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Full Length Article

Flow characteristics of natural-gas from an outward-opening nozzle for direct injection engines

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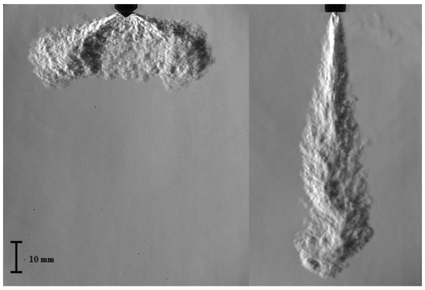
GRAPHICAL ABSTRACT



Jet penetration comparison

90° conical annular nozzle vs. round nozzle

Injection conditions: Pressure Ratio 60 · Mass injected 3 mg (CNG)

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ABSTRACT

In this research article, we present for the first time an experimental investigative study on the flow characteristics of compressed natural-gas (CNG) issued from a direct injector with an outward-opening nozzle operating at a wide range of pressures. High speed schlieren imaging is used to capture the growth of the highly turbulent transient gaseous jet with high spatial and temporal resolution in a quiescent chamber at atmospheric conditions. The existing penetration scaling correlations for gas jets issued from single round nozzles were found to apply to outward-opening nozzle as well. The penetration constant is found to be **1.15 ± 0.05** for fuel pressure ranging from 20 bar to 160 bar. A new method to calculate combined penetration for radially spreading jets such as the one used in this study is presented which can also be used for jets of irregular shape. The data from these tests show that the axial penetration from a 90° conical annular nozzle is roughly about 3 times lower than round nozzles for similar injection and ambient conditions. The lower penetration rate of such annular nozzles can be beneficial for stratified mixture formation in spray-guided direct-injection spark-ignition engines.

1. Introduction

Natural-gas is regarded as one of the most promising alternative fuels. Natural-gas engines have the potential to reduce CO_2 emissions by more than 20% compared to gasoline engines and also other harmful pollutants [1,2]. Currently all production CNG spark-ignited engines are port-injected. Port-injection of natural-gas results in reduced peak torque due to the reduction in volumetric efficiency caused by the fuel's displacement of air. Direct-Injection can overcome this drawback by injecting the fuel during and/or after the inlet valves are closed. Automotive manufacturers and OEMs are currently exploring the direct-injection concept. Natural-gas intrinsically is a better fuel for spark-

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Nomenclature

aSOI	after start of injection
CNG	compressed natural gas
DI	direct injection
FPS	frame per second
GDI	gasoline direct injection
PLIF	planar laser induced fluorescence
PR	pressure ratio (upstream fuel pressure/ambient pressure)
P	combined penetration
RON	Research Octane Number
SI	spark ignition
x	radial penetration
y	axial penetration

Subscripts

a	ambient
ch	chamber
e	exit (nozzle)
exp	experimental
n	nozzle
o	supply/stagnation
1,2	left, right

Symbols

Γ	penetration constant
θ	jet spread angle
γ	ratio of specific heats
ρ	density

ignition engines due to its higher octane rating (RON ~130) which allows higher compression ratios leading to higher engine efficiency [1,2]. Natural-gas is not toxic and also safer due to its higher auto-ignition temperature (~550°–600 °C), wider flammability limits and lower density than air at standard conditions [1,2]. Recent studies have demonstrated that an optimized CNG-DI engine can match the torque levels of a modern GDI engine and also be thermodynamically more efficient [3–6]. In light of future stringent worldwide emission norms, CNG-DI is an attractive proposition. Moreover, renewable methane produced from biomass has the potential to achieve carbon neutrality. Methane can also be renewably made from hydrogen and CO_2 using the Sabatier reaction. Natural gas-hydrogen blends can also considerably increase the engine efficiency with increasing percentages of hydrogen [7].

It is important to understand the flow behaviour of natural-gas from fuel injectors especially for direct-injection application to be able to achieve good mixture formation, stable combustion and lower emissions. This is particularly essential for stratified mixture formation as the design and performance of the direct-injector heavily influences the combustion stability which has a direct impact on engine performance. Gaseous fuel injection from direct-injectors with single round nozzles has been extensively studied in the past. They are the inward-opening type of injector that is widely used in gasoline direct injection (GDI). Another class of injector nozzle is the outward-opening poppet nozzle which creates an annular conical area of flow. This type of nozzle is often used in GDI stratified combustion applications for its specific advantages over multi-hole nozzle such as higher mass flow rates (higher flow area), lower spray penetration, multiple injection capability (piezo actuation), etc [8]. Gaseous jets issued from such conical nozzles have not been well investigated. The use of such nozzle for CNG direct-injection would be beneficial due to its outward-opening nature as lower fuel pressure can be used [4]. Multi-hole injector nozzles can have a large number of design variables such as the number of holes, diameter, length-to-diameter ratio, included angle, etc. Similarly, outward-opening nozzles also have a number of design variables such as the diameter, needle lift, cone angle, seat design etc.

High pressure gaseous injection into the combustion chamber produces complex shock structures immediately downstream of the nozzle which affects the mixing process. This kind of flow is choked at the nozzle and is highly turbulent. One of the important parameters relevant to growth of the gaseous jet is its penetration in both axial and radial directions. These are not well understood for outward-opening nozzles. This study is aimed at addressing this gap and improving the knowledge on transient gaseous fuel injection for engine applications.

1.1. Gas jets issued from inward-opening round nozzle

Many researchers have studied the gaseous jet flow from single round nozzles at a wide range of pressure ratios relevant to direct-injection engines [9–14]. Ouellette and Hill [9,15] have provided a brief historical review of transient gas jet theory. Schlieren images reveal that the gaseous jet is headed by spherical vortex as depicted in Fig. 1. They developed the relation shown in Eq. (1). to estimate the axial penetration of transient gas jet based on experimental data and momentum conservation principle.

$$z= \Gamma\left(\frac{\dot{M}_n}{\rho_a}\right)^{1/4}\sqrt{t} \tag{1}$$

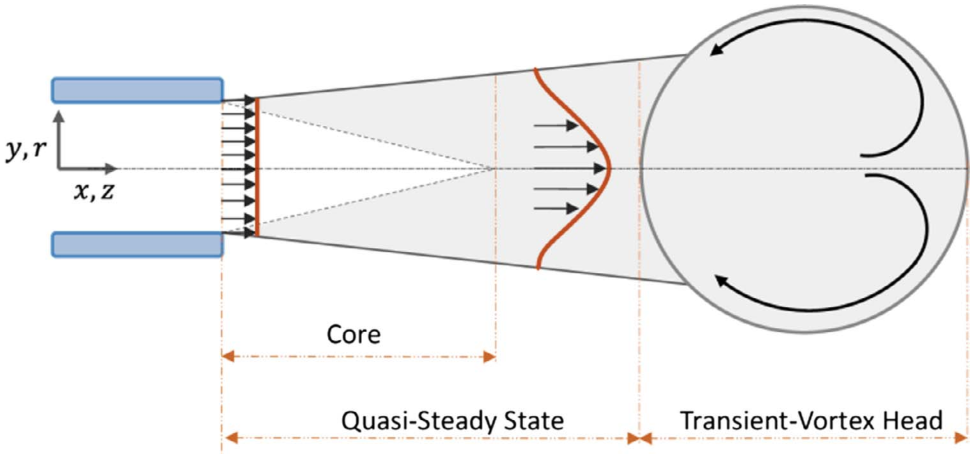

Fig. 1. Structure of a turbulent transient gas jet [16].