation distance.

The increase in inlet velocity decreases the average temperature on the outlet of the combustion chamber. For 20 mm and 50 mm, NO_x emissions are 7 and 3 ppm respectively. This is explained by the existence of a well-developed recirculation zone, which increases the gas residence time in the high-temperature zone.

Based on the experiments, it can be concluded that the best option is the distance between the corners of 30 and 40 mm, which provides optimal values of lean blowout and nitrogen oxide generation. However, it should be borne in mind that the distance between the corners depends primarily on the application. For example, in afterburners which require high power and high flame stabilization characteristics it is recommended to use a small distance, i.e. 20 mm. When harmful emissions are the determining factor, a distance of 50 mm should be selected.

Nomenclature

u – velocity [m/s];

φ – equivalence ratio [-];

L- distance between v-gutters;

B – width of flameholder, [m]

d - nozzle diameter, [m];

ω_a – air speed, [ms^{-1}]

ω_g – gas speed, [ms^{-1}];

ρ_a – density of air, [kgm^{-3}]

ρ_g – density of gas, [kgm^{-3}]

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