The effect of the flame shape on pollutant emission of premixed burner

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Abstract

The modern commercial combustion systems use lean premixed prevaporized (LPP) burners to meet the emission standards. During the operation the shape of the flame is torch like at the beginning, while the swirl property is not strong enough. With increasing the mass flow rate of combustion air, the flame opens due to the vortex breakdown of the precessing vortex core (PVC) and a significantly different shape takes place. The shift between them is sudden, but has a hysteresis behavior. That can result both flame shape at the same boundary conditions, depending on the previous state, so the flame is bistable in a certain region. As the flow and mixing pattern significantly differs, the emission and radiation characteristics will also change. This bistable behavior occur in real continuous combusting systems, like gas turbines and boilers. The current analysis examines this phenomenon experimentally in an atmospheric test rig with a gas turbine burner equipped with an air blast atomizer and utilizing diesel fuel.

Introduction

The scope of present paper is the analysis of a continuously operating burner of a Capstone C-30 micro gas turbine. Generally, gas turbines are widely used heat engines in aviation, energy industry and military as well. The reason of their application is the high power to weight or power to volume ratio with high efficiency, fast starting capability. Continuous firing with similar burner solutions is also present in industrial boilers and furnaces. The pollutant emission of heat engines and firing systems are limited worldwide.

The continuously tightening emission standards force the engineers to develop advanced heat engines and combustion systems [1,2]. To control mainly the emission of carbon monoxide (CO), nitrogen oxides (NO_x) and (total) unburnt hydrocarbons (THC), there are active and passive solutions. Active elements mean sensors and actuators (e.g. loudspeakers and moving parts), which are not favorable in an industrial environment, due to the relatively high failure possibility. The passive elements cover Helmholz-resonators and rigid parts, which influence the flow pattern, thus provide proper temperature and local air-fuel equivalence ratio for the flame. It is clear that the CO emission can be influenced by geometrical considerations, but the NO_x emission is largely temperature dependent, so elimination of hot spots is not just challenging form the point of view of maximization of turbine blade lifetime, but also the lower emission requires that. [3,4] A widely applied solution for modern combustion chambers is the so called dry low emission (DLE) burners, which can achieve low NO_x emission without water injection. A remarkable member of DLE solutions is the lean premixed prevaporized (LPP) burner, which achieve lower emission through the breakdown of the precessing vortex core (PVC), resulting larger volume for the combustion. [5] At partial loading and start the shape of the flame is torch like. This result in lower CO and higher NO_x emission compared to the designed, tulip shaped flame. Both flame shape is stable, but the former one results usually higher NO_x emission, than the allowed value by the standards in power plants. The shift between the two different shapes shows bistable behavior, which mean both shape can be present during operation, based on the previous conditions, internal and external, mainly acoustical excitations. As the flame is turbulent, a wider broadband frequency is present, which drives the shift. Furthermore the acoustical characteristics of the combustion chamber also should be considered during the design.

Measurement configuration

The experimental burner test rig is shown in **Fig. 1.** The system is suitable for combustion tests with air blast atomization, using standard diesel fuel and combustion air preheated to the required temperature under atmospheric conditions. The below mentioned values in the description are chosen based on the operational parameters of the Capstone C-30 micro gas turbine at 7 kW electric output power. The gas turbine uses 3 similar burners.

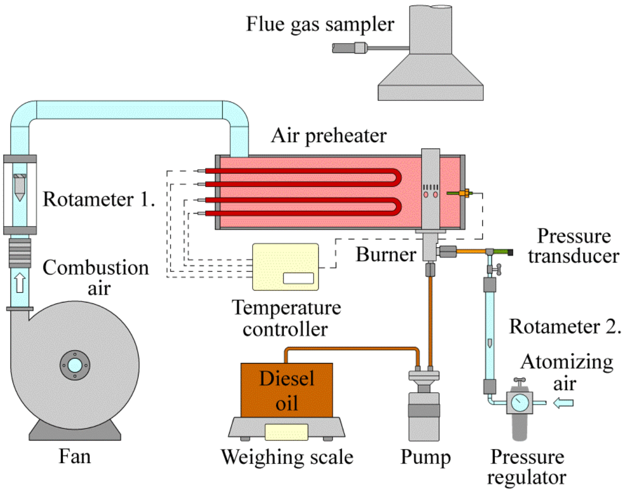

Fig. 1. Burner test rig

The air used for atomization passes from the compressed air system through a pressure regulator and

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a rotameter to the atomizer of the burner. During the experiments 0.33 bar atomization gauge pressure was applied. The combustion air supplied by the fan passes via a rotameter into a PID controlled electric air preheater equipped with four 1000 W filaments and then enters to the mixing tube through the radial orifices and tangential slots of the burner, which is shown on **Fig. 2.** The desired temperature of the combustion air was 400°C, the air-fuel equivalence ratio was 1.1 and 1.25, considering only the atomizing and combustion air. Of course, the ambient air was also used for the combustion, but not played significant role, because of its lower velocity and different viscosity.

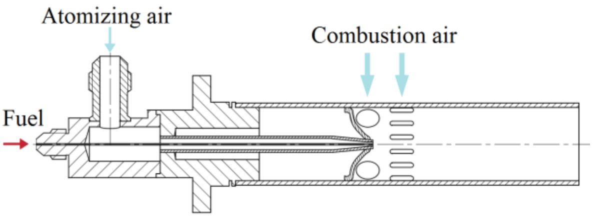

Fig. 2. Cross section of the gas turbine burner

The constant 0.35 g/s diesel fuel mass flow rate is delivered by a DC controlled electric pump, which is equal to 15 kW firing power. The atomization takes place in the mixing tube of the burner by the aid of the atomizing air flowing out at a high speed, then the atomized droplets get mixed up with the hot combustion air and evaporate. The burning of the fuel begins slightly in the mixing tube. The arising flue gas is abducted via a range hood situated above the burner. The sampling of the flue gas takes place from here.

The used flue gas analyzing equipments are Bernath Atomic 9000 (THC, calibrated with propane), Thermo Environmental Instruments 42 C HL (NO_x), 48 C HL (CO), Servomex 1400B4 SPX (CO_2 and O_2).

Results and discussion

The bistable behavior was indicated with a sudden change in the flame shape and back, shown on **Fig. 3.** When the parameters were closer to the stable torch shaped flame (case A), the tulip shape (case A) was observed for shorter period of time during the continuous shifting and vice versa. The duration of the shapes were chaotic, due to the sensitive behavior of the system. This continuously shifting phenomenon resulted fluctuations in the delivered combustion air, which was clearly caused by the different pressure conditions of the burner indicated by Rotameter 1. on **Fig. 1.**, which should be avoided in industrial systems to achieve maximum lifetime of the combustion chamber and the liner. To get rid of the chaotic factor, the measurements were carried out at the upper and lower limits of the bistable region by setting the mass flow rate of the combustion air. The emission not just depends on the air-fuel equivalence ratio, which was the side effect of setting the amount of the combustion air, but also considerably affected by the shape of the flame.

Fig. 3. Torch shaped (case A) and tulip shaped (case B) flame, 1/100 s, f/4

The second applied method for changing the shape of the flame is to add a 45° diffuser element at the top of the burner (case C), shown in **Fig. 4.**

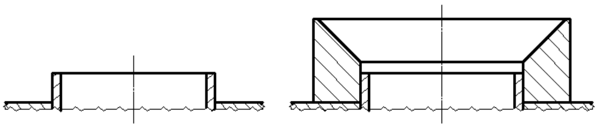

Fig. 4. Outlet of original (case A, B) and modified burner configuration (case C)

Fig. 5. Original (case B) and modified burner (case C) in operation at same operating conditions, 1/100 s, f/4

In the second case just the flame shape was changed, shown on **Fig. 5.**, the inlet parameters of the fuel, atomizing air and combustion air could be kept constant due to the change of geometry, and so the air-fuel equivalence ratio was the same and the changes in pollutant emissions were clearly caused by the 45° diffuser, which were remarkable. The results of the emission analysis with different configurations (case A, B and C) shown in **Fig. 6.** The values were calculated back to 15% O_2 level. As it was expected, the tendency of CO and THC were similar and increased, while the NO_x decreased. The difference between case A and B is the flame shape, as it was shown on **Fig. 4.**, but the air-fuel equivalence ratio was also changed, that was 1.1

(case A) and 1.25 (case B and C), the other inlet parameters were kept at constant. The NO_x emission was almost halved, while the CO emission was more, than six times higher. The THC also showed remarkable increase, which was almost eight times higher results in the latter case. Based on the theoretical relation of air-fuel equivalence ratio and NO_x, CO and THC emissions this huge difference must be greatly rely on the result of different flame shape.

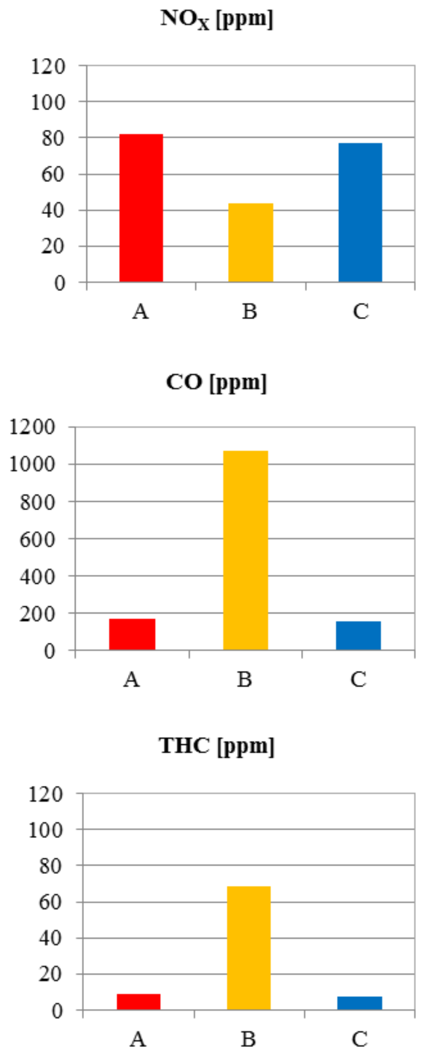

Fig. 6. Pollutant emission of different cases

The application of 45° diffuser at the same inlet conditions except the air-fuel equivalence ratio (which was 1.1 at case A and 1.25 at case C) resulted slightly lower emission of CO, THC and also NO_x, which is favorable from industrial point of view. The drop of NO_x was expected as the air-fuel equivalence ratio increased, but the theory states that the CO and THC content of the flue gas should slightly increase. Due to the geometrical modification the concentration of both components slightly decreased.

Comparing case B and C it can be stated that the inlet conditions were exactly the same, but the flame shape was different, due to the geometrical modification. The emission of NO_x almost doubled, while the CO and THC greatly dropped.

Conclusions

Experimental analysis was conducted to measure and compare different flame shapes from pollutant emission point of view under atmospheric conditions and elevated combustion air inlet temperature and elevated atomization pressure. The following conclusions were derived.

1. The bistable region means a state, when the shape of the flame chaotically changes, resulting notable pressure oscillations in the combustion system.
2. The upper and lower limits of bistable region of a gas turbine burner was investigated in a test rig, resulting remarkable changes in the emission characteristics.
3. Geometrical modifications can improve combustion characteristics of a burner, the applied 45° diffuser on the original burner resulted favorable changes in pollutant emission, namely CO and THC.

As for future work, we would like to also measure the acoustic characteristics of bistable flame. Also the numerical investigation is interesting for analyzing the details of the flame.

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References

[1] Lefebvre AH. Pollution control in continuous combustion engines. Symp Combust 1975;15:1169–80. doi:10.1016/S0082-0784(75)80381-X.

[2] Sarofim AF, Flagan RC. NOx control for stationary combustion sources. Prog Energy Combust Sci 1976;2:1–25.

[3] Huang Y, Yang V. Dynamics and stability of lean-premixed swirl-stabilized combustion. Prog Energy Combust Sci 2009;35:293–364. doi:10.1016/j.pecs.2009.01.002.

[4] Lefebvre A, Ballal DR. Gas turbine combustion, third edition. CRC Press; 2010.

[5] Syred N. A review of oscillation mechanisms and the role of the precessing vortex core (PVC) in swirl combustion systems. Prog Energy Combust Sci 2006;32:93–161. doi:10.1016/j.pecs.2005.10.002.