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Measurement and scaling of minimum ignition energy transition for spark ignition in intense isotropic turbulence from 1 to 5 atm

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Abstract

This paper presents high-pressure minimum ignition energies (MIE) and their scaling from measurements on spark discharges in lean methane/air mixtures at the equivalence ratio $\phi = 0.6$ by cylindrical electrodes with flat ends in near-isotropic turbulence over a range of turbulent intensities ($u'/S_L = 0$–50), from 1 to 5 atm, using a large dual-chamber, constant-pressure, fan-stirred explosion facility, where S_L is the laminar burning velocity. Voltage and current waveforms of spark discharges with nearly square profiles are carefully generated for accurate determination of MIE, commonly defined as the 50% successful ignitability. Applying high-speed schlieren imaging, we observe a drastic change of kernel development from turbulent flamelet to distributed like with island formation and local quench even at 5 atm, when u'/S_L is greater than some critical values depending on p. It is found that the scaling slopes of MIE_T/MIE_L versus u'/S_L change abruptly from a linear increase to an exponential increase when $u'/S_L > (u'/S_L)_c$, showing ignition transition. The subscripts T and L represent turbulent and laminar properties, $MIE_L \approx 6.84$ mJ (1 atm), 2.81 (3 atm), and 2.11 (5 atm), and the transition occurs at $(u'/S_L)_c \approx 12$ (1 atm), 24 (3 atm), and 34 (5 atm). It is also found that the above scattering MIE_T/MIE_L data at different u'/S_L and p can be merged together into a single curve when scaled with a pressure-corrected kernel (reaction zone, RZ) Péclet number, $Pe^* = Pe_{RZ}(p/p_0)^{-1/4}$, showing the first and fourth power dependence before and after MIE transition at a critical $Pe^* \approx 3.6$. $Pe_{RZ} = u'\eta_k/\alpha_{RZ}$, η_k is the Kolmogorov length scale of turbulence, α_{RZ} is the thermal diffusivity estimated at the instant of kernel formation, and $p_0 = 1$ atm. These results reveal a self-similar spark ignition phenomenon.

Keywords: High-pressure turbulent spark ignition; Minimum ignition energy transition; Turbulent flamelet and distributed like kernels; Intense isotropic turbulence; Self-similar ignition

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1. Introduction

Initiation of a combustible mixture with a critical amount of ignition energy (E_{ig}), known as the minimum ignition energy (MIE) [1], is important to most combustion devices and crucial for the risk assessment of accidental explosion in industrial and aviation safety [2]. For more than five decades, there have been extensive MIE studies for various flammable gases, most in quiescent condition and some with flow considerations, via experimental, numerical, and modeling approaches (e.g., [3–23] among many others). However, most of these previous studies were obtained at 1 atm. Without consideration of the pressure effect, could these atmospheric results [1,2,4–18,20–23] be valid when they are used to predict ignition characteristics in spark ignition engines and gas turbines that take place in high-pressure turbulent environment? This motivates the present work aiming to measure MIE in high-pressure turbulent environment up to 5 atm that is still not available in literature.

First, spark ignition in turbulent premixed gases is statistical in nature [4,5,11,13,14,16,21,23] rather than characterized by a single threshold value in classic MIE data. In other words, MIE is a probabilistic variable that should be determined statistically by repeating many ignition experiments under the same conditions except using a range of different E_{ig} to identify a transition band in which successful ignition (Go) and misfire (No go) coexist even at the same E_{ig}. In the past, several different ignition probabilities, such as 1%, 10%, 50%, and 80%, have been proposed to determine MIE, as discussed in [19]. Among them, the 50% successful ignitability was the most common one used in our community [e.g., 2,4,5,7,8,11,13,16,17,19,21,23]. Thus, all present MIE data are measured at 50% ignitability. Also, MIE depends on various factors, i.e., the electrode geometries, gap widths, discharging modes and pulse duration times, and mixture and flow properties (see [19] and references therein). For a meaningful spark ignition study, these factors and the discharged E_{ig} should be specified; otherwise, experiments cannot be repeated by other groups. Moreover, at the same breakdown voltage and pulse duration, the discharged E_{ig} is found to increase with the increase of the electrode's gap width (d_{gap}). In fan-stirred bombs, the commonly-used thin and long electrodes may be vibrated by turbulence causing a variation of d_{gap} that can alter the ignition probability ("Go" or "No go") making MIE or E_{ig} determination highly uncertain. Hence, how to assure a fixed gap width of the electrodes is crucial for any ignition studies especially when turbulence is intense.

Second, we introduce a MIE transition emanating from a series turbulent ignition experiments at 1 atm using a spark-electrode with sharp ends in randomly-stirred methane/air mixtures at various equivalence ratios ($\phi = 0.6$ [11]; $\phi = 0.7$, 0.8 [13]; $\phi = 0.6$–1.3 [16]). In [11,13,16], ignition experiments were conducted in a large fan-stirred cruciform burner equipped with a pair of counter-rotating fans and perforated plates, capable of generating a sizable near-isotropic turbulence region having a very wide range of turbulent intensities (u'/S_L) and/or turbulent Karlovitz number $\text{Ka} = (u'/S_L)^2 \text{Re}_T^{-0.5}$. $\text{Re}_T = u' L_I/\nu$, where u' is the r.m.s. turbulent fluctuating velocities, S_L is the laminar burning velocity, L_I is the integral length scale of turbulence, and ν is the kinematic viscosity of reactants. For the interested reader, the associated turbulence properties measured by extensive LDV and PIV can be found in Refs. [24–27]. In [16], it was found that there are two distinct modes for which the increasing slopes of MIE with Ka change drastically from linearly to exponentially when values of Ka are greater than some critical values ($\text{Ka}_c \approx 8$–26) depending on ϕ with the minimum Ka_c occurring near $\phi = 1$, showing a MIE transition. Such a MIE transition has been independently verified by Renou and co-workers [21] using laser-induced spark ignition of lean turbulent methane/air mixtures in a decaying homogenous wind-tunnel turbulence at 1 atm. Both previous results [16,21] using different ignition systems (conventional electrode versus laser) and different flow configurations (fan-stirred near-isotropic turbulence versus decaying homogenous wind-tunnel turbulence) found the same MIE transition phenomenon, suggesting that MIE transition may be a universal phenomenon. But how exactly would these MIE results obtained at 1 atm vary with a change of pressure from 1 atm to 5 atm? This paper addresses such question.

Third, Peng et al. [19] applied a double-chamber, constant pressure explosion facility to measure turbulent MIE at 3 atm, where an inner large 3D cruciform burner with a pair of counter-rotating fans and perforated plates (same design as in [11,13,16,24–27]) was resided in a huge pill-like outer chamber. They found that the aforesaid MIE transition also exists at $p = 3$ atm for lean methane/air mixtures at $\phi = 0.7$ but with different critical u'/S_L and/or Ka, where the same 2-mm cylindrical electrodes with sharp ends ($d_{tip} = 0.1$ mm) having a fixed electrode gap of $d_{gap} = 2.5$ mm and a constant pulse duration time of 100 μs as in [11,13,16] were applied. However, Peng et al. [19] were unable to investigate MIE transition at 5 atm, because the required E_{ig} or MIE was too small to be accurately measured (see Fig. 3 of [19]). The difficulties of generating accurate spark ignition energies at elevated pressure should not be underestimated, especially for small E_{ig}. When p increases, the required breakdown voltage to successfully discharge E_{ig} on a spark-electrode must be also increased. In general, the higher the breakdown voltage is, the higher the discharged E_{ig} is. In order to obtain a small E_{ig}