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Review article

A review on the experimental non-intrusive investigation of fuel injector phase changing flow

Shangze Yang[a], Zhen Ma[a], Xuesong Li[a,*], David L.S. Hung[a,b], Min Xu[a]

[a] School of Mechanical Engineering, Shanghai Jiao Tong University, Dongchuan Road 800, Shanghai 200240, China
[b] University of Michigan-Shanghai Jiao Tong University Joint Institute, Shanghai Jiao Tong University, Dongchuan Road 800, Shanghai 200240, China

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ABSTRACT

Two-phase in-nozzle flows, such as cavitation and flash boiling, have been well studied as effective means to enhance spray breakup and atomization via phase change both within the nozzle and outside the nozzle. However, the challenges in observing the transient and complex phase change phenomena for such sprays have prevented further insights into the physics behind. The analysis and investigation on multiphase flow inside an atomizing nozzle are significant to elucidate the physics of liquid breakup mechanism and spray evaporation phenomenon. As such, optical accessible injectors and corresponding non-intrusive measurement techniques have been utilized in recent years to thoroughly investigate the multiphase flow characteristics within the nozzle. This work presents a comprehensive review of recent experimental efforts on using optical diagnostics and/or transparent nozzles. Aspects such as typical experimental apparatus, multiphase flow characteristics, measurement capacities and limitations, etc. are presented and discussed. The advantages/drawbacks of each technique are also incorporated. Finally, this review article comments on future opportunities and challenges of non-intrusive investigations for two-phase in-nozzle flows in obtaining better spray atomization performance.

1. Introduction

The use of spray nozzles for atomizing liquid into fine droplets dispersed in gaseous flows have gained remarkable applications in various fields such as internal combustion engines and gas turbines, spray cooling/heating, agricultural sprays, skin cares, etc. In the field of internal combustion engines (ICEs), rapid fuel atomization is one of the most significant techniques in enabling rapid fuel combustion and energy conversion. With an increasing demand of combustion emission control and stricter government regulations to limit engine-out emissions, it is of great significance to further improve fuel atomization efficiency and in-cylinder fuel-air mixing performance. To achieve such goals, internal flow, which governs the atomization of liquid fuel and the combustion of fuel spray, should be thoroughly investigated [1–4]. However, the study of internal flow of fuel injector nozzle is challenging because the size of practical fuel injectors is too small to adopt commonly used intrusive sensors, not to mention such sensors would disturb the internal flow. At the same time, the internal flow can be quite complex. For instance, under typical gasoline direct injection (GDI) conditions and diesel injection conditions, the internal flow has an extremely high velocity and strong fluctuations. Hence, highly resolved temporal and spatial measurements are needed to fully reveal the internal flow properties [5]. Such challenges have hampered the development and progress of interpreting precise attributes of internal flow inside a nozzle.

In most recent decades, with the development of non-intrusive diagnostics methods, more insights have been gained via advanced measurement techniques. For optical measurements, practical injectors are usually made of non-transparent materials. Therefore, making an optical access to the inside of an injector nozzle becomes a daunting task. Fortunately, different kinds of transparent nozzles are fabricated to investigate the in-nozzle flow or near nozzle spray characteristics. There is also an increasing number of studies that adopted X-ray diagnostics method for non-transparent nozzles to analyze the effect of needle movement within the nozzle, etc [6–8]. With these advanced measurement approaches, it was found that due to the high flow velocity and highly unstable feature of internal flow, vaporized fuel bubbles would occur inside injector nozzle under many practical conditions, making the internal flow a gas-liquid multiphase flow [9–13]. The fuel vapor bubbles can remarkably affect the jet breakup near the nozzle exit and macroscopic spray evaporation characteristics.

Based on different vaporization mechanisms, in-nozzle bubbles can be categorized as cavitation and flash-boiling bubbles [14]. Cavitation bubbles are those induced by the local pressure drop caused as the local

* Corresponding author.
E-mail address: xuesonl@sjtu.edu.cn (X. Li).

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Nomenclature

s	strength of cavitation
n	refractive index
I	light intensity
L	length
D	Diameter
V	velocity
b	half angle
P	pressure
T	temperature
f	frequency
UA	umbrella angles
VCO	valve covered orifice
ECN	Engine Combustion Network
SEM	scanning electron microscope
MN	methyl naphthalene
LDV	laser Doppler velocimetry
PIV	particle imaging velocimetry
ICE	internal combustion engine
PDI	phase Doppler interferometry
GDI	gasoline direct injection

Greek

α	angle
λ	wavelength
τ	time interval

Indices

0	initial position
a	ambient
s	saturated
b	breakup
ch	chamber pressure

flow velocity increases. The bubbles would form when the local pressure of the fluid is lower than local saturated vapor pressure of the fuel. Such cavitation bubbles usually take place where the geometrical profile of flow channel varies sharply, for instance, near the corners of the needle valve seat or the inlet of the nozzle. In contrast, flash-boiling bubbles are mainly induced by the variation of thermal properties of the fuel usually at elevated temperature. With an increase in fuel temperature, local saturated vapor pressure increases. At the locations where local pressure becomes lower than the elevated saturated vapor pressure, flash-boiling/superheated bubbles would occur. Such phenomenon usually happens near the exit of the nozzle when a rapid pressure drop is expected [15]. It is worth noting that although there is some difference between cavitation and flash-boiling bubbles, their natures are quite similar. Sometimes it is very hard to distinguish whether the bubbles are caused by cavitation effect or flash-boiling effect, and therefore many researchers have considered flash-boiling bubbles as one type of cavitation. In this review, we would distinguish these two types of fuel vapor bubbles for the purpose of discussion. It has been established that the characteristics of the internal multiphase flow would be affected considerably by nozzle geometry [9,16–26], location of the needle valve [27–35], and experimental conditions [3,9,20,36–52]. Such boundary conditions should be taken into account when analyzing the internal multiphase flow.

Given the influence of nozzle boundary conditions on the performance of liquid breakup and atomization, it is desirable to utilize such impacts to actively control the phenomenon of in-nozzle flow as well as the jet breakup to achieve the desirable spray characteristics for optimized applications such as engine combustion. However, the

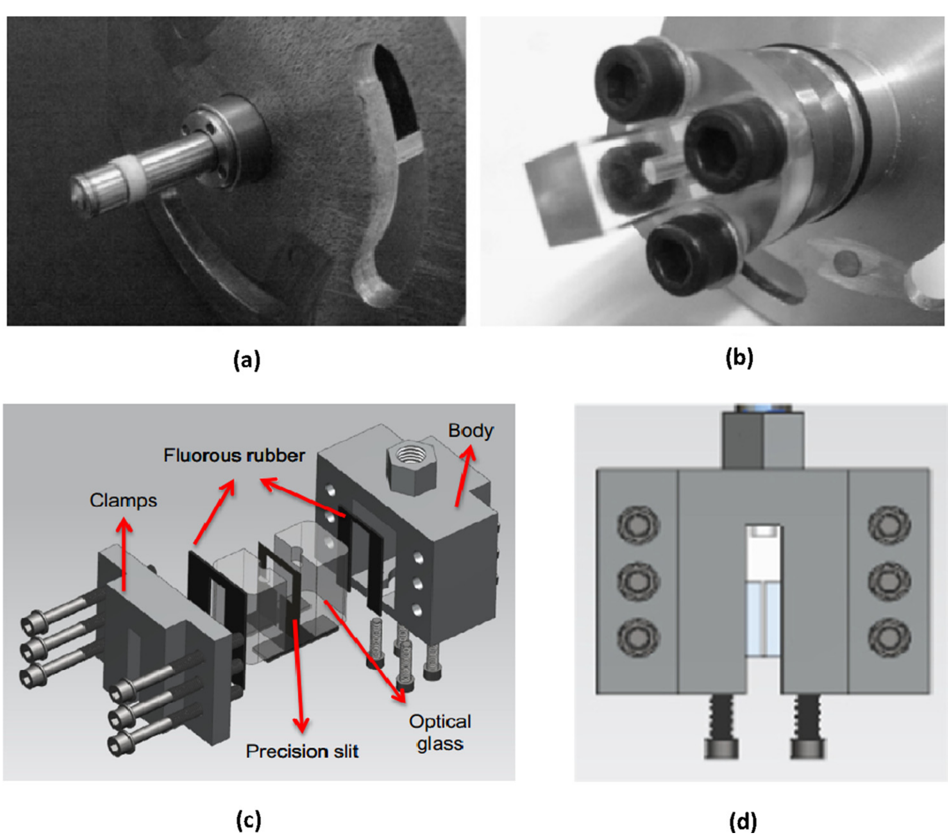

Fig. 1. Typical three-dimensional and two-dimensional transparent nozzles. Panel (a). Practical fuel injector before modifications [62]. Panel (b). Optical accessible three-dimensional fuel injector with the metal flow channel removed and transparent nozzle installed coupled with the existing needle valve [62]. Panel (c). Explored diagram of a typical two-dimensional transparent nozzle [25]. Panel (d). Schematics of the transparent two-dimensional nozzle [25].