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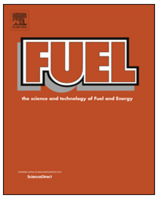

Full Length Article

Scaling fuel sprays for different size diesel engines

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ABSTRACT

Diesel engines are widely used not only for heavy-duty vehicles such as ships and trucks but also for light-duty passenger cars, with a wide range of bore diameters. Since development of a new diesel engine is usually expensive and time consuming, the ability to accurately predict engine performance from existing models can reduce the resources and time required in the engine development procedure. However, so far knowledge on scaling diesel engines is far from adequacy, particularly for spray combustion processes. In this paper, two injectors with nozzle hole diameters of 0.11 mm and 0.14 mm are adopted for scaling fuel sprays under the non-evaporating conditions based on the three similarity rules. Firstly, the existence of similarity is theoretically analyzed in diesel fuel sprays of both free injection and impinging upon a wall. Then, the similarity of diesel injection rate is experimentally verified by using the Bosch long tube method. Finally, the similarity of spray angle, tip penetration length, excess air ratio and impinging spray characteristics are investigated under various injection pressures and ambient densities in an optically accessible constant volume vessel by the high-speed shadowgraphy. The theoretical analysis and experimental results reveal that the similarity rule keeping the injection pressure constant is more preferable for scaling the spray angle, tip penetration length and excess air ratio, while the other two similarity rules with reduced injection pressure result in narrowed spray angle and increased spray tip penetration length. With respect to the post-impingement behavior, although the spray from the large-hole nozzle impinges upon the wall later than those of the small-hole nozzles with the speed rule and the lift-off rule, the rebound height of the large-hole nozzle is higher than those by the small holes with the speed and the lift-off rule. The mechanism of the above phenomena is discussed in depth.

1. Introduction

With superior durability, reliability and fuel economy, diesel engines are widely used in modern industry and transportation with a wide range of bore diameters. Future regulations for less pollutant emissions and better fuel efficiency are driving diesel manufactures to optimize the combustion system of diesel engines, which is generally a time consuming and expensive process. Since spray combustion researches are usually repeated in different size diesel engines that share similar characteristics, the ability to accurately reproduce engine performance by existing engines will be beneficial for reducing time, cost and energy consumption in new engine development.

Researchers have considered how to apply the similarity theory to diesel engine design for over thirty years. Based on the hypothesis that the in-cylinder heat release processes are controlled by diffusion (or mixing-controlled) combustion and the diesel spray is approximated by a high-density gas jet, Chikahisa et al. [1] summarized the dimensionless similarity criterion numbers in diesel combustion and derived the possibility of similarity. They suggested a similarity rule that keeps the engine speed constant for different size diesel engines (i.e. the speed rule) [2]. Later, they validated to some extent the existence of diesel combustion similarity using the data from eight diesel engines with bore diameters ranged from 85 to 800 mm [3]. Bergin et al. [4] demonstrated that the similar combustion behavior can be achieved for diesel engines with different bore diameters by keeping the fuel injection pressure constant (i.e. the pressure rule). Following the work by Bergin, Stager et al. [5] proposed a similarity rule taking the flame lift-off length into consideration (i.e. the lift-off rule). They concluded that the lift-off rule is preferable for scaling the flame structure and location, while the pressure rule can give better emissions predictions. Shi et al. [6] investigated the lift-off rule using the computational fluid dynamics (CFD) simulation under the 5 bar and 7.5 bar indicated mean effective pressure (IMEP) conditions. They reported that the heat release rate (HRR) and pressure trace are in good agreement between two engines with different bore diameters, while more nitrogen oxides (NOx) emissions are produced in the large engine due

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Nomenclature

ΔP	the pressure difference across the injection hole [MPa]
AF_{stoich}	the theoretical air-fuel ratio
Br	Brinkman number
c	the orifice coefficient of area-contraction
CFD	computational fluid dynamics
c_p	the mean specific heat of gas [J/kg·K]
D	bore [m]
d_{32}	the Sauter mean diameter [μm]
Da_{I}	Damköhler number
d_d	the droplet diameter [m]
d_n	the nozzle hole diameter [m]
e	the restitution coefficient
f	the droplet frequency [Hz]
H	stroke [m]
HRR	heat release rate
H_u	the lower calorific value [J/kg]
H_u/c_pT_0	non-dimensional lower calorific value
IMEP	indicated mean effective pressure [bar]
ISFC	indicated specific fuel consumption [g/(kW h)]
LES	large eddy simulation
$\mathrm{l_n}$	the nozzle hole length [m]
LTC	low temperature combustion
m_f	the amount of fuel delivery [$\mathrm{mm^3}$/stroke]
n	engine speed [rpm]
NOx	nitrogen oxides
P_{inj}	the fuel injection pressure [MPa]
Pr	Prandtl number
R	swirl ratio [%]
r	the similarity ratio
RANS	Reynolds averaged numerical simulation
Re	Reynolds number
R_h	the rebound height [mm]
R_r	the rebound radius [mm]
S	spray tip/jet penetration [m]
S/V	surface to volume ratio [%]
Sc	Schmidt number
S_{onset}	the splashing onset
t	the time after start of injection [s]
T_0	the reference temperature [K]
t_b	the breakup time [s]
T_B	the liquid boiling temperature [K]
t_{imp}	the impingement starting time [ms]
T_{pa}	the pure adhesion temperature [K]
T_w	the wall temperature [K]
u_0	injection rate [mg/ms]
V'_{nd}	the bouncing droplet normal velocity [m/s]
V_{nd}	the incident droplet normal velocity [m/s]
V_{ni}	the normal velocity of *i*-th splashing droplet [m/s]
$V'_{\tau d}$	the bouncing droplet tangential velocity [m/s]
$V_{\tau d}$	the incident droplet tangential velocity [m/s]
$V_{\tau i}$	the tangential velocity of *i*-th splashing droplet [m/s]
We	Weber number
α	the spray angle [°]
λ	excess air ratio
μ_f	the fuel viscosity [Pa·s]
ν	the droplet viscosity [$\mathrm{m^2/s}$]
θ	injection duration in crank angle [°]
θ_i	the incident angle [°]
θ_r	the reflection angle [°]
ρ_a	the ambient density [$\mathrm{kg/m^3}$]
ρ_d	the droplet liquid density [$\mathrm{kg/m^3}$]
ρ_f	the fuel density [$\mathrm{kg/m^3}$]
σ	the droplet surface tension [N/m]
τ	injection duration in time [s]

to the lower engine speed. With two single cylinder engines with a bore diameter ratio of 1.67, Staples et al. [7] studied the pressure rule and the lift-off rule at 9 bar IMEP. They exhibited that the overall engine performance including IMEP and indicated specific fuel consumption (ISFC) are well scaled between the two engines with different sizes, and they concluded that the unscaled emissions are caused by the different engine speeds and heat transfer loss. Lee et al. [8] conducted a computational study at 22.7 bar IMEP to investigate the sensitivity of the single value condition to the engine out emissions. The considered parameters were the engine speed, compression ratio, intake valve closing time, fuel injection pressure, injection duration, nozzle hole diameter and so on. They claimed that the injection duration has the biggest impact on scaling the combustion characteristics. They further reported that the lift-off rule is inadequate for the low temperature combustion (LTC) condition, where the premixed combustion dominates the heat release processes. They recommended the speed rule for scaling the LTC to maintain an identical timescale for chemical reactions [9].

Chikahisa et al. [2] discussed the factors which may cause deterioration in similarity, and they claimed that the heat transfer loss should have the same effect for different size diesel engines. However, the relatively large surface to volume (S/V) ratio of the small engine will result in a larger heat transfer loss than the large engine. The recent study by the present authors [10] demonstrated that the pressure rule, which enables a constant piston speed, is more preferable for scaling the heat transfer loss. Arisawa et al. [11] conducted a numerical study on the speed rule. They reported that the indicated thermal efficiency increases with the engine size due to the reduced heat transfer loss. Inagaki et al. [12] studied experimentally and theoretically the effects of bore size on the heat transfer loss. They exhibited that the ratio of heat transfer loss between the large and small engines is independent of the engine speed and operation conditions.

Following the pioneer theoretical work by Chikahisa et al. [1], the present authors [10] deduced the sufficient and necessary conditions for enabling similarity of premixed combustion and diffusion (or mixing-controlled) combustion, and they conducted a comprehensive comparison among the existing three similarity rules. The theoretical analysis and simulation results revealed that the speed rule is superior than the others under the operating conditions where the premixed combustion dominates the heat release processes, while the pressure rule is more favorable when the diffusion (or mixing-controlled) combustion dominates the heat release processes.

It is therefore clear that the combustion similarity can be achieved to some extent for engines with different bores, when employing the existing three similarity rules with appropriate designs. To further improve the predictive ability of the similarity designs, much more studies are necessary. For example, relatively little information about the spray similarity has been reported, though this information has critical influence on diesel spray combustion and exhaust emissions. Recently, with the Reynolds averaged numerical simulation (RANS) [13] and the large eddy simulation (LES) [14], Kawaguchi et al. examined the spray similarity using the speed rule. They reported that the vapor penetration length, liquid length, and droplet distribution can be well scaled. Inagaki et al. [15] investigated the similarity of spray characteristics in an optically accessible vessel. In contrast to the works by [13,14], they found that the spray of the small engine has a narrower spray angle and longer penetration than those of the large engine, when employing the speed rule. To solve this problem, Takada et al. [16] achieved the similarity of spray characteristics by tailoring the nozzle outlet geometry. However, the above researches about the similarity of spray mixture