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A phenomenological model of knock intensity in spark-ignition engines

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ABSTRACT

In experimental calibration of mass production spark-ignition (SI) engines, knocking cycles are usually determined by a specified threshold of knock intensity (KI). In engine cycle simulation, however, modeling of knock is usually limited to prediction of knock onset (i.e. auto-ignition of end gas), or merely simple parameters such as unburned mass fraction (UMF) for KI are taken into account, causing considerable deviation from actuality. The objective of this study is to develop a phenomenological KI model to improve predictability of engine cycle simulation. The experiments with a turbocharged 1.5 L gasoline engine operated by spark sweeps around knock limits over a wide speed range are conducted to generate the data base for the model formulation and evaluation. With assumption of lognormal distribution of KI in consecutive cycles, a knock factor (KF) based on the likelihood ratio is proposed as a criterion for definition of knocking cycles. The model developed in the previous study, which includes the cylinder pressure, end gas temperature, exhaust gas recirculation (EGR) ratio and excess air ratio as variables, is used to predict the knock onset. With in-depth analysis of the physics influencing knock intensity, the energy density and heat release rate (HRR) in hot spots are identified to play critical roles in determination of knock intensity. The heat release rate is related to the end gas temperature, pressure, EGR ratio and excess air ratio, while the energy density is determined by the amount of fresh charge in the cylinder and the charge volume at knock onset. Thus, the correlation of the two factors, including the HRR factor α and the energy density factor β, is formulated to develop the predictive model of knock intensity Y_{KI}. Finally, the newly developed KI model is evaluated through comparison with other KI models, and better performance in terms of prediction of knock intensity is obtained.

1. Introduction

1.1. Literature review

Knock is abnormal combustion phenomena in spark ignition (SI) engines, and it is one of the constraints for improvement of performance of SI engines. Although engine knock has been widely investigated over many years, it continues to be an important and challenging issue in development and optimization of spark-ignition engines, in particular for downsized, highly-boosted SI engines. Engine downsizing has been proven an effective way to improve the fuel conversion efficiency of SI engines, owing primarily to reduced proportion of breathing and frictional losses with frequently operating points shifted to higher loads in downsized engines [1]. To maintain the rated power or torque, however, intake boosting is usually required, resulting in knock, a severer problem for downsized engines [2,3]. Plenty of the state-of-the-art technologies for improvement of fuel conversion efficiency of SI engines are relevant to suppression of knock. Direct injection of fuel into cylinder could help lower the charge temperature due to evaporation of fuel droplets, reducing knock [4]. Variable valve timing and lift were adopted to reduce the residual gas [5] as well as shorten the effective compression ratio [6,7], lowering the charge temperature at top dead center (TDC) to suppress knock. Split fuel injections could be used to promote the mixture stratification to reduce knock [8,9]. Cooled exhaust gas recirculation (EGR) was employed to dilute the fuel-air mixture, increase the specific ratio of heat capacity, lower flame temperature, and impede the auto-ignition reactions of end gas, mitigating knock [10,11]. With these technologies, the fuel conversion efficiency can be improved either by advancing the spark timing or by increasing the geometric compression ratio [12,13].

While engine cycle simulation plays increasingly important roles in development and optimization of SI engines, modeling knock remains a challenging task. So far most researches on modeling knock focus on predicting the knock onset based on the end

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Nomenclature

a	local sound speed [m/s]
AC	alternating current
A_f	surface area of the flame front [m^2]
aTDC	after top dead center
BDC	bottom dead center
BMEP	brake mean effective pressure [bar]
BSFC	brake specific fuel consumption [g/(kW h)]
C	model constant [–]
CAD	crank angle degree [–]
CFD	computational fluid dynamics
CR	compression ratio [–]
D	dimensional
E	energy density [J/m^3]
FFT	fast Fourier transform
EGR	exhaust gas recirculation
GCR	geometric compression ratio [–]
HRR	heat release rate [J/s]
IMEP	indicated mean effective pressure [bar]
IVC	intake valve closing [CAD]
KF	statistical knock intensity [–]
KI	knock intensity [bar]
KLSA	knock limited spark advance [CAD]
l_M^*	Taylor micro-scale length [m]
m_1	flame kernel growth multiplier
m_2	turbulent flame speed multiplier
m_3	Taylor length scale multiplier
m_4	dilution exponent multiplier
m_5	convection multiplier
m_{air}	mass of fresh air [g]
MAPO	maximum amplitude of pressure oscillations [bar]
m_b,	burned mass [kg]
MBF	mass burned fraction [%]
m_e	entrained mass [kg]
$\dot{m}_F$	the mass flow rate of fuel [kg/s]
M_{KI}	knock index by McZenie et al. [–]
NA	naturally aspirated
P	pressure [bar]
PFI	port fuel injection
Q	the cumulative apparent heat release [J]
Q_c	the heat transfer loss [J]
R	hot spot size [m]
r_0	radius of hot spot [m]
R_{KI}	acoustic knock intensity [–]
rpm	round per minute
S	heat release rate per volume [1/s]
SER	signal energy ratio [–]
SI	spark ignition
S_L^*	adjustable laminar flame speed [m/s]
SPK	spark angle [CAD]
T	temperature [K]
t	time [ms]
TDC	top dead center
t_{IVC}	moment at intake valve closing [CAD]
t_{knock}	moment at knock onset [CAD]
u_a	propagation speed of reaction front [m/s]
$\bar{u}_i$	mean velocity of intake charge through the intake valves [m/s]
UMF	unburned mass fraction [%]
u_T^*,	turbulent flame speed [m/s]
V_{knock}	the in-cylinder volume at knock onset [m^3]
WOT	wide open throttle
Y_{KI}	knock index of this study [–]
α	the heat release rate factor [–]
β	the energy density factor [–]
χ_{EGR}	EGR ratio [%]
χ_{O2}	mass fraction of oxygen in air [%]
δ	the standard deviation [bar]
ε	reactivity parameter, $(r_0/a)/\tau_e$
ϕ	equivalence ratio [–]
γ	ratio of specific heats [–]
η	turbocharger efficiency [%]
λ	excess air ratio [–]
μ	the mean value [bar]
θ	crank angle [CAD]
τ	auto-ignition delay [ms]
τ_b^*	characteristic burning time of turbulent flame [s]
τ_e	characteristic time of heat release of hot spots [s]
ξ	resonance parameter, a/u_a [–]

gas auto-ignition theory. In general, these models can be classified in three categories: (1) detailed chemical kinetic mechanisms for the pre-flame (or low-temperature) reactions, (2) simplified chemical kinetic mechanisms for the pre-flame reactions and (3) phenomenological models based on Arrhenius expression. Detailed chemical kinetic mechanisms are usually coupled with zero- or quasi-dimensional combustion models [14]. With recent advances in computer technologies, simulations based on detailed chemical kinetics coupled with 3-dimensional computed fluid dynamics (3-D CFD) have appeared to study knocking combustion [15]. Evolution of local thermodynamic states including pressure, temperature, and velocity as well as species concentrations could be calculated and detailed locations of knock onset could be predicted with the detailed chemical reactions and 3-D CFD simulation [16,17]. However, a detailed chemical kinetics mechanism of gasoline surrogates is usually comprised of hundreds of species and thousands of elemental reactions. When coupled with 3-D CFD, the huge computational cost inhibits its application to the multi-variables and multi-objects optimization based on engine cycle simulations. Efforts have also been taken on use of simplified chemical kinetics. Even with the reduced mechanism, however, both the sizes of mesh and time step in the calculations of 3D-CFD need to be sufficiently small to simulate the pressure wave and analyze the knock characteristics, leading to a very high computing cost that is not applicable for the optimization involving multiple variables and objects. Phenomenological models based on the Livengood-Wu Integral [18] typically employ a one-step reaction and predict the knock onset reasonably well with much less computing time than detailed chemical kinetics models [19]. A typical correlation based the Arrhenius equation can be found in Douaud and Eyzat [20], and it has been widely utilized without any changes or with merely the model constants recalibrated [21]. Desantes et al. proposed a method based on the critical concentration of chain carriers to predict auto-ignition [22,23], and later they improved their models to predict both low and high temperature ignition delays [24,25]. Since most of these models do not include exhaust gas recirculation (EGR) and excess air ratio (λ) as explicit variables and they failed to give an acceptable prediction of knock onset when the engine running with EGR or fuel enrichment [11,12]. Hoepke et al. [26] proposed a correlation with EGR ratio as an explicit variable, but without λ. Chen et al. [27] developed a model considering multiple variables as explicit variables,