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Investigation of Flash Boiling Spray and Combustion in SIDI Engine under Low-Speed Homogeneous Lean Operation

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Abstract

Homogeneous lean combustion is expected to be a key technology to further improve the combustion and reduce emissions of spark-ignition direct-injection engines. The application of lean combustion is facing many challenges such as slow flame propagation and combustion fluctuations. Under severe operating conditions such as low-speed lean-burn conditions, the weak in-cylinder airflow worsens the fuel and air mixing yielding difficulties in stable flame kernel initiation and consequently deteriorating flame propagation. In this study, the effect of flash boiling spray on flame kernel generation, flame propagation, engine performance, and exhaust emissions of the spark ignition direct injection (SIDI) engine under homogenous lean-burn conditions are investigated. A single-cylinder four-stroke optical SIDI engine was used in this study. The in-cylinder flash boiling and subcooled sprays during engine operation were compared using the Mie scattering technique. The in-cylinder flame propagation was recorded using a high-speed camera and analyzed using a digital image processing model. The results reveal that both subcooled and flash boiling sprays have collapsed, but the liquid phase particle concentration intensity of the subcooled spray was higher compared with flash boiling spray, indicating a higher vaporization rate of the fuel droplets in the flash boiling case. Consequently, the air-fuel mixing is improved, and the wall-wetting and fuel-rich regions are reduced. The flame images and combustion analysis demonstrate that flash boiling spray can effectively improve the flame kernel initiation and accelerate flame propagation. Additionally, flash boiling lean-burn combustion showed higher in-cylinder pressure, more heat release, improved IMEP with advanced combustion phasing, and lower cyclic variation compared to subcooled case. The color model showed that the premixed flame was enhanced under the flash boiling spray. This study shows that flash boiling spray can be an effective method to improve combustion efficiency in homogenous lean-burn mode under low engine speed.

Introduction

The development of SIDI engines is still needed to keep pace with new stringent emission and efficiency regulations as well as fossil fuel depletion [1, 2]. Among many advanced combustion technologies, homogeneous lean combustion is considered to be one of the main technical paths to revolutionize the thermal efficiency in engines and reduce harmful emissions [2, 3, 4]. Lean combustion lowers the combustion temperature and consequently reduces heat transfer losses, thereby enhancing thermal efficiency. Meanwhile, the low-temperature oxygen-rich environment can suppress harmful emissions and effectively improve combustion [5, 6]. However, lean combustion commonly experiences uneven fuel/air mixing and low in-cylinder temperature, which results in ignition difficulties, misfiring, and significantly reduced flame propagation speed, thus, the engine performance is degraded [7, 8]. To stabilize the ignition process, a high-energy ignitor can be used to initiate the flame kernel and enhance combustion stability. However, the stable generation of the flame kernel cannot accelerate the flame propagation speed, especially in low-speed conditions due to the weak airflow. Therefore, the plasma cannot be effectively propagated, and the generation of the flame kernel will also be limited [4, 8, 9, 10, 11].

Engine researchers have adopted several strategies to achieve faster flame propagation under lean-burn mode in SIDI engines. These strategies include different spark discharge characteristics, strong in-cylinder turbulence, high spark-energy [12], and using a secondary fuel such as hydrogen or natural gas to accelerate the flame development [13, 14]. Some other studies considered the combined effect of two strategies such as Jung et al. [11, 15]. The impacts of both high energetic spark plug and high levels of turbulence on the lean burn and engine cyclic fluctuations were studied. However, limited research has considered the optimization of the spray atomization process to enhance the mixture formation and flame propagation under lean-burn operation. Flash boiling spray is regarded to be a promising method to strengthen fuel-air interactions and lessen fuel impingement. When the fuel temperature increases or the backpressure decreases, the micro-explosion flash boiling spray occurs and effectively enhances the fuel atomization and fuel droplet evaporation. Therefore, the possibility of wall film formation was reduced and the distortion in the spray propagation process is