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Experimental and numerical investigation of an ultra-low NO_x methane reactor

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Abstract

This work investigates a patented novel methane reactor, the Lean Azimuthal Flame (LEAF) Combustor. The combustor operates with non-premixed combustion where both the air and methane enter the combustor volume through small, high momentum jets. The air jets, located at the top of the combustor, are angled to create a swirling flow that mixes with the fuel entering from the bottom of the combustor. The resulting toroidal flow is intended to increase mixing and hot product recirculation within the burner to reduce operating temperatures, increase residence time, and limit the formation of NO_x with preliminary emissions levels measured at sub-20 ppm. The main objectives of this paper are to: (i) experimentally characterize the combustor behaviour; and (ii) improve the physical understanding of the combustion process in the system under investigation through the use of numerical simulations. Experiments were performed at various air and fuel flow rates to determine the stability range of the combustor. Direct visualization of the combustion process indicates the formation of a low luminosity stable flame with a toroidal shape. Flame photographs and OH* chemiluminescence images are presented to provide a qualitative comparison of flame structure and reaction zone, as well as to analyse the effect of varying air and fuel flow rate on combustor operation. Numerical simulations were performed using the Large Eddy Simulation (LES) approach with the Conditional Moment Closure (CMC) sub-grid combustion model to analyse the flame behaviour within the combustion chamber. The regions around the fuel jet flow in particular were investigated to explore the phenomena of flame lift-off and local extinction in the bottom of the combustor.

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Keywords: MILD combustion, Large Eddy Simulation, Conditional Moment Closure, low emissions, natural gas burner

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1. Introduction

Stringent legislation limiting the emission of pollutants such as carbon monoxide (CO), nitrogen oxides (NO_x), and unburnt hydrocarbons (UHC) has led to the development of new combustion technologies [1]. Moderate or Intense

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Low oxygen Dilution (MILD), is a combustion regime that often involves high levels of hot combustion product recirculation in order to dilute the reaction zone and reduce its peak temperature with the objective of reducing emissions without compromising efficiency [2].

Cavaliere and De Joannon [2] highlighted the potential benefits of utilizing the MILD regime. They showed that MILD combustion is defined by a low maximum reaction temperature and low overall temperature increase within the system, which limits both NO_x and soot production [2]. The successful application of MILD combustion to furnaces suggests the potential for its use in gas turbine applications. The aim is to maintain the combustor temperature within the narrow “low-emission window” between 1600 K and 1800 K and the corresponding residence time, where emissions of both CO and NO_x are minimal without compromising combustor stability and the thermal efficiency of the process [3]. The many inherent differences between furnaces and gas turbines have made the application of MILD combustion to gas turbines difficult. A gas turbine’s combustion chamber is smaller with constraints on the weight and size, especially for aviation, which hinders hot product recirculation (HPR) feasibility [4]. A gas turbine combustor operates adiabatically at elevated pressures approaching 30 bar, elevated temperatures, high power densities of up to 50 MW/m^3 higher than power densities of laboratory scale MILD combustors, and by maintaining a significant level of O_2 throughout the combustion process, which makes the O_2 deprivation characteristic of MILD combustion difficult to implement [4]. Despite these challenges, progress has been made through the success of various combustor geometries at achieving MILD characteristics accompanied with reduced emissions [5, 6]. Though some of these combustors have been operated at elevated pressures, none have approached the operating pressures and power densities of modern gas turbines [4]. More work is needed in order to develop a combustor capable of operating stably in the MILD regime under the conditions compatible with gas turbines [4].

The Lean Azimuthal Flame (LEAF) combustor is a novel combustor based on MILD principles developed and patented at the University of Cambridge [7]. The present work aims to explore some features of the LEAF reaction zone both experimentally and numerically. The geometry, operation, and reaction zone location and structure will be described in this work through experimental investigation and CFD analysis.

2. Methods

2.1. Experimental Methods

A schematic and photograph of the LEAF combustor are shown in Figure 1. The combustor has a cylindrical quartz body for optical access and is 150 mm in both diameter and height, fitted with stainless steel plates on the top and bottom. It has a 36 mm diameter central air channel, hereafter referred to as the core air, fitted with a 25 mm central bluff-body and a swirler upstream of it. This arrangement may provide a conventional swirl premixed flame, if fuel is introduced together with this core air, but in the experiments discussed here the core flow was only air. The core air has a bulk velocity, U_C, ranging from 0.4 to 2.5 m/s. At the top center of the LEAF lies a 40 mm diameter exhaust exit. The exhaust and the core air align along the central axis of the combustor. Eight fixed, equally spaced and sized air jets 2 mm in diameter and angled at 30° are evenly spaced at a radius of 45 mm around the top plate with an incoming jet air velocity, $U_{J,A,}$ of 23 – 93 m/s. They are angled such that the air is fed into the combustor with a tangential, or azimuthal, component, generating a clockwise bulk flow. Four 1.1 mm diameter fuel jets are arranged at a radius of 55 mm in the bottom plate of the combustor with an incoming jet fuel velocity $U_{J,F}$ of 35 – 70 m/s. Two premixed spark ignited pilots of 20 mm diameter are placed tangentially at the bottom half of the combustor, and are used to ensure ignition and to promote bulk swirl. Pilot fuel is only used during ignition to generate a stable flame.

Once the LEAF combustor is operating stably, the pilot fuel is switched off while the pilot air velocity $U_{P,A}$ is maintained within the range of 1 – 3.5 m/s. The larger diameter and number of the jet air inlets compared to the fuel inlets allows for a larger amount of air to enter the combustor; additionally, the higher jet air flowrates lead to a higher jet air momentum. The total air volumetric flow must be higher than the fuel volumetric flow so that the system can operate globally lean [7]. Two equivalence ratios are used to describe the flow: the overall equivalence ratio (ϕ_t) which is kept lean between 0.5 and 0.8, and the jet equivalence ratio (ϕ_J) defined based only on the jet air and jet fuel. Out of the 36 test cases run on the LEAF, the conditions with the most impact on reaction zone and flame shape can be found in Table 1. The first stable flame established without pilot fuel assistance was taken as the base case for this work at a ϕ_t of 0.6 and is the first entry in Table 1. Photographs were taken with a Nikon DX AF-S Nikkor 18-55 mm camera. For each condition, 100 OH* chemiluminescence images were taken with a LA VISION SLOWCAM2