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Full Length Article

Development of a quasi-dimensional, fractal-base combustion model for SI engines by simulating flame-wall interaction phenomenon

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ABSTRACT

A quasi-dimensional thermodynamic model was developed using concept of the fractal-geometry combustion model by focusing on the behavior of the natural gas flame near the combustion chamber walls in SI engines. A new wall-flame interaction sub-model was designed and implemented in the thermodynamic model by considering the flame geometry and temperature of the combustion chamber walls. Near the walls, the dimensionless factor affects the fractal combustion model which reduces the heat release rate (HRR). First, the combustion process of natural gas fueled SI engine was simulated using a CFD software and the flame geometry was extracted for each crank angle. The results were validated with experimental data at various engine operating conditions so that the results were in good agreement with the corresponding experimental data. The results show that the concentric spherical flame propagation assumption is not true for the off-center spark plug. The walls near the flame prevent its propagation and its shape deviates from the spherical form. The points of flame collisions on the walls are one of the determinant factors in the heat release process. The flame quenching and HRR vary at different walls of the combustion chamber and both of them are proportional to the wall temperature and flame area affected by the walls. Finally, it can be concluded that, natural gas turbulent flame propagation is occurred in three stages: 1- The initial propagation of flame with high acceleration, in which 15% of the fuel is burned with a high HRR. 2- Collision of the flame with the floor of the piston, HRR continues with almost constant rate, in which 30% and 50% of the fuel is burned for the off-centered and centered spark plug locations, respectively. 3- Deceleration of the flame propagation after colliding with the side walls, in which 55% and 35% of the fuel is burned for the off-centered and centered spark plug locations, respectively.

1. Introduction

With the advancement of human societies and the growing need for the use of internal combustion engines in various industries, extensive efforts have been made to optimize the engine performance, increase efficiency and reduce fuel consumption and emissions. Research on the internal combustion engines requires the development of engine simulation models which are able to guarantee acceptable results of the engine performance over a wide range of operating conditions [1].

To create a reliable simulation model in spark ignition engines, there should be a precise prediction of heat-release, which involves the evaluation of the in-cylinder turbulence flow pattern, expanding the flame front, flame-turbulence and flame-walls interactions [2,3].

In the SI Engines, the main part of the heat release is due to the turbulent premixed flame propagation. Although the structure of the turbulent premixed flames has been studied theoretically and experimentally for several decades, but understanding and inferring on the turbulent flame structure is still restricted [4,5].

The turbulent premixed combustion in SI engines usually happens in the flamelet regime, so that the combustion flame spreads in two modes, the wrinkled flame and corrugated flame, the wrinkled flame with peninsulas [6].

One of the models widely used in simulation of the premixed turbulent flames is the power-law approach. The theory is based on the flamelet models that reactions occur in a thin flame layer, so it separates the combustion products and reactants, meanwhile the flame surface is wrinkled by the turbulent flow [7]. In several researches, flame-wrinkling is modeled by the fractal theory. This theory needs sub-model for the fractal dimension and the maximum and minimum turbulence length scales as shown in Eq. (1) [8,9].

$$\Xi = (A_T/A_0) = (\varepsilon_o/\varepsilon_i)^{D-2} \quad (1)$$

In Ref. [10], the concept of “Laminar Flamelet” has been studied by the two approaches, namely the fractal description and flame surface

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Nomenclature

T	temperature
P	pressure
m	mass
t	time
K	turbulent kinetic energy
S_L	laminar flame speed
S_{L0}	reference laminar flame speed
S_T	turbulent flame speed
A_L	laminar surface area
A_T	turbulent surface area
D_a	Damkohler number
Le	Lewis number
R_e	Reynolds number
D	fractal dimension
l_{max}	maximum length scale
l_{min}	minimum length scale
c_1	constant coefficient
s_p	instantaneous distance from piston surface to cylinder head
u'	turbulence intensity
ν	unburned gas kinematic viscosity
δ_L	flame thickness
D_m	mass diffusivity
r_f	flame radius
T_{act}	activation energy
T_{ad}	adiabatic flame temperature
F_{ex}	flame extinction factor
I_0	flame stretch factor
f	relaxation factor
e	dissipation rate
φ	equivalence ratio

Greek

ω	weighting term
Ψ	flame-wall interaction factor
ρ	density
ζ	normalized velocity
Ξ	flame wrinkling factor
ε_o	maximum length scale
ε_i	minimum length scale

Subscripts

u	unburned
b	burned
L	laminar
T	turbulent

Acronyms

CAD	crank angle degree
IVO	inlet valve opening
IVC	inlet valve closing
EVO	exhaust valve opening
EVC	exhaust valve closing
LIV	lift of inlet valve
LEV	lift of exhaust valve
CFM	coherent flame model
HRR	heat release rate
FCHW	flame-cylinder head wall
FCW	flame-cylinder wall
FPW	flame-piston wall
FBZ	flame-burned zone
FUZ	flame-unburned zone

density. The assumption that, the turbulent flame front surface is a passive scalar cannot be confirmed. Hence, the flamelet approach is limited to the specific range of dimensionless turbulence intensities and fractal dimensions.

Many researchers [9,11] have estimated the fractal dimensions of the premixed turbulent flames as a function of the laminar flame velocity and turbulence intensity and expressed a widely-applied correlation, as Eq. (2).

$$D = \frac{2.05}{1 + u'/S_L} + \frac{2.35}{1 + S_L/u'} \tag{2}$$

The turbulence plays an important role on combustion process in the spark ignition engines, greatly enhancing the flame propagation velocity and heat release rate through a meaningful wrinkling of flame front [2,12]. In Ref. [13], a new quasi-dimensional K-k turbulence model for SI engines has been developed based on an energy cascade from mean flow to viscous eddy dissipation, formally derived from 3D transport equation of turbulence. This model is able to simulate the progression of the turbulent and mean kinetic energies over the complete engine cycle, which also includes the effects of gas exchange process.

Many studies have been done to predict the flame propagation, flame area, flame-turbulence interaction inside the combustion chamber of internal combustion engines. But, it is still needed to investigate on the combustion process, flame propagation, flame-wall interaction and slope of heat release rate near the piston and cylinder walls, accurately and comprehensively. In general, a weighted function, ω, that displays a switch between the two combustion modes, namely fractal combustion and wall-combustion, was implemented [14]. When the distance between the flame front and cylinder wall was half of the maximum length scale, the combustion mode was switched from the fractal equation to the wall-combustion equation.

In Ref. [15], laser tomography was used in a transparent SI engine for imaging of the flame surface near the walls. The images are taken for five horizontals and one vertical planes. A parameter called quenching parameter was defined to take into account the part of the flame surface quenched by the cylinder walls. The results showed that the fractal dimension decreases and tends toward 2, when the distance between the flame front and the walls reaches about twice of the maximum integral length scale. The burning rate was estimated as a function of distance between the wall and flame front and decreased linearly as the flame approached the wall.

In Ref. [16], the dimensionless function, Ψ, was dedicated to the flame front surface fraction close to the walls. The dimensionless function was multiplied to the burning rate equation to decrease the heat release rate in the vicinity of the walls. In the definition of Ψ, as shown in Eq. (3), two different aspects were considered: the distribution

Table 1
Technical specifications of the engine.

Bore * Stroke	100 mm * 127 mm
Compression Ratio	9.5:1
Connecting Rod length	219 mm
Displacement Volume	3.99 L
Combustion Chamber	Heron
Breathing System	Natural aspirated
Fuel Type	Natural Gas
Valve Timing (relative to the induction TDC)	IVO = 710°(−10°), IVC = 210° EVO = 497°, EVC = 25°
Max. Valve Lifts	LIV = 10.71 mm LEV = 10.84 mm