Applied Thermal Engineering 123 (2017) 377–389

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Experimental and numerical study of flash boiling in gasoline direct injection sprays

Muhammad Mahabat Khan [a,b,c,*], Jerome Hélie [a], Mikhael Gorokhovski [c], Nadeem Ahmed Sheikh [b]

[a] Advanced System Engineering, Continental Automotive France, Toulouse, France
[b] Department of Mechanical Engineering, Capital University of Science and Technology, Islamabad, Pakistan
[c] Laboratoire de Mécanique des Fluides et d'Acoustique, CNRS – Ecole Centrale de Lyon INSA Université Claude Bernard Lyon, Ecully, France

HIGHLIGHTS

- A new spray injection model for flash boiling conditions is purposed.
- Flash boiling intensity depends on engine conditions and design parameters of multihole injector.
- Smaller distance between injection holes increases spray collapse intensity.
- Higher opening velocity of the injector helps in reducing the spray collapse.

ARTICLE INFO

Article history:
Received 17 November 2016
Revised 5 May 2017
Accepted 19 May 2017
Available online 22 May 2017

Keywords:
Flash boiling
Multi-hole injector
Air entrainment
Spray collapse

ABSTRACT

Multi-hole gasoline direct injection (GDI) sprays under flash boiling conditions are investigated experimentally and numerically. GDI injectors produce multiple spray plumes that expand and eventually collapse under flash boiling conditions. The experimental studies provide limited information regarding the collapsing sprays. The numerical investigations provide further insight to these complex flow fields. However, the spray injection model that is generally used in spray simulation is incapable of modelling flash boiling effects. Therefore, a new spray injection model is introduced that can capture the rapid expansion of the flash boiling sprays in the near nozzle region. The spray penetrations obtained from the simulations compare reasonably well with the experimental results. The effects of air entrainment on the spray collapse are also investigated. In the end a parametric study has been performed in order to identify the important control parameters of flash boiling in GDI injectors.

1. Introduction

Automobile engines have evolved greatly over the course of last few decades. Although the source of energy generation is combustion of fossil fuel primarily, however, strategies to obtain better combustion while reducing the environmental impacts have led to many advancements such as electronic controlled injection. With continual growth in the production of automobiles especially the passenger cars the impact of emissions is a great threat to environment. The sustainable growth in the automotive industries rely on engine performance and emission controls enforced by regulatory bodies. Gasoline combustion produce large quantity of CO_2 that has a very serious environmental effect. To control the environmental impact, regulatory bodies around the world have introduced tight regulations so that the automobile industry retains its environmental sustainability in evolving world. For instance, Fig. 1 summarizes the criteria imposed for the CO_2 emission, main area of focus from environmental impact, has been toughened remarkably in different countries around the world. Modern engines are expected to reduce CO_2 emission to 100 mg/km by year 2025 [1].

Electronically controlled advanced fuel injection technologies are devised to utilize fuel in efficient way. Direct injection (DI) is commonly used in spark ignition engines. With better adherence to emission controls, gasoline direct injection (GDI) engines are expected to replace conventional gasoline port fuel injection. It is shown in Fig. 2 that by 2025, GDI engines are expected to replace half of gasoline engine production. GDI offers control on fuel injection with load and operating conditions, thereby ensuring stoichiometric spark ignited engine performance. Allowing higher compression ratios, GDI are 15% more efficient in fuel consumption compared to their counterparts [2].

* Corresponding author at: Department of Mechanical Engineering, Capital University of Science and Technology, Islamabad, Pakistan.
E-mail address: drmahabat@cust.edu.pk (M.M. Khan).

http://dx.doi.org/10.1016/j.applthermaleng.2017.05.102
1359-4311/

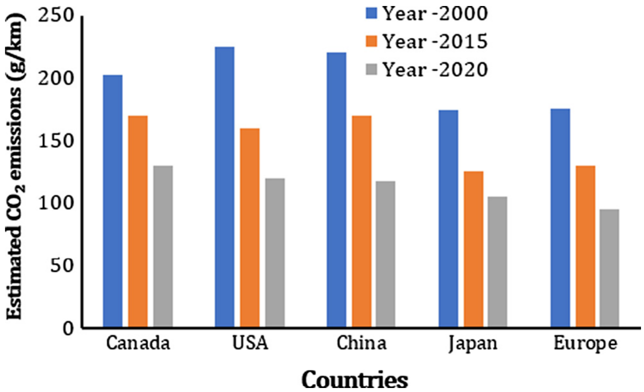

Fig. 1. CO_2 emission standards [1].

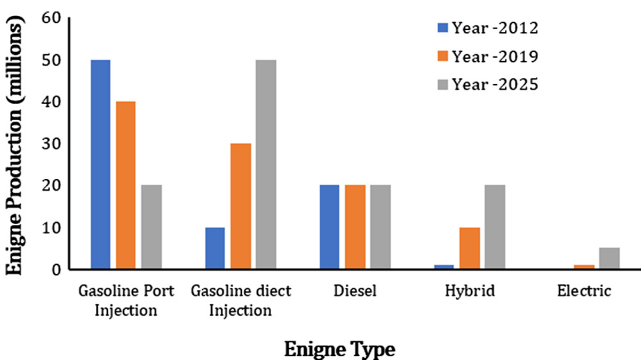

Fig. 2. Global Engine Production [1].

However optimal performance of GDI engines rely on the injector geometry and the patterns of fuel flow embarking the nozzle exit. Injectors with 5 to 7 cylinders or conical holes with each hole of 150–250 μm are available, producing up to 200 bar injection pressure. The performance of these injectors is critical in order to ensure engine performance as well as abidance of emission controls. The performance of an injector depends on the spray mixture formation and efficient combustion.

Multi-hole GDI injectors inject multiple spray plumes directly into the engine at a high injection pressure which results into fine atomization and therefore better mixture formation. The most important design aspect of a GDI injector is the direction of the injected sprays. The ill directed spray plumes impinge on valves, piston, cylinder walls or spark plug which produce unwanted emissions and erode the engine components. However, the flash boiling conditions i.e. superheated conditions cause the spray plumes to merge and eventually collapse to form a single spray cone [1,3,4]. The collapsing sprays are usually uncontrollable and can cause serious problems in terms of spray targeting in engines.

In GDI injector fuel is forced through the nozzle at a high velocity causing the pressure loss in the nozzle. This can lead to two important physical processes in the nozzle of the injector that are cavitation and flash boiling. Both of these processes affect the spray in the near nozzle region leading to high jet-to-jet interactions and possible collapse of spray. Cavitation occurs locally due to local drop of fuel pressure below vapour pressure at a local fuel temperature leading to fuel acceleration in the nozzle. Cavitation is usually initiated by the sharp edges of injection holes inside the nozzle of the injector [5]. Cavitation can be controlled by the smoothing out the sharp edges of the injection holes. However the phenomena of the cavitation is not as vigorous as the flash boiling. Flash boiling in GDI injectors occurs due to pressure loss when heated fuel is forced through the nozzle at a high velocity causing the superheating of the fuel. As the nozzle pressure drops below the saturation vapour pressure flash boiling phenomena takes place. The superheating of the fuel causes the immediate phase change process due to temperature variations. The variations in the temperature are limited by the characteristic time of heat transfer. During this phase change process a fraction of the fuel converts to vapour producing bubbles in the remaining liquid fuel [6]. The growth of bubbles in droplets is in fact quite rapid. Therefore the bubbles instantly explode producing finely atomized drops with a significant increase in their momentum in radial direction [7,8]. A schematic gives a visual description of this process in Fig. 3. The explosion of bubbles in flash boiling sprays enhances the atomization process significantly in comparison to sprays without flash boiling [9,10]. The degree of flash boiling is governed by the difference in engine and saturation pressure and temperature [11].

A detailed experimental study of flash boiling multi-hole gasoline direct injection sprays investigates the role of these parameters on the degree of flash boiling [11]. They observed that in the absence of superheating conditions the spray did not collapse. Modest superheating conditions increased spray angles and evaporation which lead to full spray collapse. Experimental images of six hole injector in Fig. 4 show that the spray under flash boiling conditions collapse dramatically.

In general flash boiling improves the injector performance by reducing the size of droplets and enhancing the evaporation of spray [1]. In spite of large number of experimental investigations of flash boiling in sprays only a few notable numerical studies have been performed. The main reason for that is the lack of spray models that can deal with complexity of the flash boiling phenomena. In this regard a modification in atomization model of the spray based on the simplified bubble growth model is presented in [12]. Numerical simulations of spray under flash boiling conditions are also performed for gasoline-ethanol blends in [13]. A study regarding the modelling of flash boiling process in GDI engines introduces the concept of flash evaporation of droplets [14]. The nozzle flow of GDI injector under flash boiling conditions and its effects on the resulting spray angles and penetration is investigated numerically using empirical time scales for deducing thermal equilibrium conditions that showed the expansion of the spray [7]. However, none of the numerical studies of flashing sprays focus on the effect of flash boiling in the near nozzle region that increases the interaction of spray plumes leading to collapse of spray. It is always very challenging to predict the spray behaviour correctly in the absence of injection conditions at the outlet of the injector in such complex flow conditions [15]. The velocity profiles and drop sizes in multi-hole injectors under flash boiling conditions are extremely difficult to measure in experiments except for the general shapes of the spray. Although internal flow simulations of the injector are possible for estimation of these quantities but under flash boiling conditions the cavitation and bubbles growth are very difficult to model. Consequently the usual approach to model the spray under flash boiling conditions is to adjust spray models based on the physical behaviour of the flashing sprays observed in experiments. In the current study the focus has been to model the effects of flash boiling in the near nozzle region of GDI multihole sprays and to identify the controlling parameters that enhance or reduce these effects.

2. Numerical modelling

The numerical investigation of GDI sprays is carried out in OpenFOAM 1.7® using modified dieselFoam solver with additional capability of adaptive mesh refinement. The numerical simulations