On combustion regimes of syngas-air and methane-air lean flames for swirl-stabilized burners

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Abstract. This work presents result of visualisation of the characteristic combustion regimes of methane-air and syngas-air swirl-stabilized flames for an unconfined premixed burner (Re = 5000) and non-premixed combustion chamber (Re = 30000). Equivalence ratios were selected to have nearly equal values of the laminar flame propagation speed for the methane/air and syngas/air flames. Visualization for the premixed combustion for the model swirl burner revealed a similar shape of the flames for all mixtures. In contrast, during combustion of methane and syngas in the combustion chamber in the case of combustion in the combustion chamber, these differences in parameters cause completely visually diverse combustion modes.

1. Introduction

Increasingly stringent environmental regulations for harmful emissions of power plants, as well as rising fuel prices, stimulate the development of new innovative solutions for the design of gas turbines (GT) with low-emission combustion chambers that operate with a high efficiency. In modern gas-turbine combustors, the improvement of liquid fuel injection systems is crucial due to the constant need to increase the combustion efficiency and increase the life cycle of the supply systems. Detailed measurements in full-scale burners aimed for optimization of combustion chambers are extremely expensive and, in fact, are hardly possible to date, while numerical methods have not reached the required level for solving this problem [1]. An obvious strategy is to study the fundamental aspects of new technologies on laboratory-scale model burner devices, which possess practically important features of real devices and provide an ability to measure the characteristics of processes that are taking place.

Lean premixed combustion is currently one of the most promising technologies for reduced nitrogen oxides concentration in exhaust gas. However, lean premixed flames are highly prone to thermoacoustic instabilities, often resulting in resonant oscillations [2-6]. Problems with stabilization of lean flames are, on the other hand, provided by fuel supply modulation due to pressure, leading to a periodic change in stoichiometry of the fuel-air mixture [7]. Another source of the perturbations can also be due to the hydrodynamic instabilities of the shear layer, leading to formation of large-scale vortex structures [3]. This effect is enhanced by high sensitivity of the reaction rate to variation of the temperature and composition of the fuel-air mixture [7, 8].

It is known that organization of intensive flow swirl provides favorable condition for stabilization of flames, including a high probability of successful flame ignition and a stable combustion for a wide range of fuel-air ratios [9, 10]. Besides, an additional source of instability appears when an intensely
swirling flow enters the combustion chamber through a region of sudden expansion. This effect, known as precessing vortex core (PVC) is described in a number of works, e.g., [11-13]. The effect of PVC on the combustion process depends on a number of factors, such as the fuel supply method and the fuel-air ratio [9, 14, 15]. It has also been shown that PVC can contribute to NOx reduction and a more complete burnout of fuel through an increased level of turbulence, as was noted for a precessing jet burner [16, 17]. PVC can also be a factor that increases the stability of the lean premixed flames to the flashback effect [18]. All this points to the importance of the PVC studies in relation to burners with a strong flow swirl.

The aim of this work was to analyze shapes of lean syngas and methane flames for swirl-stabilized burners under fully premixed and non-premixed combustion.

2. Experimental setup
The measurements for premixed combustion were carried out using a combustion rig consisted of a swirl burner (fig. 1-B), premixing pipe and section for the air and fuel flow rate control. The burner was a contraction nozzle (with the exit diameter \( d = 15 \text{ mm} \)) with a vane swirler mounted inside to produce a swirling flow. Swirl rate of the flow (the ratio between fluxes of the angular and axial jet momenta) was corresponding to the swirl ratio \( S = 1 \) (the inclination angle of the blades was 55°). The Reynolds number \( \text{Re}_{\text{air}} \) (based on \( d \), the bulk velocity of the air flow at the nozzle exit \( U_0 = 5 \text{ m/s} \), and viscosity of the air) was 5000.

Figure 1-A shows the 3D sketch of the non-premixed combustor, where the measurements for high Reynolds number (30000) took a place. The air was supplied in the annular chamber via four holes, whence it gets into a plenum chamber. A swirler nozzle with the geometry similar to that in [19] was mounted in the plenum chamber. The fuel was supplied via the central pipe. The air and fuel were mixed inside the combustion chamber. The inner diameter of the swirler nozzle outlet was equal to 38 mm and the distance between walls of the combustion chamber was 180 mm. An efficient cooling of the swirler nozzle and was provided by a water, circulated in closed cavity inside a bottom wall of the combustion chamber. The sidewalls of the combustor were cooled via air that was supplied from slots between the bottom and side walls.
3. Results

Experimentally studied syngas and methane combustion regimes were selected as a result of simulation using the GRI-Mech 3.0 mechanism. For methane-air mixture, a lean methane flame (equivalence ratio $\Phi = 0.7$) was chosen, which is relatively close to the lean blow off limit. The air volumetric flow rate for all cases was equal to 52.8 l/min. For syngas with a 1:1 and 1:2 ratios of hydrogen and carbon monoxide in the fuel mixture, the regimes with $\Phi = 0.45, 0.48, 0.54$ was selected since the flame front propagation velocity was close to the velocity in a methane flame and was approximately 19 cm/s.

The figure 2 and 3 shows photographs of the main combustion regimes. The volumetric flow rate of air was 783 l/min for combustion in non-premixed swirl-stabilized combustion chamber. The volumetric flowrates of syngas (ratio of hydrogen and carbon monoxide was 1:1) and methane were, respectively, 74.5 l/min ($\Phi = 0.45$) and 61 l/min ($\Phi = 0.71$).

It can be seen from the photographs (fig. 2) that the flame shape in all cases $Re = 5000$ takes the form of an inverted cone and is stabilized on the body of the flow around the swirl. In case C, the flame has a more pronounced bluish tint relative to other cases. In the case of $Re = 30,000$ (fig. 3), the syngas flame has the shape of an elongated bundle, while the methane flame takes the “M” form. In the second case, the combustion regimes are very different for a number of reasons that need to be investigated in more detail.
Conclusion

In this work, visualization of the characteristic combustion regimes of syngas and methane with swirl and combustion in the combustion chamber was carried out. The information obtained indicates that the pre-mixed mixture presented by the combustion regimes for the case with a low Reynolds number is poorly distinguishable, while the results obtained in the combustion chamber are very different for the syngas and methane in terms of flame shape. Despite the differences in the amount of fuel contained in the mixture and in a proportional amount of the components of the syngas, significant and qualitative differences between the photos of the flame, namely in shape, color and other are not observed. However, this difference in $\Phi$ affects the case of a high number of Reynolds. In the case of methane and syngas during combustion in the combustion chamber, a fundamental difference was observed in the shape of the flame and its stability.

Figure 2. Visualization of combustion regimes for fully premixed swirl burner ($S = 1$, $Re = 5000$). (A-C) Syngas: (A) $\Phi = 0.45$, $CO_2:H_2:CO = 0:1:1$, (B) $\Phi = 0.48$, $CO_2:H_2:CO = 0.045:1:1$, (C) $\Phi = 0.54$, $CO_2:H_2:CO = 0:1:2$. (D) Methane: $\Phi = 0.71$.

Figure 3. Visualization of combustion regimes for non-premixed combustion chamber ($S = 0.74$, $Re = 30000$). (A) Syngas: $\Phi = 0.45$, $CO_2:H_2:CO = 0:1:1$. (B,C) Methane: $\Phi = 0.71$. 
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References
[1] Reynolds W 2002 ASCI PI Meeting (USA: Stanford University)
[2] Sivasegaram S and Whitelaw J 1991 J. Combust. Sc. Tech. 85 195–207
[3] Ballal D, Vangsness M, Heneghan S and Sturgess G 1993 81st Symposium of the AGARD
[4] Shih W, Lee J and Santavicca D 1996 J. Proc. Combust. Inst. 26 2771–8
[5] Lieuwen T and Zinn B 1998 J. Proc. Combust. Inst. 27 1809
[6] Huang Y and Yang V 2009 J. Prog. Eng and Comb. Sc. 35 (4) 293–364
[7] Lieuwen T, Torres H, Johnson C and Zinn B 2001 J. Eng. Gas Turb. Power. 123 182–9
[8] Di Benedetto A, Marra F and Russo G 2002 J. Combust. Sc. Tech. 174 1–18
[9] Gupta A, Lilley D and Syred N 1984 J. Swirl Flows (Kent Engl.: Abacus Press)
[10] Weber R and Dugue J 1992 J. Prog. Energy Combust. Sci. 18 349–67
[11] Stöhr M, Boxx I, Carter C and Meier W 2012 J. Combust. and Flame 159 2636–49
[12] Moeck J, Bourgouin J, Durox D, Schuller T and Candel S 2012 J. Combust. Flame 159 2650–68
[13] Litvinov I, Shtork S, Kuibin P, Alekseenko S and Hanjalic K 2013 J. Heat Fluid Fl. 42 251–64
[14] Coats C 1996 J. Prog. Energy Combust. Sci. 22 427–509
[15] Froud D, O’Doherty T and Syred N 1995 J. Combust. Flame 100 407–12
[16] Schneider G, Froud D, Syred N, Nathan G and Luxton R 1997 J. Exp. in Fluids 23 89–98
[17] Megalos N, Smith N and Zhang D 2001 J. Combust. Flame 124 50–64.
[18] Shtork S, Vieira N and Fernandes E 2008 J. Fuel V. 87 (10–11) 2314–21
[19] Janus B, Dreizler A and Janicka J 2005 J. Flow Turbul. Combust. 75 (1–4) 293–315