Modeling Plasma-Assisted Methane Ignition with Plasma Energy Fraction Manifolds

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Abstract: This work advances a phenomenological plasma-assisted combustion model by incorporating spatiotemporally varying plasma energy fractions for gas heating, vibrational excitation, and chemical dissociation. A 2D manifold of energy fractions, based on reduced electric fields (E/N) and gas progress variables, is generated from 0D plasma-assisted combustion calculations and integrated into the model. Spatiotemporally evolving plasma power density (PPD) from detailed 2D simulations is also included to capture plasma streamer evolution during discharge. The enhanced model is validated against experimental data and used to investigate the ignition kernel evolution in a methane-air discharge.

1. Introduction

Nanosecond repetitively pulsed (NRP) discharges in fuel-air mixtures produce reactive radicals and heat the gas mixture, enhancing its reactivity [1]. Modeling plasma-assisted combustion (PAC) systems is challenging due to the complex coupling of plasma-phase and gas-phase processes. Phenomenological models have been developed to simulate PAC systems by capturing key effects like gas heating and species dissociation while reducing computational costs [2]. This study aims to improve existing models by incorporating spatiotemporally varying plasma energy fractions, enabling more accurate simulations of PAC in methane-air mixtures.

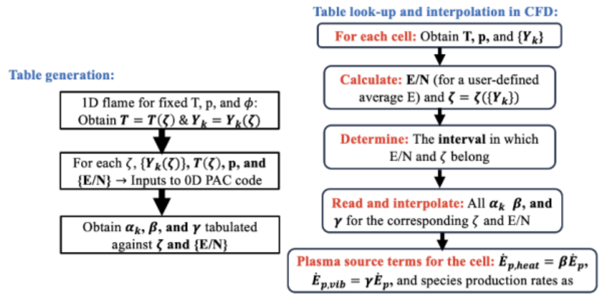

Fig. 1. Schematic of the manifold generation of 2D plasma energy fractions and their utilization in the phenomenological model.

2. Methods

A 2D axisymmetric mesh is used, with non-reflecting boundary conditions applied to outflow boundaries and no-slip conditions at the electrodes. The plasma-assisted combustion model adapts a phenomenological NRP model [2], dividing the deposited plasma energy into components for ultra-fast heating, species dissociation, and vibrational energy increase. Governing equations account for the effects of NRP discharges, while a 2D manifold for plasma energy fractions closes the model. Plasma energy fractions are obtained from simulations with a 0D PAC code [3].

3. Results and Discussion

Fig. 1 shows the schematic of the generation of plasma energy fraction manifolds and their utilization in the phenomenological ignition model. The present model accurately captures the temporal evolution of gas temperature and O radical concentration during the discharge phase, and the post-discharge dynamics of the pressure wave and heated channel without adjusting energy deposition. Further investigations reveal a slower expansion of the ignition kernel for CH_4/air discharge using the present model when compared to the original model in the literature.

4. Conclusion

A phenomenological model for plasma-assisted combustion has been developed with spatiotemporally varying plasma energy fractions and plasma power density, capturing fast gas heating, vibrational excitation, and chemical dissociation. This enhanced model, validated against experimental data, has been used to study plasma-assisted ignition in methane-air mixtures, revealing different ignition kernel dynamics and additional radical production pathways compared to the original model.

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