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Investigations on the Optimal Ignition Strategy of Internal Combustion Engines via Various Spark Discharge Conditions

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ABSTRACT: Spark discharge ignition can be effectively enhanced by increasing the plasma volume and its duration, but evaluation and realization of an optimal ignition performance under engine working conditions are big challenges due to the complex in-cylinder flow field and thermodynamic environment. In this investigation, ignition strategies with various spark discharge parameters were tested, and their effects on the initial flame kernel formation and propagation in the early stage of combustion were compared and analyzed in a single-cylinder optical engine. The experimental results indicate that the combustion under stoichiometric conditions is not sensitive to the spark discharge settings; it mainly depends on the fast chemical reaction rate of the combustible mixture and the flow field inside of the cylinder. However, as the mixture becomes leaner, the increased ignition delay makes the ignition difficult gradually. Once the ignition capacity is insufficient, a flame displacement would occur during the flame propagating at the early stage of the combustion; the ignition performance is not fully released. A new spark discharge around the unburned zone can further improve ignition performance. Larger flame displacement means a later combustion phase and worse combustion performance. By boosting the discharge current and duration, the flame displacement and its duration are reduced, and the initial flame kernel formation and propagation can be effectively improved. The fitting results for the flame displacement indicate that each discharge current corresponds to a critical discharge duration; longer discharge duration than the critical discharge can achieve an optimal ignition performance of internal combustion (IC) engines.

1. INTRODUCTION

With increasing concerns on fuel consumption and greenhouse gas emission of road vehicles, the concept of lean or diluted combustion has been widely considered as a feasible technical pathway for increasing fuel efficiency and reducing pollution from combustion emissions, especially for internal combustion (IC) engines.[1−4] However, when lean or diluted combustion is used (especially when stratified combustion is not utilized), the lean combustible mixture can be hard to ignite or be sustained for satisfactory combustion performance.[5,6] Under these scenarios, the high cross-flow speed near the spark plug can further degrade ignition performance due to the higher heat loss under strong flow field conditions.[7−9] Besides, the complex in-cylinder thermodynamic environment (such as high background pressure, random temperature, and pressure distribution) increases the uncertainties of the initial flame kernel behavior, which may aggravate the cycle-to-cycle variations of IC engine combustion under lean conditions.[10] Therefore, the ignition characteristics need to be thoroughly investigated to understand and optimize initial flame kernel formation and development.

One of the critical parameters in evaluating the ignition performance is the critical flame radius (Rc), which is defined by Kelley et al.[11] and Kim et al.[12] and believed to be strongly related to successful ignition.[7,13] The critical flame radius quantifies a minimum initial flame radius for successful ignition. In addition, the minimum ignition energy (MIE) for successful flame initiation is proportional to the cube of the critical flame radius.[14−16] Essmann et al.[17] studied early flame propagations with low discharge energy. They found that increasing the ignition energy can effectively enhance the ignition process. The discovery also has been confirmed by other investigations.[18,19] The use of MIE to understand the impact of ignition characteristics has been widely accepted by researchers.[15,20,21] MIE as a criterion still has some inevitable drawbacks, especially for the ignition of the IC engines. On the one hand, ignition energy is a state variable and it is a time cumulant of power; when MIE is regarded as the criterion for evaluating the ignition performance, the information of both discharge power and discharge duration is ignored. In fact, the discharge current and duration have significant influences on the plasma kernel volume.[22−24] Besides, compared to the ignition energy, the discharge current has a more direct relationship with the initial plasma kernel radius. On the other hand, MIE is a basic ignition sensitivity parameter, which is defined to characterize the safety of the flammable material rather than appraising the ignition performance.[25] However, for IC engines, ignition has strong timeliness; a long ignition delay may deteriorate the engine performance due to the slow heat release and large heat loss. Therefore, for the combustion

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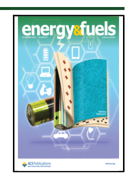

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