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CFD modelling of soot entrainment via thermophoretic deposition and crevice flow in a diesel engine

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ABSTRACT

Combustion soot entrainment into engine oil has been linked to oil starvation and damage of the engine piston. In this computational work, the direct impact of different injection strategies on the spatial evolution of combustion soot and the soot entrainment process in a light-duty diesel engine is examined. Here, the main focus is on the thermophoretic soot deposition on the cylinder liner as well as soot transport into the crevice region via blowby. Numerical simulation of in-cylinder diesel combustion is performed using a commercial Computational Fluid Dynamics (CFD) software, ANSYS FLUENT 13, coupled with a chemical kinetic model via a plug-in chemistry solver, CHEMKIN-CFD. A chemical reaction mechanism of *n*-heptane combined with soot precursor formation mechanism is adopted as the diesel surrogate fuel model, with the Eddy-Dissipation Concept (EDC) model employed to represent the turbulence-chemistry interaction. The inclusion of a top land volume in the computation mesh and the implementation of crevice model in the CFD solver allow soot mass to be predicted in this region, which is used here to represent the soot mass transport into the crevice via blowby. With thermophoresis as the primary mechanism of soot deposition on the liner, a User-Defined Function (UDF) is written to incorporate the transport equations for the calculations of the mass and particle size of soot deposited. During the closed cycle combustion process, the mass of soot deposited on liner via thermophoresis is more significant, averaging to between 17 and 170 times of those transported into crevice region through blowby. Other than the soot concentration near the liner, thermophoretic deposition is observed to be also affected by the wall temperature gradient. With single injection strategy, advancement in the start of injection (SOI) timing from +2 crank angle degrees (CAD) to −6 CAD after top dead centre (ATDC) is found to reduce soot entrainment by 22% and the size of deposited soot particles by 4%. The adoption of split-main injection scheme with early injection reduces the quantity and size of the entrained soot as the fuel split ratio is lowered. However, the split injection scheme produces an opposing effect at late SOI timing, where the smallest quantity and size of the entrained soot is produced. Variation in the injection strategy is found to affect the soot entrainment process by influencing the in-cylinder gas motion, the location of combustion event and the evolution of soot cloud. This study provides a detailed insight into the effects of injection parameters on key in-cylinder processes governing soot entrainment, which can potentially help in formulating engine operating guidelines to mitigate soot-in-oil problem.

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Nomenclature

B_1	breakup time constant (–)
C_α	model constant for soot inception rate (s^{-1})
C_β	model constant for coagulation rate (–)
C_c	Cunningham coefficient (–)
C_m	coefficient of momentum exchange in the thermophoretic coefficient (–)
C_{oxid}	oxidation rate scaling parameter (–)
C_s	coefficient of thermal slip in the thermophoretic coefficient (–)
C_t	coefficient of temperature jump in the thermophoretic coefficient (–)
C_ω	oxidation model constant (kg m $kmol^{-1}$ $K^{-1/2}$ s^{-1})
C_γ	surface growth rate scaling factor (kg m $kmol^{-1}$ s^{-1})
d_p	mean diameter of soot particle (m)
F_{ty}	Thermophoretic force in the y direction (kg m s^{-2})
k_g	thermal conductivity of gas (W m^{-1} K^{-1})
k_{soot}	thermal conductivity of soot particle (W m^{-1} K^{-1})
Kn	Knudsen number (–)
K_t	thermophoretic constant (–)
M	soot mass concentration (kg m^{-3})
M_p	mass of incipient soot particle (kg $kmol^{-1}$)
N	soot particle number density (particles m^{-3})
N_A	Avogadro number (k mol^{-1})
η_{coll}	collisional efficiency parameter (–)
P	gas pressure (Pa)
R	universal gas constant (J K^{-1} mol^{-1})
R_s	particle radius (m)
T	temperature (K)
T_α	activation temperature of soot inception (K)
T_γ	activation temperature for surface growth (K)
V_{ty}	Thermophoretic velocity in the y direction (m s^{-1})
ν	kinematic viscosity (m^2 s^{-1})
λ	gas mean free path (m)
μ	gas dynamic viscosity (kg m^{-1} s^{-1})
X_{prec}	mole fraction of soot precursor (–)
X_{sgs}	mole fraction of surface growth species (–)
y^+	dimensionless wall distance (–)
ρ	density of gas (kg m^{-3})
ρ_{soot}	density of soot (kg m^{-3})

1. Introduction

The increasingly stringent regulations of diesel emissions in recent years have prompted concentrated efforts to improve engine designs and operations. However, certain modifications such as the use of exhaust gas recirculation (EGR) (Agarwal et al., 2011) and biodiesel as an alternative fuel in diesel engine (Park et al., 2012; Rakopoulos et al., 2011) have shown to have detrimental effects on the concentration of other pollutant species in the exhaust stream and the level of contaminant in engine oil. It is well known that high soot concentration in engine oil can clog filters and pyrolise into hard carbon deposit, which eventually lead to oil starvation and damage to the engine. Rounds (1977) proposed that wear occurs when the anti-wear additives which prevent metal-to-metal contact are adsorbed onto soot. Additionally, the viscosity of engine oil is raised, resulting in higher friction and invariably an increase in engine wear rate. The size of the soot particles also plays a significant role. Although nanosized soot particles are more dangerous in terms of health effects (Kittelson, 1997), an increase in soot diameter approaching the oil film thickness accelerates the engine wear rate (Sato et al., 1999).

During normal diesel engine operations, high soot concentrations are produced within the combustion chamber, and often exceed tenfold the exhaust soot concentrations. Within few hundred microns from the chamber wall, the local temperature is much lower and the soot particles in this region may escape oxidation (Eastwood, 2008). The existence of this temperature gradient gives rise to the thermophoretic process, where the particles move towards the region of lower temperature and deposit on the chamber wall. Thermophoresis is reported to be the major pathway of the soot deposition on the in-cylinder surfaces (Suhre & Foster, 1992). These soot particles are eventually scraped off by moving piston and entrain into the engine oil through the crevice during exhaust blowdown (Agarwal et al., 2011). Another pathway of soot entrainment into the engine oil is via crevice blowby, where the bulk mass of combustion product is transferred into the crankcase region through the crevice gap between the piston and the cylinder liner.

While extensive experimental work such as those reported by Shu et al. (2012) have been conducted to determine the key factors of combustion chamber deposit and its adverse effects, computational studies of soot deposition mechanism are employed to further understand this process. Most of these have been specifically focused on the thermophoretic effect. Dahlén (2002) conducted a CFD study of thermophoretic soot deposition in a diesel engine, where the predicted soot mass deposition data was fitted to the measurements of soot concentration in engine oil by adjusting the thermophoretic model constant. The predicted amount of soot deposition on the liner was found to agree well with the measured data, verifying the significance of the thermophoretic effect on soot entrainment process into engine oil. Thermophoretic deposition was also incorporated in a modelling study by Wiedenhoefer & Reitz (2003) to examine its effect on radiation in a heavy duty diesel engine. Here, radiative heat loss by soot in the near wall region was observed to be negligible. Ra & Reitz (2006) further investigated the engine soot deposition through the multidimensional modelling approach by introducing grids for complex geometry of the piston ring pack and submodels to represent the dynamics of crevice flow. The study concluded that crevice born hydrocarbon plays an important role in the formation of soot deposits.