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Spark ignition of annular non-premixed combustors

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ABSTRACT

The ignition behaviour of a laboratory-scale multiple-burner annular combustion chamber is investigated experimentally in this paper. The work specifically focuses on the lightround mechanism ensuring burner-to-burner flame propagation. The system comprises 12, 15 or 18 bluff-body non-premixed burners, each fitted with a swirler, and an annular combustion chamber. A spark located in the neighbourhood of one injector initiates the combustion. The measurements show that the extinction stability limits are much wider than the ignitability limits, but when the inter-burner spacing is reduced, they become closer. Side visualisation shows that successful flame propagation from one ignited burner to its adjacent non-ignited one is associated with the latter being ignited by its own recirculation zone capturing a flame fragment from downstream. The sequential progression of the ignition front from burner to burner was determined by fast OH* imaging from the top of the chamber. The time taken from one burner to ignite the next one varies during the full propagation sequence. The speed of lightround was, in every case, faster in the direction of the swirl of each injector due to the differential tangential velocity induced between the inner and outer combustion chamber walls. With an increase in velocity, the time taken for the overall combustor to ignite did not change significantly. However, decreasing the spacing between burners resulted in an increase in the speed of lightround and decreasing the overall equivalence ratio resulted in a slower burner-to-burner propagation. The results presented in this paper can be used for validation of numerical models of transient combustion processes.

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1. Introduction

The transient process of ignition in gas turbines involves complex phenomena and is scientifically very rich [1,2]. In gas turbines, surface-discharge igniters usually accomplish ignition by depositing large amounts of energy through large sparks. However, propagation and stable establishment of the flame is not always achieved, especially in high altitude and with very lean overall equivalent ratios required by pollutant emission targets, leading to a possible major safety issue.

The ignition process of a gas turbine combustor occurs in four different distinct phases summarised as follows [1,2]. Phase 1 is the formation of a kernel of a flame containing sufficient energy to propagate successfully. Phase 2 is the propagation of flame from this kernel. Phase 3 is the stabilization of the flame within a single fuel injector. Phase 4 is the spread of flame from an ignited burner to an adjacent unignited one. This flame propagation around the annular combustion chamber is called "lightround" and has only been partially studied previously and only through premixed burner configurations.

Lightround has been investigated through a lab-scale annular combustion chamber consisting of 16 identical swirling premixed burners confined between two concentric transparent quartz walls [3]. For different sets of bulk velocities, the overall time taken to ignite the combustor was determined. The flow motion generated by the volumetric expansion across the flame and the normal burning velocity were considered as the mechanisms responsible for the flame displacement velocity. The effect of spacing between burners on the lightround process has been studied through experiments with a multi-injector linear burner [4]. For small spacing, the flame was found to propagate in a spanwise mode associated with quick burner-to-burner propagation while for high spacing an axial propagation mode characterized by longer propagation times and higher variability was identified. The ignition sequence has also been studied in an annular premixed combustion chamber consisting in 18 swirling injectors equipped with a central bluff-body [5,6]. During the propagation each burner was ignited by its own recirculation zone (RZ). The observed mechanism of propagation from burner to burner was denoted "sawtooth" as it consisted of a flame convected downstream by the flow and then was captured and moved upstream by the RZ of the adjacent burner. This behaviour was more pronounced at high velocities.

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Nomenclature

Roman

D	inner diameter of the tubes (m)
da	inner diameter of the bluff-bodies (m)
S	separation distance between bluff-body centres (m)
Re	Reynolds number (dimensionless)
S_{LR}	speed of lightround (m/s)

Greeks

α	angle of the vanes of the swirlers (rad)
Φ	overall equivalence ratio (dimensionless)

Acronyms

RZ	recirculation zone
LES	Large Eddy Simulation
AFR	air-to-fuel ratio

Subscripts

LR	lightround

Spark ignition of non-premixed flames has been studied experimentally in the context of single burners [7–10]. A low-order computational model based on the main physical findings has been developed as well [11,12]. Moreover, numerical simulations based on Large Eddy Simulation (LES) have been conducted in order to reproduce the burner ignition process for a single combustor [13–18]. The simulations of a complete ignition sequence of a full gas turbine annular combustor comprising 18 burners and, more recently, of the annular combustor consisting in 16 identical swirling premixed burners described above have been conducted using LES [19,20]. However, the way the flame can propagate from burner to burner in non-premixed mode is a problem that has not been studied extensively in the laboratory before and this is of relevance to gas turbine combustors that have significant spatial equivalence ratio non-uniformities.

The present paper aims to examine the ignition behaviour of annular non-premixed combustors focusing on the burner-to-burner flame propagation. First, the experimental configuration is described. Then, the results obtained are presented and discussed. The paper concludes on the next steps of research to be conducted to determine the exact mechanism by which the flame moves from one burner to the next.

2. Experimental configuration

2.1. Non-premixed annular burner setup

The annular non-premixed burner is shown in Fig. 1 and is closely related to the premixed annular burner developed at the University of Cambridge [5,6]. The airflow is delivered to a unit consisting of a 200 mm long cylindrical plenum chamber with an inner diameter 212 mm containing flow straighteners and a series of grids. A hemispherical body 140 mm in diameter is positioned inside the plenum to improve uniformity. The air is exhausted from the plenum through a number of identical 150 mm long circular tubes with an inner diameter D = 18.9 mm. Each tube is fitted with a centrally-located duct consisting of a 5-mm-diameter tube of wall thickness 1.0 mm. To its end, at the burner exit, is attached a conical bluff-body of diameter da = 13 mm, giving a blockage ratio of 50%. Each duct is connected to a methane supply through a 5 mm diameter flexible tube leaving through the plenum's wall allowing gas from the outside of the plenum to feed each tube. The pipe – bluff bodies assemblies are arranged around a circle of diameter 170 mm and fixed between upper and lower plates. A six-vane, $\alpha = \pi/3$ rad (60°), counter-clockwise swirler (as viewed from inside the combustion chamber) is fitted 10 mm upstream of each bluff-body giving a geometrical swirl number of 1.22 [6]. The combustion chamber is made of optical-quality quartz inner and outer tubes of diameter 127 mm and 212 mm and lengths 195 mm and 155 mm respectively mounted on the top plate, which serves as a chamber backplane.

Three sets of plates were manufactured with the same circumference enabling 12, 15 and 18 flame configurations to be tested [6]. These correspond to flame separation distances of $S = 1.56D$, $S = 1.87D$ and $S = 2.33D$, where S denotes the arc distance between the bluff-body centres.

2.2. Flow conditions and ignition unit

The experiments were carried out at ambient temperature and pressure at three overall equivalence ratios $\Phi = 0.30$, $\Phi = 0.35$, $\Phi = 0.40$, and for bulk velocities of air and methane (Reynolds numbers (Re) ranging from $Re = 3950$ to $Re = 7100$) reported in Table 1. The annular chamber is equipped with an inductive ignition system consisting of two free tungsten electrodes of 1 mm diameter with a 5 mm gap from each other. The electrodes had pointed edges to reduce the heat loss from the spark. In every case, the electric energy delivered by the circuit was much higher than the minimum ignition energy (6.41 mJ) for methane–air mixtures within the flammability limits under atmospheric conditions [21]. A full description and the characteristics of the ignition unit are given in [7]. The spark location is $(z/d_a, r/d_a) = (2.2, 0.0)$, where the coordinate system is fixed at the centre of the bluff body at the burner exit plane.

2.3. Chemiluminescence measurements

Fast imaging of OH* chemiluminescence was used to image the ignition transient. It was recorded by a Photron SA1.1 monochrome high speed CMOS camera with a 1024 * 1024 pixel resolution up to 5.4 kHz coupled to a La Vision IRO high-speed two stage intensifier gated at 190 μs with a spectral range of 190–800 nm. The frame rate was set at 5000 Hz for the side imaging and 1000 Hz for the top imaging, making it possible to resolve the flame dynamics reliably during the ignition process. The width and delay of the intensifier were chosen depending on the measurement. Fast imaging of OH* chemiluminescence were recorded through a UV bandpass filter (270–370 nm). In order to protect the intensifier from the possibility of intense emission from the spark, the acquisition started once the spark had ended. For the top imaging of the burner, a cooled mirror was placed above the combustor doing a 45° angle from the vertical, in order to image burner from the top and hence allowing a visualisation of the lightround process.

2.4. Data processing

In order to quantify the flame evolution in the annular combustor, a Matlab code was used for the analysis of the films. First, the movies taken from the top of the burner were decomposed in

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