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Understanding spray and atomization characteristics of butanol isomers and isooctane under engine like hot injector body conditions

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ABSTRACT

Spray characterization of GDI injectors is of significant importance as it influences the overall engine performance and its emissions. Spray morphology under various engine like conditions influences engine design. Vapor bubbles are formed inside liquid droplets when hot fuel is injected into the sub-saturation pressure conditions leading to flash boiling of GDI sprays. This dramatically alters the spray morphology and therefore needs to be understood thoroughly. A spray undergoing flash boiling experiences catastrophic breakup of the liquid jet resulting in fine atomization which in turn enhances droplet evaporation. However, spray structure is significantly altered under such conditions. In the present work, effect of hot injector body was studied to understand flash boiling behaviour of alcohol fuels and which were then compared to isooctane spray characteristics under similar conditions. Experiments were performed at five different injector temperatures: 298 K, 373 K, 423 K, 473 K and 523 K. Significant difference in spray morphology was observed when the fuel temperature was increased. Reduction in overall spray cone angle was observed with increase in temperature for all the fuels considered in this study. Vapour penetration lengths increased with increase in temperature, whereas liquid penetration initially increased and then decreased significantly due to higher evaporation rate. PDPA data showed significant reduction in SMD and AMD when the temperature was raised from 298 K to 423 K. SMD for n-butanol, isobutanol and isooctane reduced by 58.45%, 54.51% and 64.87%, respectively. Similarly, AMD reduced by 65.58%, 57.12% and 74.24%, respectively.

1. Introduction

Fuel injection and the subsequent air/fuel mixture preparation are significant processes in advanced Gasoline Direct Injection (GDI) engines. Although GDI engines offer several advantages over conventional Port Fuel Injection (PFI) engines, such as precise fuel metering, faster transient response, higher compression ratio etc., it has been reported that GDI engines have higher unburnt hydrocarbon and particulate emissions due to wall wetting as a result of spray impingement on cylinder walls and air/fuel mixture stratification as a result of limited time for the fuel to evaporate [1,2]. Continuous improvement in the fuel injection strategy is necessary to address these issues. Ex., first generation GDI engines made use of piston bowl geometry to direct the fuel towards the spark plug. This concept was subsequently replaced by second generation stratified charge engines in order to reduced instances of piston wall wetting and pool fire on the piston head [3]. In case of second generation GDI engines, fuel injector and spark plug are placed in close proximity to create an ignitable mixture in the vicinity of the spark plug [2,3].

Current GDI fuel injectors are high pressure multi-hole injector which directs the spray plume towards the desired location. These high pressure injectors create a spray pattern which is suitable for fuel stratification near the spark plug. It is expected that a GDI injector with a given plume morphology will meet the engine requirement for all operating conditions. However, in reality this is a difficult task to perform. Under stratified condition, fuel is injected during compression stroke and therefore, spray is subjected to higher than ambient pressure and temperature conditions. On the other hand, during homogeneous mode operation, fuel is injected during the intake stroke and therefore pressure and temperature conditions are near ambient. Additionally, during engine running condition, the injector body gets heated due to heat transfer from the hot in-cylinder gases which in turn increases the fuel temperature before it is injected. Flash boiling of the injected fuel has been reported [4–8] when it is injected under sub-saturation pressure conditions. Vapour bubbles formed due to flash boiling result in catastrophic breakup of the liquid jet resulting in improved fuel atomization and shorter droplet evaporation times. Therefore, it has been suggested that flash boiling can be effectively used to enhance the air-

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fuel mixing within the available cycle duration [9].

She [10] experimentally investigated the effect of heated diesel fuel on droplet size distribution, combustion characteristics, engine performance and emission in a diesel engine. NO_x and HC emissions significantly reduced by increasing the fuel temperature. It was also claimed that flash boiling has potential use in diesel HCCI engines. Senda et al. [11] made some efforts to reduce diesel emissions by using the concept of flash boiling. They tested liquefied CO_2 and n-tridecane spray in rapid compression machine. It was observed that soot and NO_x formation reduced with the addition of dissolved CO_2. Shen et al. [12] used extended glare point velocimetry and sizing to understand the spatial distribution of the fuel under flash boiling conditions. It was reported that SMD decreases slowly and larger droplets were observed at the spray tip and spray periphery under non-flashing conditions. However, SMD reduced twice as fast under transitional flash boiling condition when compared to non-flash boiling condition. SMD decreased even faster than the previous two conditions under flare flash boiling condition. Smaller droplets and a more uniform droplet size distribution were observed under this condition.

As seen above, spray structure is significantly altered when fuel is subjected to flash boiling conditions. Though it has been reported that the spray cross-sectional area and its cone angle increases in case of single hole injectors [6,13,14], the same is not seen for multi-hole injectors. It was postulated that for multi-hole GDI injectors, improved evaporation and expansion of individual spray plume initiate the jet to jet interaction. This creates a low pressure region among the spray plumes, which results in collapsed spray structure [15]. Spray collapse due to flash boiling reduces the overall spray cone angle and it affects air entrainment and fuel-air mixing. Additionally, plume penetration was observed to be longer under flash boiling conditions. Therefore, it was suspected that higher spray penetration may result in potential wall wetting situations due to fuel impingement on cylinder wall. To encounter this issue, Wang et al. [8] adopted a split injection strategy to control fuel impingement situations. Considerable reduction in spray penetration was reported for the split injection strategy compared to the single injection strategy. Several papers [4,6,7,9] have discussed the effect of sub-atmospheric pressure conditions on flash boiling. Xu et al. [9] reported that ambient pressure to fuel saturation pressure ratio (P_a/P_s) is the driving factor in case of flash-boiling sprays. They compared this parameter for different fuels and showed that collapse spray is observed when P_a/P_s is less than 0.3.

Spray directionality is very important when stratified Direct Injection Spark Ignition (DISI) engines are considered. Specific orientation of the nozzle orifices helps to direct the spray plume to get the desirable effect. For example, fuel spray plume must be present in the vicinity of the spark plug during stratified charge condition of a GDI engine. Additionally, the same nozzle arrangement should create a homogeneous mixture under homogeneous charge condition. Therefore, understanding spray patternation for different engine operating conditions is very important for efficient operation of an engine. Additionally, it is reported in literature [4] that spray morphology significantly changes under hot fuel condition. Such variations can adversely affect engine performance.

Alcohols like methanol, ethanol and butanol derived from alternative source are being actively considered either in blends with petro-fuels or in pure form as alternative fuels for Spark Ignition (SI) engines [16–22]. Although ethanol is a well-established renewable fuel for SI engines, longer carbon chain alcohols like butanol are also being actively considered for SI and CI engines. Some of the advantages of butanol over ethanol are higher calorific value and lower water solubility. Additionally, it is less corrosive as compared to ethanol and therefore it can be handled by the same gasoline engine components [21,23–25]. However, it is important to understand their spray characteristics under different engine relevant conditions. Different thermo-physical properties of alcohols can result in significant variation in spray structure and evaporation characteristics [26].

The objective of the present study is two-fold:

a. Most of the flash boiling spray studies reported in open literature were performed for fuel temperature ranging between 323 K and 423 K. However, it is expected that the injector body may exceed this temperature limit for commercial GDI engines [3]. Therefore, effect of higher injector body temperature is considered in the present study. Spray characteristics for temperatures ranging from 298 K to 523 K are reported here.
b. Due to environment concerns, several alternative fuels like alcohols derived from bio-sources are being actively considered by the engine research community. The isomers of butanol have thermodynamic properties that are closer to petro-fuels as compared to other alcohols like methanol and ethanol. Additionally, it can be blended in all proportions with petro-fuels like gasoline. Spray characteristics of n- and iso-butanol at elevated GDI injector body temperature have not been reported in open literature. Therefore, spray characteristics like liquid and vapour penetration lengths, spray cone angle and droplet statistics were measured and compared among three fuels: n- and iso-butanol and iso-octane. Iso-octane was selected because it is considered as a surrogate to gasoline in several other studies reported in open literature [27,28].

Focused shadowgraph and Schlieren techniques were used to determine spray penetration lengths and spray cone angle. Droplet statistics was estimated using Phase Doppler Particle Analyzer (PDPA).

2. Experimental setup and procedure

2.1. Constant volume spray chamber with injector heating arrangement

A constant volume spray chamber was fabricated to study engine like hot injector body conditions. This spray chamber has a cubical geometry with sides of approximately 220 mm. It has four optical windows for spray visualization and the window length is approximately 150 mm. A fuel injector was mounted on the top wall of this chamber. In order to simulate engine like hot injector body, this injector was housed in a solid mild steel block in which two cartridge heaters were inserted, each providing 350 W of power. This resulted in the whole metal block getting heated by these heaters. Heat was transferred from this block to the injector and the injector temperature was elevated to the desired temperature. It should be noted that the measured metal block temperature is expected to marginally higher than the injector body temperature. Therefore, a dummy injector was fabricated and 1 mm K-type thermocouple was inserted near the tip of the injector. After the block was heated for sufficiently long time, temperatures of the dummy injector and block were measured. This was then used to calibrate injector temperature as a function of the block temperature. A closed loop PID controller was used to maintain the block temperature at ($T \pm 2$ K). Feedback signal to the heater controller was taken from a K-type thermocouple attached in the block. Due to sufficiently long residence time of the fuel inside the injector, it was assumed that the fuel is in thermal equilibrium with the injector and fuel temperature was assumed to be same as that of the injector body temperature.

2.2. Multi-hole injector

A Bosch 6 holes GDI injector was used in the present study. A schematic representation of the injector spray plume structure is shown in Fig. 1. The injector was vertically installed in the spray chamber. The six holes have different turning angle which directs the fuel to the six different locations inside the spray chamber. The spray patternation study revealed that the spray plumes are almost symmetric about the injector centre line. Therefore, only three plumes were visible when seen from the optical window of the spray chamber. As explained by Lefebvre [29], atomization quality depends upon the nozzle diameter