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The probabilistic nature of ignition of turbulent highly-strained lean premixed methane-air flames for low-emission engines

Samer F. Ahmed *

Thermofluids Group, Department of Mechanical and Industrial Engineering, College of Engineering, Qatar University, P.O. Box 2713, Doha, Qatar

HIGHLIGHTS

- The ignitable region shrinks with an increase in the bulk velocity.
- Ignition can be achieved where a flammable region exists with finite probability.
- Ignition is not possible at large adverse radial velocities.
- The edge flame speed increases with the velocity.
- Failed ignition has been viewed close to the extinction flow conditions.

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ABSTRACT

The probabilistic nature of ignition of turbulent highly-strained lean premixed flames has been investigated. Two flow configurations have been considered in this study; counter-flow and bluff-body flames. Different successful and non-successful ignition events in both flows have been observed directly with high-speed imaging. In addition, the flame front structure during the flame propagation following the ignition has been observed using OH-PLIF technique. Moreover, the ignition probability has been measured in both flows with different equivalence ratios and flow velocities. It has been found that high bulk velocities decrease the ignition probability in all locations and for all flames. For counter-flow flames, ignition is sometimes possible even in locations where there is negligible probability of finding flammable mixture and is sometimes impossible in locations with high probability of flammable flow. The edge flame propagation speed has also been detected in this type of flames. For bluff-body flames, the flame propagation behavior following the spark ignition depends mainly on the location of the spark in respect to the recirculation zones. Furthermore, the flame inside the side recirculation zone (SRZ) quenches soon after the whole flame lights-up. Failed ignition has been viewed close to the extinction flow conditions of the flame. Igniting the flame away from the extinction conditions results in 100% ignition probability regardless of the ignition location. However, close to extinction, ignition probability decreases gradually and achieving ignition is not possible at all outside the central recirculation zone (CRZ). The obtained ignition probability contours of both flows have been compared with the previously-studied ignition probability contours of turbulent non-premixed flames of the same burners.

1. Introduction

Lean combustion is currently under consideration in almost all combustion technology fields including gas turbines, internal combustion engines (ICEs), boilers and furnaces. This is mainly because combustion under lean-fuel conditions usually results in low emissions and high operating efficiency. Lean premixed flames have received increasing attention as an attractive alternative for combustion systems since 1980s [1]. Currently, major gas turbine manufacturers (e.g., Siemens and GE) are placed emissions and efficiency at the frontline of their research and development. However, for aviation gas turbines in particular, moving toward very lean combustion is restricted by two main difficulties; lean stability (blow-off) and altitude relight (ignitability). Extensive work has been done to understand the stability of lean premixed flames especially if operating close to the extinction limit [2,3]. However, the altitude relight or the ignitability of the combustor under this condition has not been studied extensively yet. In general, ignition

* Tel.: +974 4403 4307; fax: +974 4403 4301.
E-mail address: sahmed@qu.edu.qa

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of turbulent premixed flames has been well characterized in terms of minimum ignition energy (MIE) and flame propagation speed either in flowing mixtures [4–9] or inside a combustion bomb [10,11]. However, studying the ignitability of very lean highly-strained premixed flames has not been considered yet. Two flow configurations have been selected for this study; turbulent counter-flow, which is useful in understanding the effect of strain rate on the ignition probability, and a more complex flow pattern such as turbulent bluff-body flow, which is quit similar to the real flow pattern of a gas-turbine combustor.

The term "ignition probability" (P_{ign}) has been first introduced in the study of Birch et al. [12] and Smith et al. [13]. They have successfully correlated the ignition probability (defined as just initiation of a flame kernel regardless a stable flame is formed or not) in a non-premixed turbulent jet with the probability of finding a flammable mixture at the ignition location. Recently, a series of experiments [14–19] and simulations [20–24], driven by the altitude relight problem of the aviation gas turbine, have investigated the ignition probability (defined as a fully formation of a stable flame) in different turbulent non-premixed and spray flames. In these studies, the successful ignition (practically) includes not only an initiation of a flame kernel, but also flame propagation and overall stability of the flame. This aspect of ignition has been denoted as "phase 2" of a gas turbine ignition process [25]. The above studies have concluded that the failed ignition can happen because of two main reasons; first, failure of the spark to initiate a flame kernel and second, if the flame kernel is initiated, failure of the kernel to propagate and form the stable flame. Both reasons result in reducing P_{ign}.

Previous experimental work have found that failure of the spark to initiate a flame kernel is associated with some local and non-local effects at the spark location. The local effects include: mixture fraction fluctuations [16], velocity fluctuations [14], strain rate [15,20], turbulence [16] and droplet SMD for sprays [18]. On the other hand, the non-local effect can be attributed to the diffusion of the spark energy from the spark location to another location probably due to the influence of the global flow field [15,16]. It can be observed that most of these factors, except the mixture facture fluctuations and spray characteristics, can still affect the ignitability of fully premixed turbulent flames. In particular, ignition of lean premixed flames with high degree of strain rate is expected to be affected severely with these factors. The second reason of the failure of flame kernel propagation has been found to be linked to the mean mixture fraction, mean flow velocity and mean turbulence ahead of the flame kernel [14–16]. If all these parameters are favorable for upstream flame propagation, the flame kernel will propagate and establish the stable flame. In this case, the ignition can be described as successful. Again, if mean mixture fraction is excluded, the other parameters may still affect the flame kernel propagation in fully lean premixed flames and, as a result, affect the success of ignition.

Some modelling work have also tried to explain the reasons behind ignition failure. Birch et al. [26,27] have used CFD techniques that employ complex probability density function (pdf) forms that include an intermittency-based turbulence model to study the ignitability of turbulent flammable flow. They have found that failure to initiate a flame kernel governs with the local mixture fraction probability distribution for non-premixed flames. In addition, the duration of turbulence fluctuations in relation to the chemical ignition delay period can be the reason behind the failure of the spark to initiate a flame kernel in both premixed and non-premixed turbulent flows. On the other hand, failure of the flame kernel (if initiated successfully) to propagate is mainly related to the probability that the burning velocity of the flame is higher than the local flow velocity. Recently, Alvani and Fairweather [28] have used a model based on fluid flow equations with a new intermittency-based second moment closure to predict the bimodal mixture fraction distribution in intermittent free shear flows. They reported that the model is capable of predicting P_{ign} in many practical flows.

It is clear from what has been mentioned that running the combustion engines with very lean turbulent highly-strained premixed flames is expected to be a challenging task regards the ignitibility of these engines. Therefore, investigating P_{ign} (defined as the probability of creating a stable flame) in an engine-like flow filed forms the main goal of the present work. This investigation aims to first: study the effect of the parameters mentioned above on the ignitability of such flames; second: give the engine manufacturers a brief image about the ignition capability of these engines. Two flow configurations will be considered in this study; turbulent counter-flow and turbulent bluff-body flow. The first one is useful in studying the effect of different degrees of strain rate on the two stages of ignition, mentioned above, that lead to the success of ignition. The second flow selected for this study (turbulent bluff-body) will give a clear view about the ignition probability of turbulent lean premixed flames in a configuration similar to that exists in actual gas turbines. The two burners, used in the current work with exactly the same dimensions, have been used before for flame stability and ignition investigations of turbulent non-premixed flames [15,16,29]. However, in the present work, ignition probability of turbulent highly-strained premixed flames is investigated. This type of flame ignition has not studied before using these burners. The axial and radial mean and rms velocity fluctuations have been measured accurately using LDV. More details about the flow measurements in the selected burners can be found in Refs. [16,30].

2. Experimental methods

2.1. Apparatus

The first test rig used in the present work is the turbulent premixed counter-flow burner, which is shown in Fig. 1. The burner consists of two straight pipes of inner diameter $D = 25$ mm, surrounded by co-flows of nitrogen of diameter $D_0 = 50$ mm, following the design of the counter-flow burner of Refs. [15,30]. The pipes are separated by a distance $H = D$ for the experiments reported here. Air flows from the upper pipe, while the lower pipe carries a flammable methane–air mixture and its composition is described by the equivalence ratio, $ø$. In the current work, only lean premixed flow with $ø = 0.8$ has been studied. The bulk velocity of the top jet (air) is U_b. To achieve a symmetric flow, the momentum flow rates of the two jets must be equal which implies that the velocity of the lighter (fuel) jet is higher than the velocity of the air jet, although the difference is very small for the premixed flames since the density of the two streams are approximately equal. At a distance of 60 mm from the exits, perforated plates with 40% solidity and a hole size of 3 mm have been used to promote turbulence. Following Ref. [30], the turbulent fluctuations, u', and the integral length scale, L_t, at the exit of the jets are uniform across the pipe and approximately $u'/U_b = 10\%$ and $L_t = 3$ mm. For the current flow configuration, the axial profile of the velocity across the jets is approximately top-hat [30].

The second test rig is the bluff-body burner, Fig. 2. It comprises two concentric circular ducts of length 400 mm. The outer duct has an inner diameter, D_s, of 35 mm. The inner duct has a 6-mm-internal diameter tube and a wall thickness of 0.5 mm. It ends with a conical bluff-body of diameter $D_b = 25$ mm at the burner exit, which results in a giving blockage ratio of $BR = D_b^2/D_s^2 = 50\%$. The flame area was surrounded by an 80-mm-long optical-quality quartz cylinder with an inner diameter of 70 mm. This enclosure provides an optical access for imaging in addition to avoid air