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Importance of the inlet air velocity on the establishment of flameless combustion in a laboratory combustor

A.S. Veríssimo, A.M.A. Rocha, M. Costa *

Mechanical Engineering Department, Instituto Superior Técnico, Technical University of Lisbon, Lisbon, Portugal

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ABSTRACT

This article examines the importance of the inlet air velocity (V_{air}) on the establishment of flameless combustion in a 10 kW laboratory scale combustor. Variations in V_{air} were accomplished by changing the air nozzle diameter while maintaining constant all remaining input parameters. Initially, laser-Doppler anemometry was employed to evaluate the combustor flow aerodynamics under non-reacting conditions. Subsequently, flue-gas composition data and hydroxyl radical chemiluminescence (OH^*) imaging were obtained as a function of V_{air}. For two of these combustor operating conditions, spatial distributions of temperature, recorded with fine wire thermocouples, and of O_2, CO_2, unburned hydrocarbons, CO and NO_x concentrations, measured with the aid of a sampling probe, were also obtained. The OH^* images showed that as V_{air} increases at a constant excess air coefficient (λ) of 1.3, the main reaction zone, typical of flameless combustion condition, remains approximately in the same region of the combustor, because of the flow aerodynamics similarity, but the OH^* intensities decrease, which indicates higher entrainment ratios of the fuel and burned gases by the central air jet. For λ greater than 1.7, however, flameless oxidation could not be established regardless of the air jet momentum. This suggests that the establishment of the flameless combustion condition in future gas turbines through the dilution of the reactants with a substantial amount of flue gases in configurations where the combustion air is provided by a central high-momentum air jet that is surrounded by a number of low-momentum fuel jets may be problematic.

1. Introduction

Under flameless oxidation conditions combustion takes place in a distributed reaction zone rather than in a thin flame front, with relatively uniform and low temperatures and temperature fluctuations, in comparison to conventional flames. The fuel is oxidized in an environment that contains a significant amount of flue gases and a low concentration of oxygen, as a result of internal or external exhaust gas recirculation. The radiative heat fluxes are relatively high and uniform, there is no visible flame, the level of noise is low, soot formation is negligible and NO_x and CO emissions are very low.

Flameless combustion is a technology relatively well established for industrial applications where heat is extracted from within the furnace while processing material, and is among the most promising technologies that can meet the stringent demands of reduced pollution and increased efficiency in future gas turbines. Gas turbine would operate lean adiabatic combustion (high oxygen content) while furnaces feature higher equivalence ratio (low oxygen content) [1]. This may pose difficulties in establishing the flameless combustion regime in gas turbines. In this case, there is a need to recirculate, by aerodynamic means, a large amount of hot combustion products, with a relatively high oxygen content, which can make difficult to establish the proper reactants dilution for the onset of the flameless combustion condition. For instance, Li et al. [2] examine this combustion mode in a gas turbine combustor operating at atmospheric conditions. They found that the flameless combustion mode occurred only for a limited range of conditions at fuel lean conditions, high preheat temperature and high air flow rates.

Very recently [3], we examined the operational, combustion and emission characteristics of a small-scale combustor as a function of the excess air coefficient (λ), which implied also changes in the inlet air velocity (V_{air}). We observed that for λ below 1.5 it was possible to establish the flameless combustion regime, while for higher λ the fuel oxidation occurred in a conventional lean combustion mode. Due to the burner configuration, it was not possible to analyze independently the importance of λ and V_{air} on the combustion regime. In the present article we examine separately the effect of V_{air} on the establishment of flameless combustion.

Review articles on flameless combustion, also called flameless oxidation, moderate or intense low oxygen dilution (MILD) combustion, high temperature air combustion or colorless distributed combustion, include those of Wünning and Wünning [4], Cavaliere

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* Corresponding author.
E-mail address: mcosta@ist.utl.pt (M. Costa).

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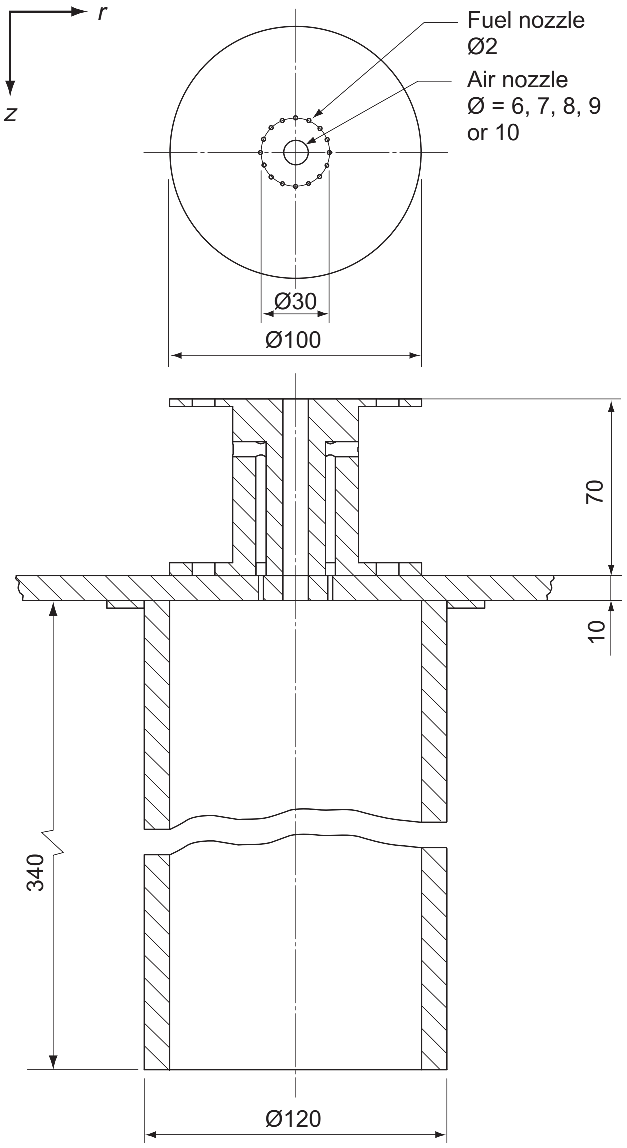

Fig. 1. Schematic of the combustor.

Table 1
Test conditions used to characterize the flow inside the combustor under non-reacting conditions.[a]

Run	Air nozzle diameter (mm)	V_{air} (m/s)
1i	10	48.1
2i	7	98.2
3i	6	133.7

[a] For all conditions: inlet fuel (air) velocity = 6.2 m/s, air mass flow rate = 4.4×10^{-3} kg/s, inlet air temperature = 25 °C.

and de Joannon [5] and Tsuji et al. [6]. The effect of the initial air–fuel jet momentum on the establishment of flameless combustion has been studied by a number of investigators [7–13]. Szegö et al. [10] found that a certain fuel jet momentum threshold was needed to achieve flameless combustion conditions in a recuperative furnace. This momentum ensured the penetration of the fuel jets to a region classified as the oxidation zone. Also in a recuperative furnace, Mi et al. [11] reported an investigation on the importance of the initial air–fuel injection momentum rate and the air–fuel premixing on flameless combustion. The authors concluded, numerically, that there is a critical momentum rate of the inlet fuel–air mixture below which the flameless combustion cannot occur. Also, they found, both experimentally and numerically, that, above this critical rate, both the momentum rate and the inlet fuel–air mixedness affect only marginally the stability of and emissions from the flameless combustion. In combustors other than recuperative furnaces, Mancini et al. [7] and Derudi et al. [8] also evidenced the threshold below which flameless combustion cannot occur not only for gaseous hydrocarbon fuels but also for highly reactive fuels, as hydrogen-containing fuel mixtures.

2. Materials and methods

Fig. 1 shows a schematic of the combustor used in this study. The combustion chamber is a quartz-glass cylinder with an inner diameter of 100 mm and a length of 340 mm. During the tests, the quartz cylinder was well-insulated with a 30-mm-thick ceramic fiber blanket. The burner is placed at the top end of the combustion chamber and the exhaustion of the burned gases is made by the bottom end through a convergent nozzle with a length of 150 mm and an angle of 15°. As seen in Fig. 1, the burner consists of a central orifice with a variable inner diameter (6, 7, 8, 9 and 10 mm in this study), through which the combustion air is supplied, surrounded by 16 small orifices of 2 mm inner diameter each, positioned on a circle with a radius of 15 mm, for the fuel (methane) supply. The combustion air is preheated by an electrical heating system.

A two-component velocimeter from Dantec^{TM}, which was operated in the dual-beam backward-scatter mode, was employed to characterize the flow inside the combustor under non-reacting conditions. This was accomplished in a combustor similar to that represented in Fig. 1, but made of stainless steel with two opposed rectangular quartz windows (320×90 mm) for optical access. Data rates of 0.5 kHz were obtained by seeding the flow with 1 μm alumina particles. The back-scattered light from the particles was collected by a fiber-optics probe with a beam separation of 38 mm and a focal length of 400 mm. Subsequently, the analog signal from the photomultipliers was band-pass filtered and processed by two Dantec^{TM} 57N20/57N35 Burst Spectrum Analyzers interfaced with a personal computer, using "burst" data collection mode and a record length of 32 samples per burst. Velocity statistics were evaluated by ensemble averaging, calculated from 10,000 samples, using BURSTware software. Errors incurred in the measurement of velocities by displacement and distortion of the measuring volume due to refraction on the combustor model side walls (10 mm thick optical quartz glass windows) were negligible.

The data acquisition techniques used in the combustion tests along with the associated uncertainties are fully described in Veríssimo et al. [3]. Local mean temperature measurements were obtained using 76 μm diameter fine wire platinum/platinum:13% rhodium (type R) thermocouples. The uncertainty due to radiation heat transfer was estimated to be less than 5% by considering the heat transfer by convection and radiation between the thermocouple bead and the surroundings.

The sampling of the gases for the measurement of local mean O_2, CO_2, unburned hydrocarbons (HC), CO and NO_x concentrations was achieved using a stainless steel water-cooled probe. The analytical instrumentation included a magnetic pressure analyzer for O_2 measurements, a non-dispersive infrared gas analyzer for CO_2 and CO measurements, a flame ionization detector for HC measurements and a chemiluminescent analyzer for NO_x measurements. Quenching of the chemical reactions was found adequate, but no attempt was made to quantify the probe flow disturbances. On average, the repeatability of the gas species concentration data was within 10%. Flue-gas composition data, obtained at the begin-