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PAPER

Shaping of the flame geometry by non-conventional cold plasma arrangements

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Abstract

Experimental examination of possibility to affect the shapes of flames under combustion of the liquified petroleum gas (LPG) were performed by several non-conventional cold atmospheric plasma arrangements. The lateral fused hollow cathode, the microwave surface wave plasma jet and the combination of these systems confirmed possibility of an efficient control of the flame shapes, increasing stability of flames and broadening of their front parts.

1. Introduction

Among the main requirements to gas turbines in power stations or to aircraft engines is the reduction of emissions. This can be achieved by lowering the temperature in the combustor, for instance in the lean regimes with more air in the fuel. The effect of lower temperature on pollutions and requirement for optimization the flame intensity and efficiency were emphasized already 50 years ago [1], but lowering of the flame temperature usually leads to slower chemical reactions and consequently flame instabilities and extinctions. It was confirmed more than 50 years ago that parts of the flames can be ionized by certain plasma-chemical reactions [2]. Recent measurements in a premixed methane flame by double Langmuir probes revealed even as much as 10^{11} cm^{-3} ions [3]. An interacting of non-equilibrium (cold) gas discharges with the flame can therefore generate reactive radicals and plasma-chemical reactions to stabilize combustion processes, increase the flame extinction limits and affect the flame geometry. A consequence is an improved overall performance of the combustor and stabilization of flames during transients.

One of the first discharge applications in combustion was a supersonic hydrogen plasma jet [4]. Despite of a number of following experimental studies [5–7] and numerical models [8–10], the mechanisms of plasma-assisted combustion are still not fully understood. Numerical models of optimal designs of the plasma-assisted combustion arrangements are often not very useful for real arrangements in practical applications. It is for example important to study how the plasma can affect the flame geometry, where is an optimal position of the plasma source [11], or how to control the discharge effects. In gas turbines there is for example requirement for ‘flat fronts’ of the flames to increase an interaction efficiency of the flame in the combustor.

The objective of this work was experimental testing of such geometrical effects by several non-conventional cold atmospheric plasma arrangements interacting with the simple flames under combustion of the liquified petroleum gas (LPG).

2. Experimental arrangements

The LPG (also liquid propane gas) represents mixes of propane (C_3H_8) and butane (C_4H_{10}). It is usually used as a fuel in heating appliances, cooking equipment, or in vehicles. For tests of the effects of the cold atmospheric plasma two arrangements shown in figure 1 were used first. The arrangement in figure 1(a) represents a circumferential fused hollow cathode (FHC) mounted on the top of a commercial air premixed LPG burner

Figure 1. The arrangements tested in experiments. (a) A lateral Fused Hollow Cathode (FHC) plasma in air generated by the pulsed DC power, affecting an axial LPG flame from the commercial burner. (b) The microwave waveguide surfatron with central antenna generating long axial air plasma, affecting flames from the lateral system of four LPG inlets.

Figure 2. Comparison of the LPG flames mixed with the neutral air and the same arrangement with the air FHC plasma generated by the pulsed DC power.

18 mm in diameter. Here the hollow cathode plasma is generated in air in radial slits between circular cathode plates $400\ \mu\text{m}$ from each other. More details about the FHC were published elsewhere, [12–15]. The hollow cathode plasma was generated by pulsed DC power at average value as low as 20 W in 7 slm flowing air. The LPG flow rate used in this arrangement was 5 slm. The arrangement in figure 1(b) shows a microwave surface wave antenna [13] combined with an attached system of four LPG nozzles blowing the gas into axis of the antenna. The tubular antenna was terminated by a nozzle blowing low air flow of 0.5 slm (measured by rotameter), which is enough for generation of about 6 cm long air plasma slab at the microwave power below 400 W. To generate long plasma plumes the surface waves require laminar gas flows and the gas flow rates in this source must be low enough to avoid turbulences [16]. In this arrangement the plasma has been started by a spark igniter, but it was often possible to ignite the plasma even just by the LPG flame, which has actually confirmed some ionization level in the flame.

The B-type thermocouple (Thermocoax) for maximum temperature of $1700\ ^\circ\text{C}$ was used for measurement of local temperature. The thermocouple wires Pt (30% Re) and Pt (6% Re) were installed in a 1.5 mm diameter rhenium cartridge (Re melting is $3186\ ^\circ\text{C}$).

Figure 3. The LPG flames without and with the microwave air plasma jet. (a) The flame at low LPG flow rate. (b) The LPG flame close to the extinction. (c) Stable and broad LPG flame supported by the central microwave air plasma jet.

3. Affecting of the flame shapes

An interaction of the FHC air plasma with the LPG flame in the arrangement shown in figure 1(b) intensified the combustion in the flame, but there were no significant effects on the shape of the flame. The comparison of the LPG flame without and with the FHC air plasma is shown in figure 2. It is evident that after switching on the hollow cathode without changing individual flows the flame became more intense and somewhat longer.

Considerable effects of the plasma on the flame shape were achieved with the microwave air jet arrangement in figure 1(b). It was observed that in the used arrangement the LPG flame remains stable below flow rates of about 5 slm. Above this flow the flame has always extinguished. However, after switching-on the microwave power the shape of the flame was changed substantially and it was possible to increase the LPG flow rate up to about 8 slm, still keeping the stable flame. Moreover, the front part of the flame has been broadened to a ‘flower’ shape, with ‘branches’ following four LPG nozzles used in this arrangement. The comparison of individual phases described above can be seen on photographs in figure 3.

To broaden the LPG flame even more the two experimental arrangements shown in figures 1(a) and (b) have been combined. This combined arrangement and the resulting shape of the flame is shown in figure 4. It is evident in the photograph in figure 4 that the resulting flames are considerably more intense and denser than those in previous tests. The flame has also very broad front parts.

4. Affecting the flame temperature profile

The temperature measured by the B-type thermocouple in the axis of the microwave air plasma jet are shown in figure 5. The measurements were slightly affected by spatial instability of the flames and strong heating of rhenium cartridge near the nozzle.

The measurements near the microwave antenna were affected by the tendency to melt the rhenium cartridge, as well as by disturbances by electric interactions between the microwave antenna and the electrically grounded thermocouple. In the measurements the microwave power delivered to the 0.5 slm air jet was 360 W. The temperature measurements of the LPG flame were then performed without and with this plasma jet, still keeping in both cases the 0.5 slm in the air jet stream. The thermocouple was positioned at six different distances above the nozzle tip at the microwave antenna and the temperature was recorded at several radial distances from the axis to find the temperature profiles after broadening the flame by the plasma. The results are shown in figure 6. The temperature of the LPG flame with an axial flow of 0.5 slm of air is shown in figure 6(a). The LPG

flow rate was kept at 4 slm to avoid the extinction instabilities, but high enough to elevate the flame above the air nozzle. This explains a lower temperature value measured in the axis at 1.5 cm from the nozzle than that at 3 cm and 4.5 cm, where the temperature reached about 1200 °C. After switching on the microwave power, the flame became very stable and acquired broader shape with side 'branches' in the flame 'bouquet'. Consequently, the temperature field is also evidently wider and the temperature of the side 'branches' is comparable with the axial parts of the flame. This can be seen in figure 6(b).

The systematic temperature measurements in the broad flame produced by the combined system shown in figure 5 were not performed due to considerable heating of long sections of the rhenium cartridge on the thermocouple in a densely distributed flame intensity. However, the measurements at peripheral parts of this broad flame confirmed temperature exceeding 1000 °C, like those measured in the flame 'branches' shown in figure 6(b).

5. Conclusion

The performed experimental tests of the geometrical effects in three non-conventional arrangements with cold atmospheric plasma on the LPG flames confirmed possibility of controllable shaping of the flame geometry. Moreover, the plasma assistance confirmed earlier findings of an increased stability of the flames. Even though the experiments have rather phenomenological character the obtained results could help in new designs of efficient auxiliary plasma units for gas turbines or for aircraft engines. Such units could contribute to the flame stability under lean combustion, as well as to an increased efficiency of the combustor with reduced emissions.

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Conflict of interests

The authors confirm no conflict of interests related to this work.

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