

A Numerical Simulation Study on Improving the Thermal Efficiency of a Spark Ignited Engine --- Part 1: Modeling of a Spark Ignited Engine Combustion to Predict Engine Performance Considering Flame Propagation, Knock, and Combustion Chamber Wall ---

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ABSTRACT

The first objective of this work is to develop a numerical simulation model of the spark ignited (SI) engine combustion, taking into account knock avoidance and heat transfer between in-cylinder gas and combustion chamber wall. Secondly, the model was utilized to investigate the potential of reducing heat losses by applying a heat insulation coating to the combustion chamber wall, thereby improving engine thermal efficiency. A reduction in heat losses is related to important operating factors of improving SI engine thermal efficiency. However, reducing heat losses tends to accompany increased combustion chamber wall temperatures, resulting in the onset of knock in SI engines. Thus, the numerical model was intended to make it possible to investigate the interaction of the heat losses and knock occurrence. The present paper consists of Part 1 and 2. Part 1 deals with the description of the numerical model and the fundamental characteristics of instantaneous temperature swings in the combustion chamber wall.

The numerical model is developed by utilizing GT-POWER combined with three sub-models; a non-dimensional two-zone combustion model, an autoignition model in the unburned gas and an instantaneous heat transfer model in the combustion chamber wall. The combustion model considers the flame speeds affected by the in-cylinder conditions. The Shell model was utilized to predict autoignition. The heat transfer model in the combustion chamber wall calculates the instantaneous one-dimensional thermal conductivity, and further predicts wall surface and inside temperatures. The fluctuation range of calculated temperature swings is reasonably similar to measured data obtained in previous studies.

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INTRODUCTION

Reduction of heat losses is an important factor of improving thermal efficiency of internal combustion engines. The instantaneous heat flux through the combustion chamber wall is determined by coupling equations (1) and (2), which describe the unsteady thermal conductivity inside the wall and the heat transfer at the wall surface, respectively.

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + \dot{s} \quad (1)$$

$$q_B = h \Delta T = h(T_f - T_B) \quad (2)$$

where,

ρ : Density

c : Specific heat

t : Time

k : Thermal conductivity

$\dot{s}$: Source term

q_B : Boundary heat flux

h : Heat transfer coefficient

T_f : Surrounding-fluid temperature



T_b : Boundary temperature

x, y, z : Position

It is conventional to attempt to reduce k , h and ΔT in the equations (1) and (2) for the reduction of heat losses.

Kawamura et al. utilized a low thermal conductivity (k) ceramic material to construct a thermally-insulated engine with no cooling system and demonstrated its reliability [1]. Xin and Shih et al. performed an integrated 3D-CFD calculations in which the combustion process and cooling system of an engine were modeled simultaneously, and showed optimized water jacket improved knock resistance and fuel consumption [2,3]. Inagaki et al. proposed a new concept of diesel combustion that uses a highly dispersed spray with restricted in-cylinder swirl and squish flows. This approach reduces the heat transfer coefficient (h), and achieved low emissions and high efficiencies by minimizing cooling losses [4]. Fujimoto et al. developed a non-dimensional combustion model coupled with heat conduction analysis in the combustion chamber, and used it to determine how compression ratios and cooling losses affect the calculated thermal efficiency [5]. Kosaka et al. applied low thermal conductivity and low heat capacity materials to the combustion chamber wall of gasoline and diesel engines, resulting in reduction of the value of ΔT . And they clarified that it was possible to prevent the intake air heating and reduce the heat losses simultaneously [6]. Das et al. investigated how heat losses are affected by the shape of the piston bowl, the EGR ratio, the properties of the combustion chamber material and the injection regime [7].

The studies discussed above have demonstrated that a variety of methods can be used to reduce heat losses. However, reduction in the heat loss from the engine tend to increase the wall surface temperatures, which has unfavorable effects on the onset of knock in spark ignited engines [3,8,9]. Therefore, when evaluating methods for reducing heat losses in spark ignited engines, it is important to also consider the effect on the knock occurrence simultaneously. Here, we present a numerical simulation model consisting of a non-dimensional two-zone SI combustion model, autoignition model in the unburned gas and unsteady one-dimensional heat transfer model in the combustion chamber wall, and a spark ignition timing optimization scheme was also coupled. This numerical model made it possible to investigate the interactions among combustion wall surface temperatures, heat losses and knock occurrence in detail, including optimization of spark ignition timing. Part 1 of the present study deals with the description of the numerical model, the fundamental characteristics of temperature swings in the combustion chamber wall, and the effects of transient changes in the wall surface temperature on heat losses and knock occurrence under accelerating and steady state engine operating conditions.

THE NUMERICAL MODEL

GT-POWER was used to develop the numerical model for spark ignited engine presented in this work. An autoignition model in the unburned gas, a heat transfer model in the combustion chamber wall and a spark ignition timing optimization scheme were coupled into the non-dimensional two-zone SI combustion model in order to predict and analyze the effects of changes in the combustion chamber wall surface temperature on heat loss and knock occurrence.

Combustion Model

The engine's combustion characteristics were predicted using the SI turbulent combustion flame model [10], one of the objects in GT-POWER. This combustion model is based on the non-dimensional two-zone predictive combustion model and calculates the combustion rate by assuming that the flame grows spherically in a manner determined by the laminar and turbulent flame propagation speeds. The Wiebe function, which has been used in many previous studies, can be tuned to reproduce specific combustion rates by adjusting an exponent, while the model can be used to study the effects of diverse in-cylinder factors including the combustion chamber geometry, temperature, pressure, fuel compositions, turbulence intensity calculated from intake and exhaust flow, and so on. The governing equations of the combustion model are as follows:

$$\frac{dM_b}{dt} = \frac{M_e - M_b}{\tau} \quad (3)$$

$$\frac{dM_e}{dt} = \rho_u A_e (S_T + S_L) \quad (4)$$

$$\tau = \frac{C_\lambda L_t}{\sqrt{Re_t}} \quad (5)$$

$$S_L = \{B_m + B_\phi(\phi - \phi_m)^2\} \left(\frac{T_u}{T_{ref}}\right)^\alpha \left(\frac{P}{P_{ref}}\right)^\beta \cdot (1 - 2.06 Y_{dil}^{DEM-0.77}) \quad (6)$$

$$S_T = C_s u' \left(1 - \frac{1}{1 + C_k R_f^2 / L_t^2}\right) \quad (7)$$

where,

dM_b/dt : Combustion rate

M_e : Mass of unburned gas converted by the combustion

M_b : Mass of the burned gas

T : Time constant

ρ_u : Density of the unburned gas

A_e : Flame surface area

S_T : Turbulent flame speed

S_L : Laminar flame speed

L_t : Turbulent length scale

Re_t : Turbulent Reynolds number

B_m Constant, given in ref.(11)

B_ϕ : Constant, given in ref.(11)

ϕ_m : Constant, given in ref.(11)

ϕ : Equivalence ratio

T_u : Unburned gas temperature

Y_{dil} : Diluent factor

α : Exponent, given in ref.(11)

β : Exponent, given in ref.(11)

u' : Turbulent intensity

R_f : Flame radius

C_λ : Model constant

DEM : Model constant

C_s : Model constant

C_k : Model constant

Knock Prediction Model in Unburned Zone

The Shell model [11] was utilized to predict autoignition in the unburned gas. The model is based on a set of simplified chemical reactions for alkane fuels developed by Halstead et al.. It requires much less computational time than a detailed kinetic simulation because it considers a comparatively small number of species and reaction mechanisms. The model consists of generalized 5 species and 8 reactions, and can reproduce the autoignition processes of diverse fuels by adjusting its various reaction rate coefficients. These coefficients were determined by comparing the model's output to results obtained using the SENKIN program in the CHEMKIN package. The gasoline surrogate reaction mechanism proposed by V. I. Golovichev [12] was used in the SENKIN calculations, and the fuel compositions with RON90 was selected using the MLbV model [13] as shown in Table 1. Figure 1 shows the predicted ignition delay timings obtained using the SENKIN and Shell models, which are clearly in good agreement. The algorithm used to couple the GT-POWER and the Shell model is shown in Figure 2. It was assumed that knock occurred when the temperature of the unburned gas exceeded 1,000 K.

Table 1. Chemical reaction scheme

Reaction mechanism		Gasoline surrogate
Compositions vol. %	i-C ₈ H ₁₈	39.7
	n-C ₇ H ₁₆	20.3
	C ₆ H ₅ CH ₃	40.0

Table 2. Calculation conditions

Initial pressure atm	30, 50
Initial temperature K	600 ~ 1000
Equivalence ratio	1.0
EGR ratio %	0

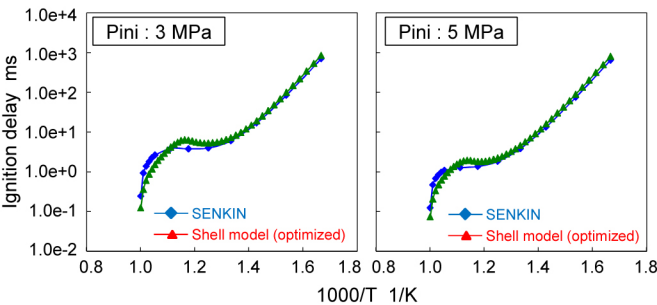


Figure 1. Comparison of the ignition delay times calculated using the SENKIN and the Shell model