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Using ducted fuel injection to attenuate or prevent soot formation in mixing-controlled combustion strategies for engine applications

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HIGHLIGHTS

- DFI can lower or prevent soot formation in mixing-controlled spray combustion.
- Entrainment downstream of the duct exit is not required for DFI to be beneficial.
- Rounding the inner diameter of the duct inlet improves DFI performance.
- The duct assembly can be shortened to ~9 mm without loss of effectiveness.
- DFI is tolerant to dilution, enabling the soot/NO_x tradeoff to be broken.

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ABSTRACT

Ducted fuel injection is a strategy that can be used to enhance the fuel/charge-gas mixing within the combustion chamber of a direct-injection compression-ignition engine. The concept involves injecting the fuel through a small tube within the combustion chamber to make the most fuel-rich regions of the micture in the autoignition zone leaner relative to a conventional free-spray configuration (i.e., a fuel spray that is not surrounded by a duct). This study is a follow-on to initial proof-of-concept experiments that also were conducted in a constant-volume combustion vessel. While the initial natural luminosity imaging experiments demonstrated that ducted fuel injection lowers soot incandescence dramatically, this study adds a more quantitative diffuse back-illumination diagnostic to measure soot mass, as well as investigates the effects on performance of varying duct geometry (axial gap, length, diameter, and inlet and outlet shapes), ambient density, and charge-gas dilution level. The result is that ducted fuel injection is further proven to be effective at lowering soot by 35–100% across a wide range of operating conditions and geometries, and guidance is offered on geometric parameters that are most important for improving performance and facilitating packaging for engine applications.

1. Introduction

Soot from combustion processes is a significant pollutant in the earth's atmosphere, and is the second most important climate-forcing species after carbon dioxide (CO_2) [1]. These and other environmental concerns have driven the implementation of requirements for modern vehicles to comply with ever-more-stringent emissions regulations, which have in turn driven the engine manufacturing industry to employ ever-more-expensive and complex combinations of exhaust-gas aftertreatment technologies. These include diesel particulate filters (DPFs) to capture particulate matter (PM), selective catalytic reduction (SCR) or lean-NO_x trap systems to control nitrogen oxide emissions (NO_x), and diesel oxidation catalysts to oxidize hydrocarbon (HC) and carbon monoxide (CO) emissions [2–5]. These systems can be very effective, but they also add cost and come with fuel-economy penalties. Additionally, they require continual management such as pressure differential monitoring and periodic regeneration, and they can require an additional on-board fluid, as is the case for SCR systems that require diesel exhaust fluid (DEF). Hence, there is interest in developing combustion strategies that reduce the amount of aftertreatment required to meet legislated emissions targets. Advanced combustion strategies such as globally premixed, low-temperature combustion (LTC) can lower both NO_x and PM emissions [6–19], but they are less suitable for high-load conditions than mixing-controlled combustion due to the de-coupling of the fuel-injection and ignition processes (i.e., ignition timing is controlled by chemical kinetics rather than injection timing). This decoupling can lead to control, noise, and emissions issues.

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Nomenclature

α	simple cylinder duct shape with sharp corners at entry and exit. See Fig. 4
β	same shape as α duct but with a full radius at the duct inlet. See Fig. 4
γ	same shape as α duct but with a taper on the outside diameter near the duct exit. See Fig. 4
δ	a shape that combines the inlet and outlet features of β and γ. See Fig. 4
θ	spreading angle of the spray
λ	peak wavelength for the DBI LED
ρ_a	ambient density
ρ_{soot}	soot mass density
CFA	certification diesel fuel, batch A
CFD	computational fluid dynamics
CL	chemiluminescence
CMOS	complementary metal-oxide-semiconductor
CO_2	carbon dioxide
CO	carbon monoxide
Ct	Craya-Curtet number
Ct_{ni}	non-isothermal Craya-Curtet number
CVCV	constant-volume combustion vessel
D	inner diameter of the duct
d	injector nozzle diameter
DBI	diffused back-illumination
DEF	diesel exhaust fluid
DFI	ducted fuel injection
D_G	estimated diameter of the spray at the duct inlet plane
dP/dt	pressure derivative
DPF	diesel particulate filter
ECN	Engine Combustion Network
fps	frames per second
FS	free spray
G	axial distance from the injector orifice tip to the duct entrance plane
gIMEP	gross indicated mean effective pressure
G_{opt}	optimal axial distance from the injector orifice tip to the duct entrance plane
H	lift-off length
HC	hydrocarbon
I_0	incident intensity
I	measured transmitted intensity
ID	ignition delay
k_e	non-dimensional extinction coefficient
K	dimensional extinction coefficient
K_{eng}	engagement parameter
K_H	lift-off length parameter
K_{ins}	insertion parameter
KL	optical thickness
L	path length through the soot cloud or duct length
LED	light-emitting diode
LLFC	leaner lifted-flame combustion
LTC	low-temperature combustion
NL	natural luminosity
NO_x	nitrogen oxides
O^2	oxygen
OH^*	hydroxyl radical
P	pressure
ΔP	total pressure rise
PM	particulate matter
Re_{noz}	nozzle Reynolds number
SCR	selective catalytic reduction
SINL	spatially integrated natural luminosity
S	penetration of the head of the jet
TIR	total internal reflector
UV	ultraviolet
X_{O_2}	oxygen mole fraction
z_i	distance from the orifice exit to the point where the free spray would interact with the duct wall

1.1. Leaner lifted-flame combustion

Leaner Lifted-Flame Combustion (LLFC) is an alternative, advanced combustion strategy wherein ignition timing is still controlled by injection timing. LLFC is a form of mixing-controlled diesel combustion that can eliminate soot if the equivalence ratio at the lift-off length is maintained at values less than approximately two [20–22], where the lift-off length is defined as the axial distance between the fuel-injector orifice exit and the position where the standing premixed autoignition zone stabilizes during mixing-controlled combustion [23,24].

Early investigations of the applicability of LLFC in a heavy-duty diesel engine using conventional fuel showed that LLFC could be sustained only at low loads and by using a two-hole injector tip with small orifices (<120 µm) and high fuel-injection pressures (>200 MPa) [21]. For higher-flow injectors (6- and 10-hole), LLFC could not be sustained due to shortening of the lift-off length (*H*) by higher in-cylinder temperatures, re-entrainment of hot combustion products upstream of *H*, and/or interactions between adjacent jets as injector tips with more orifices are used.

The use of oxygenated fuels showed some promise for achieving LLFC at lower injection pressures [25,26]. Although a significant lowering of soot was observed in these studies, LLFC was not sustained through the use of an oxygenated fuel alone. Later, through the use of both an oxygenated fuel and increased charge-gas mixing upstream of the lift-off length (through higher injection pressures and smaller orifices), another study demonstrated the ability to sustain LLFC at higher loads with a 6-hole injector tip [27]. Using a fuel blend consisting of 50% by volume of tri-propylene glycol monomethyl ether in a certification diesel fuel, LLFC could be sustained at loads of 6 bar gross indicated mean effective pressure (gIMEP), achieving the desired goal of preventing soot formation within the combustion chamber.

The preceding studies indicated that further increases in the peak load limit of LLFC would likely require further improvements in charge-gas mixing. To address this need, a novel method was proposed for achieving significantly enhanced charge-gas mixing upstream of the lift-off length by using a small tube placed a short distance downstream of the injector orifice, termed ducted fuel injection (DFI) [28]. Initial DFI proof-of-concept experiments were conducted using a single combusting spray in a constant-volume combustion vessel with *n*-dodecane fuel supplied at 150 MPa and injected through a 90 µm orifice. The results were encouraging, with DFI showing nominally an order-of-magnitude reduction in the soot luminosity signal relative to a free spray at the same charge-gas conditions, over a range of ambient temperatures from 850 to 1000 K at a density of 22.8 kg/m^3 (i.e., at conditions that are representative of those in modern direct-injection compression-ignition engines). Furthermore, [28] demonstrated the importance of achieving proper spray/duct alignment, it proposed dimensionless parameters to characterize DFI performance based on mixing within the duct and mixture autoignition, and it showed that ducts of a suitable geometry could be packaged in a typical heavy-duty