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THE STRUCTURE OF NONREACTIVE BIDIRECTIONAL AND DIRECT SWIRLING FLOWS AND ITS EFFECT ON MASS TRANSFER INTENSIFICATION AND MIXING EFFICIENCY*

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Abstract

One of the most promising methods of low-emission methane combustion is in a lean fully pre-mixed flame. A key characteristic of such an (non-stoichiometric) approach is the ability to directly control the air-to-fuel ratio. This can be achieved in the pre-mixing stage of fuel and oxidizer. The focus of the present paper is to study uniformity of fuel distribution in fully pre-mixed flame module of a concept lean bi- and mono-directional fuel- and air-flow combustion chamber. Numerical and experimental studies of fuel and air mixing have been carried out. Four configurations were considered, differing in presence/absence of flow swirl and relative flow directions of mixing components. It is found that the configuration with highest mix uniformity is one with bi-directional swirling air-flow with respect to injected fuel.

Keywords: flow swirling, mixing, fuel-air mixture, bidirectional flow

1. Introduction

One of the most promising low-emission combustion mechanisms is LPP (Lean/Premixed/Prevaporated combustion). This entails both the fuel and air to be fed into a flame module where they are mixed at a pre-determined ratio. The air-to-fuel ratio of such a mixture is usually above 2, thus the mixture is considered “lean”. The flame temperature of such a mixture is considerably lower than that of stoichiometric flame, which results in

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significantly reduced NOx emissions (Huang et al., 2006) (Huang et al., 2006; Parra-Santos et al., 2016; Zhang et al., 2020).

One of the drawbacks of said approach is the reduced normal flame propagation speed (compared to stoichiometric combustion) and flame front stabilization proves more difficult. This results in increased probability of a flameout (blow off), unstable ("pulsating") combustion and flashback (flame front propagating into the premixing chamber (Lieuwen et al., 2001; Syred and Beér, 1974)) thus disrupting the premixing process.

The features mentioned above necessitate the development of means to control the operational power ranges of the combustion chamber by way of adding stoichiometric (pilot) flames or controlling local air-to-fuel ratios. Thus, combustion of lean homogenous air-fuel mixtures with minimal NOx and incomplete combustion products emission at optimal power settings increases the complexity of the combustion chamber design and its management systems.

Additionally, lean combustion often leads to increased emission of partial combustion products, thermos-acoustic vibrations, blow-offs and flashbacks, all of which are unacceptable phenomena (Ahmed and Birouk, 2019; Bade et al., 2014; Parra-Santos et al., 2016; Valera-Medina et al., 2009). It is widely recognized, that the cause of all above mentioned effects are fluctuations in velocity, pressure, temperature, and air-to-fuel ratio fields (Lieuwen et al., 2001; Syred and Beér, 1974). Additionally, mixing of air and fuel with sufficient uniformity requires a larger (longer) combustion chamber and a more turbulent flow of air and fuel mixture (Zhang et al., 2020). Flow is often turbulised by swirling it. Studies of bidirectional swirl combustion chambers (Guryanov et al., 2017, 2019, 2020) have demonstrated a series of advantages of such a mixing intensification method. To determine the feasibility and practicality of implementing a bidirectional combustion chamber mixing module, the flow dynamic and mass transfer processes that take place in such a device and the uniformity of the final fuel and air mixture, that determines efficiency of the device must be thoroughly studied. This defines the relevance of the present study of flow structure and mixing in flame modules' premixing chambers in high-powered gas turbines.

Main objective of the present paper is in studying the effect of different fuel and air injection configurations on resulting flow features and on the uniformity of the resulting mixture in the lean flame module's premixing chamber designed for advanced combustion chambers.

There are three tasks that the authors set out to accomplish:

- Description of selected flow turbulization methods in fully pre-mixed mixing modules and justification for the selection;
- Description of numerical simulations' and experimental set-up's notable features;
- Analysis of results, comparisons between numerical and experimental data, and development of recommendations related to implementation of efficient fuel and air premixing devices.

2. Materials and methods

2.1. Mixing chambers geometry configurations

Efficient premixing of fuel and air has been achieved by a variety of known methods of air and fuel injection and burner module designs, four of which were selected for the present study. The considered configurations are presented in Fig. 1 and are as follows: axial with co-directional fuel injection (ACD), swirled air and co-directional combined axial and radial fuel injection (SACC), swirled air and opposite-directional combined axial and radial fuel injection (SAOC) bi-directional with combined axial and radial fuel injection (BDC).

First configuration utilizes axial co-directional fuel injection and is presented in Figs. 1a and 2a. Three fuel nozzles are located near the intake of the burner module separated by four air intakes.

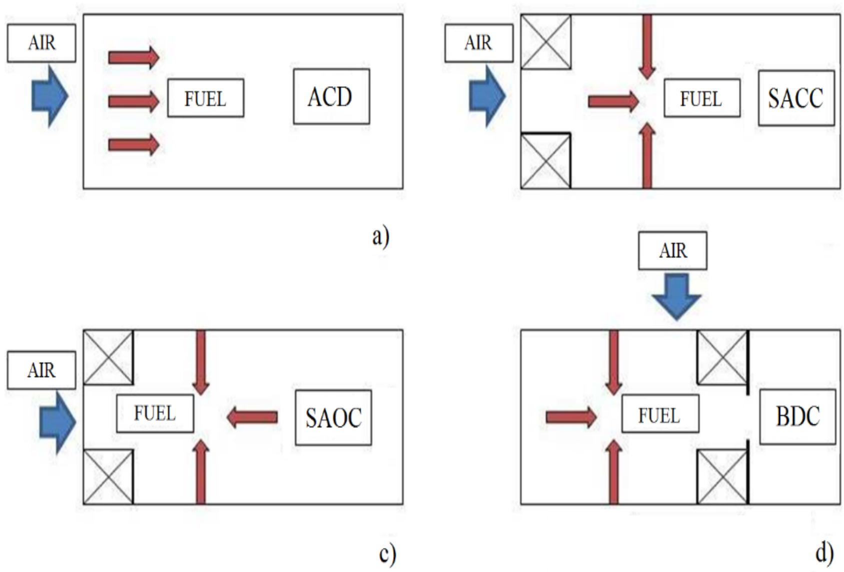

Fig. 1. Configurations of air and fuel injection into burner module model: a) axial with co-directional fuel injection (ACD); b) swirled air and co-directional combined axial and radial fuel injection (SACC); c) swirled air and opposite-directional combined axial and radial fuel injection (SAOC); d) bi-directional with combined axial and radial fuel injection (BDC)

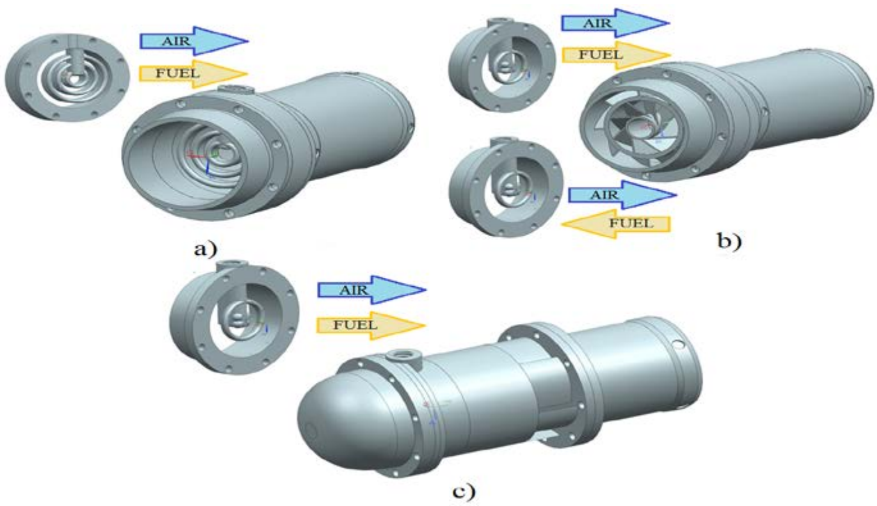

Fig. 2. Burner models:
a) model with axial co-directional fuel injection (ACD); b) model with airflow swirling and combined axial and radial fuel injection in co-directional (SACC) and opposite-directional configurations (SAOC); c) bidirectional model with combined axial and radial fuel injection co-directional with near-axis air flow

The second configuration is a combined axial and radial fuel injection scheme and is comprised of a single co-axial fuel nozzle with an axial swirler with two additional tangential fuel injectors built in to the mixing chamber downstream as seen in Figs. 1b and 2b.

The third configuration is a combination of opposite-direction axial and radial fuel injection into a swirled airflow as seen in Figs. 1c and 2b. In this configuration an axial swirler is fitted into the burner module's air intake with one opposite direction axial and two tangential fuel nozzles.

The fourth configuration shown in Figs. 1d and 2c, creates a bi-directional vortex flow. Air of the same mass flow value is fed into a tangential swirler which is located downstream from the intake location on other configurations and is positioned next to a diaphragm. This airflow forms a peripheral swirling flow, and due to the diaphragm flows in a direction opposite to normal. As the swirl strength of the flow subsides, it shifts towards the axis and leaves the mixing volume through a co-axial orifice in the diaphragm. Fuel is injected through two tangential nozzles and one co-axial and co-directional with near-axis swirled flow.

2.2. Numerical details

Numerical simulation of fuel and air mixing was conducted in ANSYS CFX. Meshes used were tetrahedral and are shown in Fig. 3.

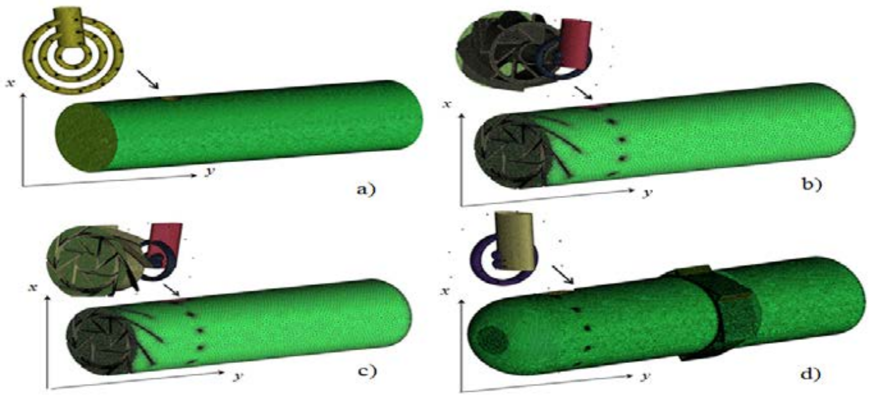

Fig. 3. Burner module mesh models: a) Axial co-directional (ACD); b) swirled co-directional combined axial and tangential fuel injection (SACC); c) swirled opposite-directional combined axial and tangential fuel injection (SAOC); d) bi-directional mixing (BDC)

Table 1. Boundary conditions

Parameter	***Value***
Total pressure of air at the inlet, P^*_{air} ACD SACC SAOC Bi-directional	 104365 Pa; 104363 Pa; 104363 Pa; 104363 Pa.
Total pressure of fuel at the inlet ACD SACC SAOC Bi-directional	 427364 Pa; 157025 Pa; 156590 Pa; 120000 Pa.
Total temperature at inlet, T^*_{in}	295 K
Static pressure at outlet, P_{out}	101325 Pa

Number of mesh elements varied between 3.5 and 5.5 million. A low-Reynolds turbulence model was used in all simulations. Boundary conditions for all studied cases are presented in table 1 and were such that air to fuel ratio was equal to 2. This simulation method was detailed and verified by author (Badernikov, 2019). All simulations were carried out with constant physical properties (specific thermal capacity, dynamic viscosity, thermal conductivity) of air and fuel (propane) set to their respective values at inlet temperature. Simulation was considered converged when domain momentum, mass and energy equations imbalances were below 0.1% and respective root-mean-square residuals were below $5 \cdot 10^{-5}$.

2.3. Experimental setup

The aim of the experiments is determining gas dynamic parameters of the mixing process and overall (integral) mixing parameters. Key indicators of burner module's premixing efficiency are as follows: air-to-fuel ratio α, pressure drop π^*, standard deviation of fuel concentration at the outlet ξ. The above parameters are derived from direct measurements as follows:

- air-to-fuel ratio

$$\alpha = \frac{G_{air}}{G_f L_0}, \tag{1}$$

where L_0 – stoichiometric coefficient; G_{air} – mass flow of air; G_f – mass flow of fuel;

- pressure drop

$$\pi^* = \frac{p_{in}^*}{p_{out}}, \tag{2}$$

where p^*_{in} – total inlet air pressure, p_{out} – atmospheric pressure at outlet;

- standard deviation of fuel's mass concentration

$$\xi = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(g_i - g_{av})^2}, \tag{3}$$

where g_i – i-th element of set (mass fraction of i-th mixture component); g_{av}– arithmetic mean of set; n – volume of set.

Study of mixing processes inside the burner module entailed determination of air and fuel mass flow characteristics in order to calculate the air-to-fuel ratio. Efficiency of mixing process was evaluated using PIV visualization. Additionally, mass flow characteristics are determined in order to ensure that all four configurations were tested under identical conditions as due to different hydraulic losses in each configuration, different pressure drops needed to be obtained to achieve an air-to-fuel ratio of 2. Fig. 4 shows experimental setup for determining mass flow characteristics.

Mixing parameters were determined using experimental setup shown in Fig. 5. During the experiment air was fed into the model burner module's inlet by a piston compressor, passing through a flow meter and an airline where temperature and pressure readings were taken.

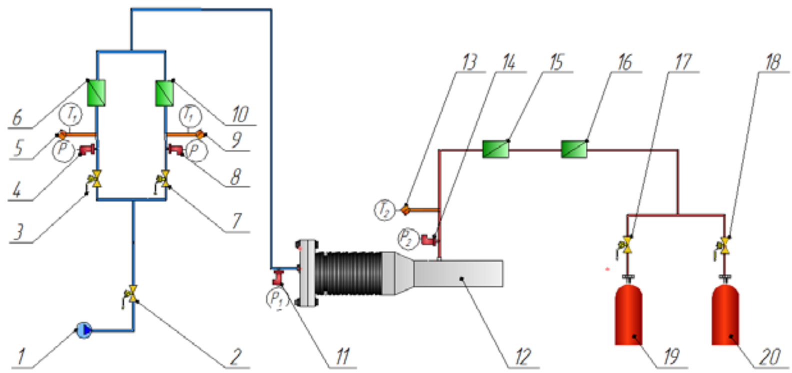

Fig. 4. Experimental setup for determining mass flow characteristics of premixing modules: 1 – compressor; 2,3,7,17,18 – valve; 4,8,11,14 – manometer; 5,9,13 – K-type thermocouples; 6 – mass flow meter D-6370; 10,16 – mass flow meter MV-306; 15 – coriolis flow meter; 12 – burner module; 19 – methane in a gas cylinder; 20 – propane in a gas cylinder

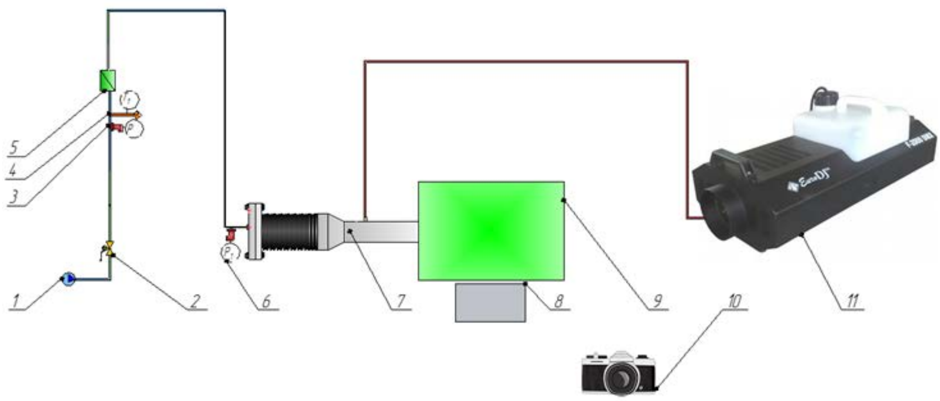

Fig. 5. Experimental setup: 1 – compressor; 2 – valve; 3,6 – manometer; 4 – K-type thermocouple; 5– flow meter MV-306; 7 – burner module; 8 – laser emitter; 9 – PIV plane; 10 – camera; 11 – smoke generator Euro DJ

a b

Fig. 6. Experimental model of fuel distribution element: a) axial fuel injection; b) combined axial and radial fuel injection

Laser 8 formed PIV plane 9. In place of fuel, smoke was fed into fuel injection nozzles (shown in Fig. 6) by smoke generator 11. These components mix in the burner module. Photo- and video-documentation of the PIV plane was carried out at the outlet of the model. Standard deviation of smoke's mass fraction was obtained using digital post-processing of recorded PIV images.

3. Results and discussion

3.1. Numerical results of fuel and air mixing in burner modules

Seen in Fig. 7 is distribution of propane's mass concentration standard deviation by length of the burner module. In contrast with axial mixing methods, the bi-directional variant facilitates the mixing process in the burner module's entire length, therefore, at l=0 the standard deviation is equal to ξ=0.005. The standard deviation is significantly increased at dimensionless length of l/d=0.28 since fuel is injected in this region. For swirling airflow configurations with combined axial-radial fuel injection the standard deviation is the same and is equal to ξ=0.015, which is lower than purely axial configurations by a factor of 8 (Fig. 7). The bi-directional mixing method also has a standard deviation maximum at l/d=0.28, equal to ξ=0.029. All mixing methods's standard deviation values improve downstream from discussed points apart from the swirled air with combined axial-radial co-directional (SACC) variant, for which a deviation maximum is observed at l/d=0.88. Standard deviation for the ACD configuration drops by 86% and is equal to ξ=0.017% at the outlet. Mixing quality of the SACC and SAOC configurations increases by 87% and 80% respectively, with their respective standard deviation values being equal to ξ=0.002 and ξ=0.003 at the outlet. The bi-directional method increases mixing quality only by 10% in the 0.28<l/d<0.58 region. This area corresponds with the location of tangential air inlets and mix flow before passing through the diaphragm. The flow after diaphragm at l/d>0.58 has can be characterized by a sharp reduction in standard deviation of mix's composition by 96%, reaching a value of ξ=0.001 at the outlet. Therefore, the bi-directional configuration provides superior mixing quality.

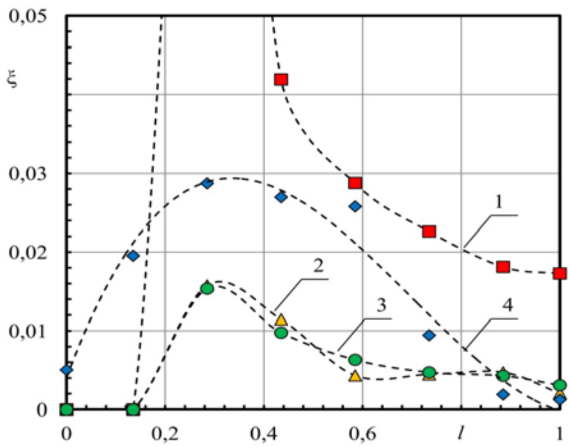

Fig. 7. Propane mass concentration standard deviation distribution by length of premixing chamber: 1 – axial with co-directional fuel injection (ACD); 2 – swirled air and co-directional combined axial and radial fuel injection (SACC); 3 – swirled air and opposite-directional combined axial and radial fuel injection (SAOC); 4 – bi-directional with combined axial and radial fuel injection (BDC)

Radial mass concentration distribution at the outlet is another way to evaluate the mixture uniformity, concentration maximums and minimums. As seen in Fig. 8, the ACD configuration is affected by the flow's history, as fuel concentration near the module's walls approaches zero. Three maximums and four minimums are observed in the free-flow area. All other methods are characterized by higher levels of mixture uniformity. The most uniform mixture is observed in the bi-directional configuration. Another method for evaluating mixing efficiency is assessment of radial relative deviation of propane's mass concentration at the outlet (Fig. 9), which also shows the BCD configuration as producing the most uniform mixture.

The ACD configuration demonstrates the highest average standard deviation of fuel mass concentration at the burner module's entire length equal to ξ_{av}=1.45%. Numerical simulations have demonstrated that average values of propane's mass concentration standard deviation for configurations with combined axial-radial fuel injection and swirled airflow are equal to within error margins (ξ_{av}=0.2% for SACC; ξ_{av}=0.25% for SAOC). The BCD configuration is found to possess the highest mixture uniformity of all tested variants at ξ_{av}=0.085%.

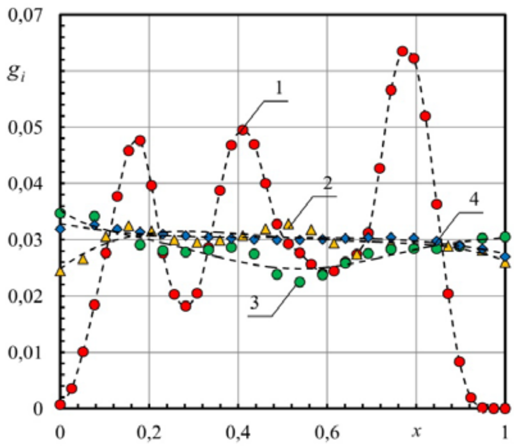

Fig. 8. Propane's mass distribution by dimensionless radius of burner module at the outlet: 1 – ACD configuration; 2 – SACC configuration; 3 – SAOC configuration; 4 – BCD configuration

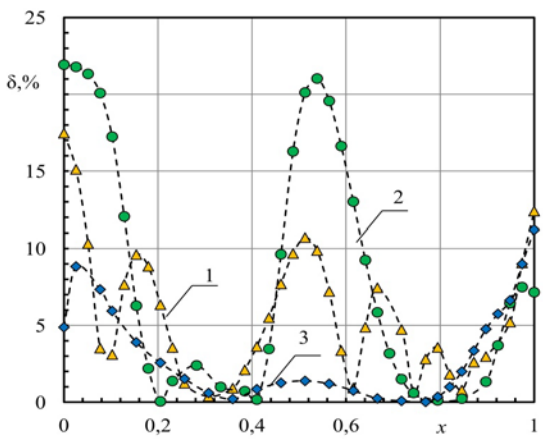

Fig. 9. Radial relative deviation of propane's mass concentration at the outlet

3.2. Experimental results

Empirical results of mixing process visualized using the PIV method are presented in Figs. 10–13. Numerical studies have been confined to the module's interior, whereas studies of mixing in the exterior have only been carried out experimentally.

Numerically acquired fuel mass concentration standard deviation values at the module's outlet have been compared against those achieved experimentally.

An overall review of achieved numerical and experimental results is presented in Fig. 14 comparing the tested configurations by fuel's mass concentration standard deviation value (representing mixture uniformity). It should be noted, that numerical and experimental data is in qualitative agreement, but deviate qualitatively. The ACD configuration possesses the highest value of ξ=19% which is unacceptably high for premixed burner modules. The SACC and SAOC variants have a standard deviation of ξ=3.2% and ξ=3.5% respectively, which is significantly higher than the numerically predicted values (ξ<1%). Empirical results show that the highest mixture quality amongst configurations tested is achieved by the BCD configuration at ξ=0.2%.

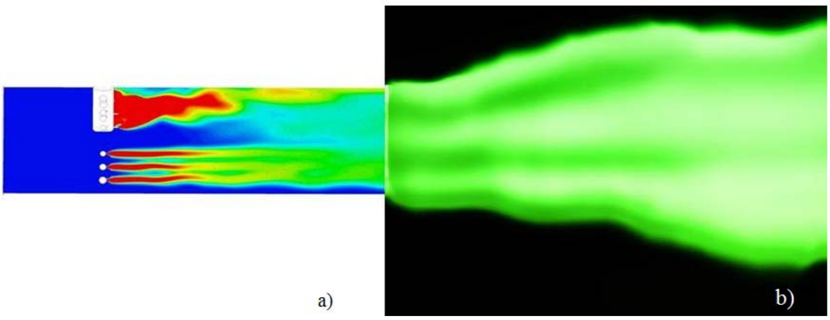

Fig. 10. Study of mixture composition in a lateral section of the ACD burner module: a) numerical results; b) experimental data, acquired using the PIV method

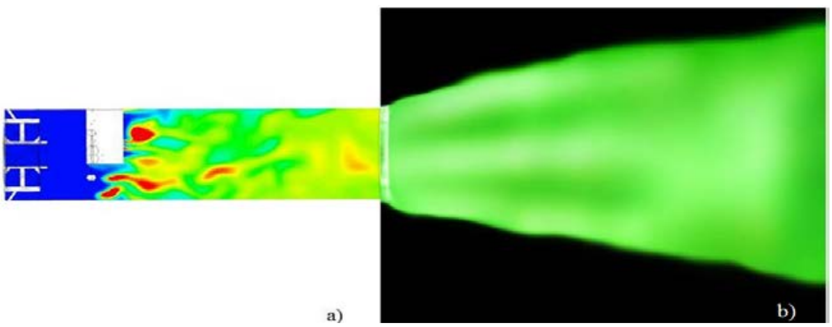

Fig. 11. Study of mixture composition in a lateral section of the SACC burner module: a) numerical results; b) experimental data, acquired using the PIV method

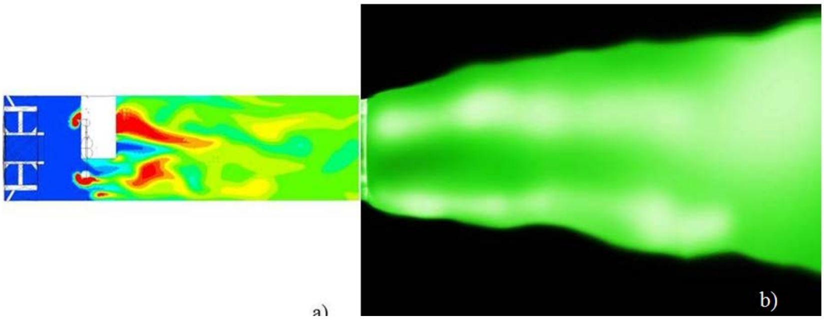

Fig. 12. Study of mixture composition in a lateral section of the SAOC burner module: a) numerical results; b) experimental data, acquired using the PIV method

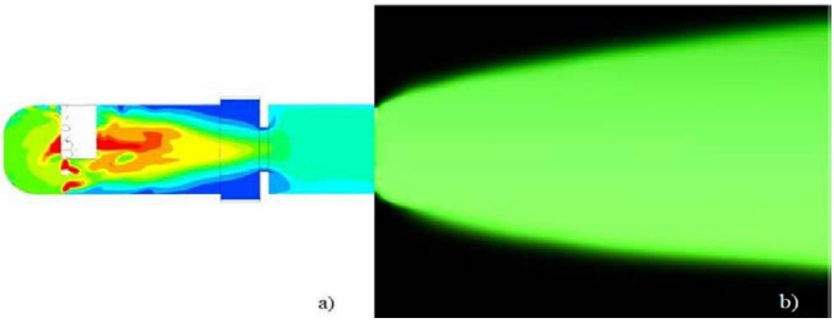

Fig. 13. Study of mixture composition in a lateral section of the BDC burner module: a) numerical results; b) experimental data, acquired using the PIV method

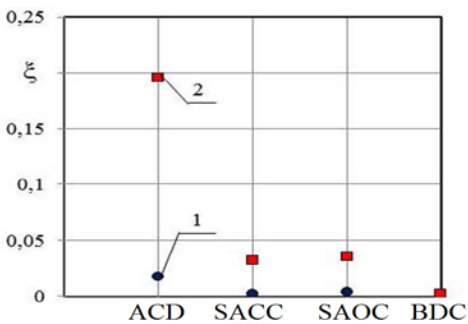

Fig. 14. Average fuel mass concentration standard deviation at the outlet: 1 – numerically predicted values; 2 – empirical values

4. Conclusions

In order to implement the concept of lean pre-mixed combustion, burner modules must be developed that can facilitate full premixing of such mixtures at air-to-fuel ratios of $1,8 \leq \alpha \leq 2,3$. Flow swirling allows to achieve necessary gasdynamic conditions needed for quick and uniform mixing of components. The need for reducing the burner module's length and advanced combustion chamber's overall size facilitates research of new methods of air and fuel mixing.

Analysis presented in the paper allows us to conclude that the optimal mixture quality at burner module's outlet is achieved by the bi-directional (BDC) configuration with a numerically predicted value of mixture non-uniformity at the outlet equal to ξ_{av}=0.085% and an experimentally measured of ξ=0.2% which fully satisfies the demands placed upon low-emission combustion chambers' fully pre-mixed burner modules.

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