Fuel 200 (2017) 345–356

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Generalizing the behavior of flash-boiling, plume interaction and spray collapse for multi-hole, direct injection

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ARTICLE INFO

Article history:
Received 25 November 2016
Received in revised form 4 February 2017
Accepted 17 March 2017
Available online 3 April 2017

Keywords:
Flash-boiling
LPG
Direct-injection
Alternative fuels
Gaseous fuels
Choked flow

ABSTRACT

This paper presents an experimental and modeling study of direct fuel injection in a constant volume chamber (CVC). Iso-octane and propane are used as surrogates for gasoline and liquefied petroleum gas (LPG) respectively, and are injected over a wide range of conditions that are relevant to modern, spark ignition engines.

Optical imaging of the liquid and vapor phases are first used to examine these sprays' overall behavior. These experimental results and thermodynamic arguments are then used to demonstrate the limitations of some existing methods for identifying the onset of spray plume interaction and spray collapse in multi-hole injectors. Further modeling is then undertaken, leading to new criteria for both spray collapse and plume interaction due to flash-boiling. These criteria employ simple physical arguments, geometrical parameters and the fuel's thermodynamic property data, and appear to be applicable to any fuel injector.

1. Introduction

Current internal combustion (IC) engine research is chiefly focused on the improvement of fuel economy and the reduction of tailpipe emissions. Addressing this challenge lies not with the implementation of one technology, but rather with the application of multiple innovations tailored to a given engine and powertrain system. To this end, promising advancements have been made with regard to the use of direct-injection (DI) and alternative fuels.

The use of DI in spark-ignited gasoline-fueled engines has several benefits over port-fuel injection [1]. These advantages include greater charge cooling that allows for higher compression ratios and more knock resistance, the capability to run in stratified operation and more precise placement of the fuel within the combustion chamber. The resulting increased fuel efficiency yields reduced emissions of CO_2. Additionally, DI technology can be used to reduce cold-start emissions and improve engine reliability. However, DI is not without its own challenges, such as the quality of fuel and air mixing, piston wetting and increased emissions of soot and particulate matter [2–5].

In recent years, the combustion of LPG in passenger vehicles has become reasonably common in many regions of the world. LPG has a higher octane number (ON) than refinery stream gasoline, giving LPG a high resistance to auto-ignition and allowing LPG-fueled engines to utilize high compression ratios that contribute to efficiency gains [6–8]. Due to its molecular structure, LPG has lower energy specific CO_2 emissions than pump gasoline. LPG also has a higher saturation pressure than conventional gasoline, which suggests that its rapid evaporation through flash-boiling may allow for better premixing of the fuel/air charge and a reduction in particulate emissions [9]. Finally, LPG is usually less expensive than pump gasoline, making LPG-fueled vehicles financially attractive to consumers.

Because the successful implementation of DI technology is reliant on understanding the dynamics of the injected fuel, it is imperative to characterize the behavior of DI LPG before it can be widely utilized in production vehicles. At gasoline direct-injection (GDI) engine conditions, LPG experiences severe flash-boiling that impacts primary atomization [10], which is in stark contrast to the conventional spray breakup that liquid fuels undergo at many GDI conditions [11]. The interplay between DI LPG and these spray processes is not well understood, as LPG has received limited attention in previous research.

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http://dx.doi.org/10.1016/j.fuel.2017.03.057
0016-2361/

Nomenclature

ASI	after start of injection
CVC	constant volume chamber
DI	direct injection
ECN	Engine Combustion Network
GDI	gasoline direct injection
IC	internal combustion
LPG	liquified petroleum gas
ON	Octane Number
VI	virtual instrument
c_t	speed of sound of the fuel flow in the nozzle throat
c_g	speed of sound in the gas phase
c_l	speed of sound in the liquid phase
d_{cc}	diameter of circle connecting the centers of nozzle holes
$d_{c,fuel}$	diameter of the expanded streamtube of fuel immediately outside the injector orifice
$d_{collapse}$	critical diameter where the expanded streamtubes of fuel from two injector nozzle holes farthest apart from one another collide
D_n	ratio of the diameter of the expanded fuel streamtube to the critical diameter for spray collapse
d_t	diameter of the nozzle throat
h_0	enthalpy of the fuel in the rail
h_t	enthalpy of the fuel in the injector nozzle throat
p_0	fuel rail pressure
p_a	ambient pressure
p_{CVC}	CVC pressure
p_{sat}	saturation pressure of the fuel
p_t	pressure of the fuel flow in the injector nozzle throat
R_I	spray plume interaction ratio
R_p	flashing ratio
R_p^*	pressure ratio of p_t/p_{CVC}
s_0	entropy of the fuel in the rail
SD	superheat degree
T_0	initial temperature in the fuel rail
T_{sat}	saturation temperature of the fuel at the rail pressure
u	speed of the fuel flow through the nozzle
$v_{c,fuel}$	specific volume of the expanded fuel streamtube
v_t	specific volume of the pure fuel in the injector nozzle throat
x	vapor quality
α	void fraction of two-phase fuel flow
ρ_g	gas phase density
ρ_l	liquid phase density
θ	angle between injector centerline and nozzle hole

A number of recent studies have proposed that flash-boiling could be exploited to promote better mixing prior to combustion [12–20]. In practice, this could be accomplished either by heating the fuel in the rail, or by using an alternative fuel with a high vapor pressure, such as LPG. Flash-boiling occurs when a liquid is suddenly exposed to a chamber backpressure that is below its saturation pressure [18], inducing a rapid boiling process. When injection conditions are sufficient to produce a flashing spray, flash-boiling typically begins inside the nozzle of the injector and dominates the primary atomization process. The flashing ratio, R_p, and the superheat degree of the fuel, SD, are defined as follows

$$R_p = \frac{p_{sat}(T_0)}{p_a}, \tag{1}$$

$$SD = T_0 - T_{sat}(p_a), \tag{2}$$

in which $p_{sat}(T_0)$ is the saturation pressure of the fuel given by its temperature in the rail and p_a is the backpressure of the chamber into which the fuel is injected. $T_{sat}(p_a)$ is the saturation temperature of the fuel at a given ambient backpressure and T_0 is the fuel temperature in the rail.

Due to the high degree of superheat at GDI engine conditions, propane is subject to severe flash-boiling throughout much of the range of GDI operation. At a fuel temperature of 363 K, roughly equivalent to the temperature of fuel in the rail in a warmed-up engine, propane has a flashing ratio that is more than an order of magnitude higher than that of iso-octane. As demonstrated by the work of Zeng et. al. [21], this should result in a flare-flashing phenomenon wherein a multi-hole injector experiences severe spray collapse with significantly increased penetration length and decreased spray angle compared with that of a conventional, non-flashing fuel spray. These behaviors are the result of plume-to-plume interaction.

This paper therefore presents an optical diagnostic study of the DI sprays of propane and iso-octane, which serve as surrogates for LPG and gasoline, to establish the behavior of these two fuels over a wide range of R_p and at engine conditions relevant to GDI. It then considers a more general flash-boiling and spray collapse metric by utilizing thermodynamic analysis and simple, physical arguments.

2. Experimental setup

A CVC is employed to isolate the sprays from the complex, turbulent environment of an IC engine. This apparatus is a non-combusting, quiescent pressure vessel with a chamber formed by the intersection of three 90 mm diameter cylinders bored into a

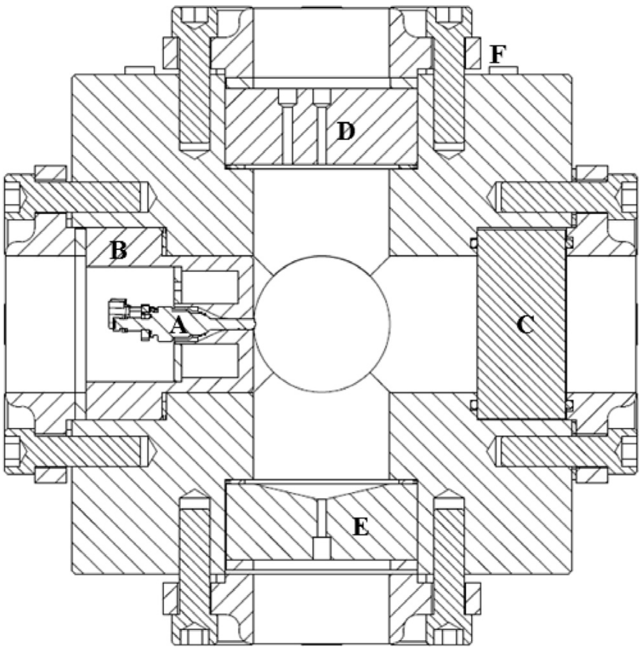

Fig. 1. Cross-sectional view of the CVC, with the main components annotated: a) ECN injector b) injector fixture with integral cooling jacket c) fused silica window d) gas entry port e) exhaust port f) cartridge heater.