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Ducted fuel injection: A new approach for lowering soot emissions from direct-injection engines

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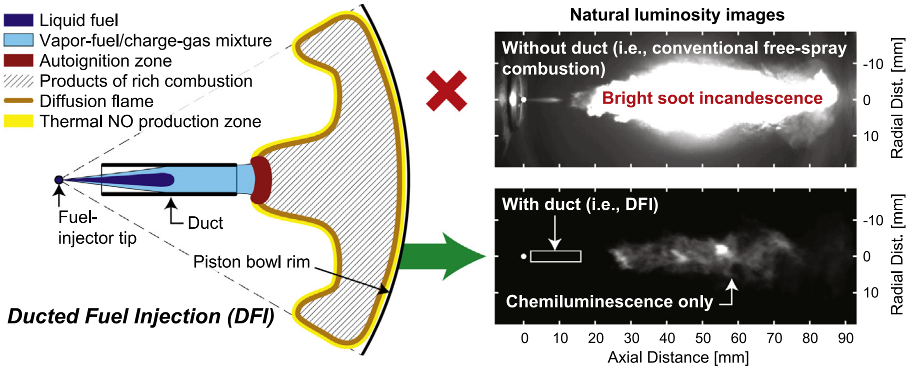
HIGHLIGHTS

- Ducted fuel injection (DFI) is a new concept for direct-injection engines.
- DFI entails injecting fuel through a tube within the combustion chamber.
- DFI can lower the amount of soot incandescence during combustion by 10× or more.
- DFI enhances the extent of premixing that takes place before ignition.
- DFI shows promise for lowering soot emissions from direct-injection engines.

GRAPHICAL ABSTRACT



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ABSTRACT

Designers of direct-injection compression-ignition engines use a variety of strategies to improve the fuel/charge-gas mixture within the combustion chamber for increased efficiency and reduced pollutant emissions. Strategies include the use of high fuel-injection pressures, multiple injections, small injector orifices, flow swirl, long-ignition-delay conditions, and oxygenated fuels. This is the first journal publication on a new mixing-enhancement strategy for emissions reduction: ducted fuel injection. The concept involves injecting fuel along the axis of a small cylindrical duct within the combustion chamber, to enhance the mixture in the autoignition zone relative to a conventional free-spray configuration (i.e., a fuel spray that is not surrounded by a duct). The results described herein, from initial proof-of-concept experiments conducted in a constant-volume combustion vessel, show dramatically lower soot incandescence from ducted fuel injection than from free sprays over a range of charge-gas conditions that are representative of those in modern direct-injection compression-ignition engines.

1. Introduction

Based on market penetration, reciprocating internal-combustion engines (ICEs) burning liquid fuels are currently the dominant powertrain solution for personal and commercial transportation around the globe. In 2016, 99.8% of the approximately one billion light-duty passenger cars and trucks on Earth were powered by ICEs burning liquid fuels [1]. ICEs are relatively inexpensive per unit of available power, and the high energy content per unit mass of liquid fuels makes them well-suited to transportation applications, where light weight, long range, and the ability to refuel quickly are critical. Nevertheless, this mobility solution also has a number of frequently cited drawbacks. In addition to the combustion of fossil fuels releasing carbon dioxide

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Nomenclature

Acronyms, Abbreviations, and Symbols

CI	compression-ignition
CL	chemiluminescence
CMOS	complementary metal-oxide semiconductor
CO_2	carbon dioxide
CVCV	constant-volume combustion vessel
D	inside diameter of duct
dP/dt	instantaneous rate of pressure rise in the CVCV
DFI	ducted fuel injection
ECN	Engine Combustion Network
FS	free spray
G	gap or stand-off distance (i.e., axial distance from orifice exit to duct inlet plane)
H	lift-off length
HR	high-reflector mirror
ICE	internal-combustion engine
ICMOS	intensified CMOS
K_{eng}	dimensionless duct engagement parameter
K_H	dimensionless duct lift-off length parameter
K_{ins}	dimensionless duct insertion parameter
L	total length of duct
LLFC	leaner lifted-flame combustion (mixing-controlled combustion that does not form soot)
MSD	misaligned steel duct
NL	natural luminosity
OH^*	electronically excited hydroxyl radical
P	pressure
PD2	Photodiode 2 (measures incandescence from hot soot)
QD	quartz duct
Re	Reynolds number
SWP	short-wavelength pass
U	centerline velocity of the spray entering the duct
z_i	distance from the orifice exit to the point where the free spray would interact with the duct wall
ΔP	total CVCV pressure rise due to combustion of directly injected fuel
μ	dynamic viscosity of the ambient charge-gas
ρ	density of the ambient charge-gas
θ	full spreading angle of spray

(CO_2) into the atmosphere, ICEs can produce carbonaceous particulate matter (a.k.a. soot), a known toxin [2] that is second only to CO_2 as a climate-forcing species [3]. Hence, substantial environmental and societal benefits can be achieved by continuing to lower the emissions from ICEs, especially in the heavy-duty sector where battery-powered vehicles face larger practical challenges.

Action to mitigate the impact of the transportation sector on the environment should be continued, and it is critical that such action lead to truly sustainable, economically viable solutions. One such course of action is to increase engine efficiency and eliminate soot emissions while transitioning to renewable liquid fuels (e.g., [4,5]). Increased engine efficiency leads to lower CO_2 emissions per unit of engine work output. Eliminating soot emissions removes a toxic and critical climate-forcing species. And shifting from fossil fuels to truly renewable, sustainable fuels – e.g., using liquid fuels made from waste biomass and/or from solar energy, atmospheric CO_2, and non-potable water (i.e., "solar fuels") [6] – can slow or even reverse the trend of increasing atmospheric CO_2. It is important to remember that, from a CO_2 perspective, it is the carbon from fossil fuels that is the problem, not ICEs. ICEs utilizing sustainable fuels remain attractive options for simultaneously achieving environmental and economic goals. The efficiency, emissions, and performance of ICEs have improved tremendously over the past century, and further improvements are continually occurring [7,8].

The research described herein is focused on combustion strategies for mixing-controlled compression-ignition (CI) engines, due to: their inherently high efficiencies, arising from higher compression ratios and lower pumping work during the intake and exhaust strokes [9]; the ease with which ignition timing can be controlled by varying fuel-injection timing; and their fuel-flexibility, because fuel processing generally increases fuel cost and refinery CO_2 emissions. Numerous studies have been devoted to overcoming the challenges of higher emissions of soot and nitrogen oxides with mixing-controlled CI combustion. In 2004, Pickett and Siebers demonstrated several paths to mixing-controlled CI combustion that does not form soot, using various fuels [10]. They went on to show that these approaches work by decreasing the highest equivalence ratios in the standing premixed autoignition zone of the combusting diesel jet below approximately two [11]. Although the results were obtained at thermodynamic conditions representative of those experienced in modern CI engines, the experiments were conducted in a constant-volume combustion vessel with a single-hole injector tip (i.e., without interactions between sprays), largely without wall interactions, and without a moving piston or a small clearance volume to amplify the unsteadiness of the thermodynamic conditions. Hence, the results were promising and relevant to engine applications, but they did not prove that the proposed techniques could be successfully employed in engines.

Around the same time, Upatnieks et al. showed that mixing-controlled CI combustion that did not form soot could be achieved in an engine at high loads using a neat oxygenated fuel [12], but the lack of sufficient commercial availability of the neat oxygenate limited the practicality of this approach. Polonowski et al. [13] attempted to achieve mixing-controlled combustion that does not form soot, termed leaner lifted-flame combustion (LLFC), using diesel fuel and several different injector-tip configurations. This approach was somewhat successful, but only with a two-hole injector tip at light engine loads. Andersson et al. presented similar results [14]. Seeking a middle road, Gehmlich et al. [15] used a fuel comprising 50 vol% oxygenate in diesel fuel, showing that LLFC could be sustained with a six-hole injector tip to loads above 5 bar gross indicated mean effective pressure (~20% of full load). Unfortunately, it was not possible to sustain LLFC at significantly higher loads without going beyond the realm of feasible engine operating conditions or the already high level of fuel oxygenation.

The fuel oxygenation, high injection pressures, small injector orifices, cool intake conditions, and retarded combustion phasing in the aforementioned studies were all employed to achieve the same end goal: an increased level of local fuel/charge-gas premixing upstream of the flame lift-off length (i.e., the distance from the injector orifice exit to the standing premixed autoignition zone [16]). Seeking a means to further increase the extent of premixing at the lift-off length, Mueller [17–19] proposed the idea of injecting a fuel spray down the axis of a small duct positioned within the combustion chamber some distance downstream of the injector orifice exit. This concept is termed ducted fuel injection (DFI), and a corresponding schematic is shown in Fig. 1.

The idea of injecting fuel through a tube to enhance premixing and prevent soot formation is at least 160 years old, as evidenced by the invention and employment of the Bunsen burner in early studies of photochemistry [21]. Since that time, a great number of studies have been conducted on various related configurations