Combustion and Flame 162 (2015) 462–469

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Investigation of the effect of electrode geometry on spark ignition

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ARTICLE INFO

Article history:
Received 28 March 2014
Received in revised form 18 June 2014
Accepted 20 July 2014
Available online 21 August 2014

Keywords:
Spark ignition
Flames
Electrode

ABSTRACT

High-speed schlieren visualization and numerical simulations are used to study the fluid mechanics following a spark discharge and the effect on the ignition process in a hydrogen–air mixture. A two-dimensional axisymmetric model of spark discharge in air and spark ignition was developed using the non-reactive and reactive Navier–Stokes equations including mass and heat diffusion. The numerical method employs structured adaptive mesh refinement software to produce highly-resolved simulations, which is critical for accurate resolution of all the physical scales of the complex fluid mechanics and chemistry. The simulations were performed with three different electrode geometries to investigate the effect of the geometry on the fluid mechanics of the evolving spark kernel and on flame formation. The computational results were compared with high-speed schlieren visualization of spark and ignition kernels. It was shown that the spark channel emits a blast wave that is spherical near the electrode surfaces and cylindrical near the center of the spark gap, and thus is highly influenced by the electrode geometry. The ensuing competition between spherical and cylindrical expansion in the spark gap and the boundary layer on the electrode surface both generate vorticity, resulting in the toroidal shape of the hot gas kernel and enhanced mixing. The temperature and rate of cooling of the hot kernel and mixing region are significantly effected by the electrode geometry and will have a critical impact on ignition. In the flanged electrode configuration the viscous effects generate a multidimensional flow field and lead to a curved flame front, a result not seen in previous work. Also, the high level of confinement by the flanges results in higher gas temperatures, suggesting that a lower ignition energy would be required. The results of this work provide new insights on the roles of the various physical phenomena in spark kernel formation and ignition, in particular the important effects of viscosity, pressure gradients, electrode geometry, and hot gas confinement.

1. Introduction

Determining the risk of accidental ignition of flammable mixtures is an important element in industrial and aviation safety. Traditionally, the method for studying ignition hazards of fuels is to determine the minimum ignition energy (MIE) through testing using a capacitive spark discharge as the ignition source. There have been extensive experimental studies to determine the minimum ignition energies of various flammable mixtures. However, recent investigations [1–3] of spark ignition suggest that ignition is statistical in nature rather than characterized by a single threshold value as presented in classic MIE data. Minimum ignition energy is found to depend strongly on the specifics of the geometry and the electrical discharge, complicating experimental investigations. There is minimal discussion in the literature on the effect on ignition of the spark channel geometry resulting from the electrical discharge and electromagnetic effects. In previous work [3], it was found that these effects contribute to variability of the ignition test results near the traditional MIE. Developing numerical tools to reliably predict ignition in different geometries is one of the outstanding issues in combustion science.

Much of the previous work on simulating ignition has idealized the problem and treated one-dimensional spherical and cylindrical spark kernels. Several authors have used two-dimensional simulations of spark discharge in a non-reactive gas [4–7] to investigate the fluid mechanics involved in the spark ignition process, and two-dimensional simulations of ignition are discussed in [8–16]. In all the two-dimensional studies, the classic toroidal shape of the hot gas kernel is observed, which occurs due to fluid flow inward toward the gap center. In most of these studies only one electrode geometry is considered and the simulations are not

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http://dx.doi.org/10.1016/j.combustflame.2014.07.017

sufficiently resolved to capture all aspects of the fluid motion. Akram [5] and Thiele et al. [10] performed simulations for several electrode geometries, however, the geometries were limited to blunt and cone-shaped electrodes with diameters of 1–2 mm. Most recently, Han et al. simulated ignition in methane–air [14] and hydrogen–air [15] mixtures and studied the effects of temperature, electrode gap distance, electrode size (cylindrical electrodes), and spark duration on the predicted minimum ignition energy (MIE). These studies used detailed chemistry and provided new insight on the effect of different spark parameters on ignition. However, the simulations did not appear to resolve the details of the fluid mechanics, and the authors primarily considered the temperature rise in the flame kernel and the heat loss to the electrodes. Also, many of the predicted MIE values were very large compared to historical values, suggesting that the model is still not complete. Nakaya et al. [16] also performed simulations of spark ignition in methane–air mixtures and focused on the interaction of chemical reactions, flow fields, and diffusion processes during ignition. The ability to accurately resolve these different physical processes is critical for a successful model and essential to our understanding of the ignition process. While the work of Nakaya et al. provides significant advancement towards accurate model development, the simulations were limited by low grid resolution and a single electrode geometry.

Many investigators have also performed experimental studies on visualizing spark discharge and ignition using optical and laser techniques. Experiments have been done to visualize the fluid mechanics of the evolving spark and ignition kernels using shadowgraph and schlieren visualization [4,17–25] and interferometry [4,26]. Laser diagnostics, such as laser-induced fluorescence (LIF) [12,23,27] and spectroscopy [23,27], have also been implemented to measure characteristics of the spark kernel such as temperature and magnitude of OH radicals. In all of these studies, the electrode geometry is not varied, and there is no direct comparison with two-dimensional simulations.

The plasma chemistry as well as the details of the spark channel formation will also largely effect the ignition process. Significant advances have been made in understanding the plasma chemistry and electrodynamics of short-duration electrical discharges. Most of the recent work has focused on non-equilibrium plasmas generated by nanosecond pulse discharges, and reviews of this work are given in [28,29]. Recent work on ignition by nanosecond discharges has included both experimental [30–32] and numerical [24,30,32–34] studies of the effect of the plasma chemistry and electrodynamics. Also, recent advancements have been made on measuring and modeling ignition by transient plasma streamer discharge [35,36]. While significant progress has been made on modeling the fluid mechanics, chemistry, and plasma dynamics of spark discharge separately, full integration into a single numerical simulation has not been achieved. While the plasma chemistry and electrodynamics are beyond the scope of the current work and therefore not considered, they are critical for a complete model of the ignition process.

In the current work, high-speed schlieren visualization and two-dimensional simulations of spark discharge in a non-reactive gas and ignition are presented. The effect of electrode geometry on the flow field subsequent to the spark discharge and on ignition is investigated for three distinctly different electrode types: cylindrical with a 0.38 mm diameter, conical with a 6.35 mm base diameter, and blunt cylindrical electrodes with Teflon flanges. Only a few authors have considered conical electrodes [5,10] and in these studies the base diameters of the electrodes were 1–2 mm. Thin cylindrical electrodes have been considered by several authors [4,5,7–10,15,16]. In all the studies except [4,15] the diameters of the cylindrical electrodes were 1–2 mm; in the present study the diameter is 0.38 mm, on the order of the thickness of the initial spark channel. Finally, in our work, flanged electrodes are also considered. This geometry is particularly important because flanged electrodes were used to obtain the classic minimum ignition energy and quenching distance data [37] that is still relied on extensively in the scientific literature and safety standards. The role of the flanges in the ignition process is not well understood and there have been few studies which consider flanged electrodes.

In both the simulations and experiments in the current study only very short sparks (on the order of 100 ns) are considered. In some of the previous modeling work [8,10,12] sparks with a breakdown phase followed by a long arc phase (10–100 μs) were used to simulate sparks from circuits with a significant inductance component, e.g., an automotive spark plug. Shorter duration (<1 μs) sparks are more consistent with electrostatic discharge hazards in aviation and other industries.

2. Numerical simulations

2.1. Model description

The spark discharge and ignition simulations were performed using direct numerical simulation (DNS) of the multicomponent, compressive, non-reactive and reactive Navier–Stokes equations. For the simulations of spark discharge in a non-reactive gas, the mass, momentum, and energy equations for two-dimensional, compressible, viscous, heat conducting flow are solved in cylindrical coordinates. The temperature dependence of the viscosity and thermal conductivity are described using the Sutherland law, and a power law model is used to account for the pressure dependence of the mass diffusivity [38]. For simulations of ignition, the gas is treated as a mixture of four perfect, reacting components and additional continuity equations for each of the chemical species are solved. The thermodynamic properties were evaluated as a function of temperature using the CHEMKIN-II library [39]. The thermodynamic model used in CHEMKIN is only valid up to 5000 K, and so constant properties are assumed for the high temperature phase. A detailed discussion of the numerical model and equations used is given in [38,40].

In this first set of simulations the focus is on the fluid mechanics and not the chemistry, and so a highly simplified one-step chemistry model for a 15% hydrogen–air mixture was used to allow for higher resolution of the flow scales with a shorter computational time. The one-step chemistry model was developed in previous work [3,41] to accurately simulate the characteristics of a one-dimensional hydrogen–air deflagration. By using this model, the effects of the complex chemical kinetics and the plasma chemistry are neglected and therefore must be taken into account in future improvements of the spark ignition simulations.

2.2. Initial and boundary conditions

In the present study, the primary objective is to investigate the influence of the electrode geometry on the fluid dynamics following the spark discharge and how the flow field affects the ignition process. Therefore, simulation of the spark breakdown phase and plasma formation is beyond the scope of the current work. Instead, a highly simplified model of the spark is used where it is approximated as a channel of gas at high temperature and pressure. This model neglects the important effects of the plasma chemistry as well as the highly complex electrodynamics and plasma formation process, which was shown in prior work [3] to significantly influence ignition. Future work to further develop and improve the spark ignition simulations would necessarily include more complex models for the spark.