

An introduction to automotive engine combustion modeling

ABSTRACT

Combustion model is the key basic part of the progress of internal combustion engine technology, and it is a major direction of the future research of internal combustion engine technology. This paper mainly analyzes the advantages and disadvantages of each of the five combustion models, ECFM, ECFM-3Z, SAGE, G-Equation, FGM, CTC and SHELL, and analyzes their respective advantages and disadvantages, as well as the most applicable types of internal combustion engines.

Keywords: Internal combustion engine; combustion modeling; simulation

1. INTRODUCTION

Internal combustion engine is a kind of heat engine that converts chemical energy into mechanical energy, and its basic principle is to produce high-temperature and high-pressure gases through the mixture of fuel and oxygen combustion, so as to push the piston movement and complete the energy conversion. Therefore, the combustion process of internal combustion engine is very critical [1]. The combustion process of internal combustion engine is extremely complex both in space and time distribution, the combustion process is a multi-component and multi-phase chemical reaction process, combustion exothermic will make the fluid transport coefficient increase, the chemical reaction process during combustion is very complex, coupled with the description of the turbulent structure is very difficult to consider the reaction process and spatial distribution of turbulent combustion at the same time is extremely difficult [2].

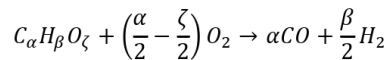
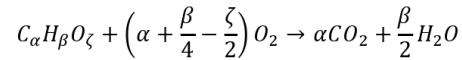
A combustion model is a mathematical model that describes the combustion process, and its main parameters include mixture concentration, pressure, temperature, and velocity. The accuracy of the combustion model has an important impact on the performance and emissions of internal combustion engines [3], among other things.

At present, internal combustion engine combustion models are mainly divided into two categories: empirical models and semi-empirical models. Each combustion model has its own characteristics and scope of application. The common combustion models are ECFM, ECFM-3Z, SAGE, G-Equation, FGM, CTC, SHELL and so on. In general, the development of combustion model is one of the bases for the progress of internal combustion engine technology, and it is also one of the major directions for the future research of internal combustion engine technology, and this paper mainly introduces five common combustion models.

2. ECFM MODEL

The ECFM (Extended Coherent Flamelet Model) model was developed primarily to describe combustion in direct injection ignition engines and was refined and improved by Colin et al [4] based on the proposed sequential flame model (Coherent Flame Model), which is fully coupled to the spray model and allows for the modeling of stratified combustion that including EGR effects and NO generation, and also predicts detonation [5], the ECFM model

46 relies on the description of the unburned and burned thermochemical conditions of the
 47 gas. The ECFM, in order to determine the flame surface density, uses the fuel-to-air
 48 equivalence ratio of the fresh gas, the composition (including residual gases), and the
 49 temperatures in the vicinity of the flame, and the resulting flame surface densities are used
 50 to characterize large-scale burned and unburned stratification. Based on the ECFM model,
 51 the ECFM-3Z model was further developed, with 3Z denoting three zones, i.e., a fuel-only
 52 zone, an air-only zone and including possible exhaust gases, and a mixing zone in which
 53 fuel and air coexist, and the ECFM-3Z model can be used to compute both premixed and
 54 non-premixed flames.
 55 For turbulent combustion, ECFM calculates the average reaction rate and the fuel switching
 56 is done using a two-step reaction mechanism:



57 where α , β and ζ are the atomic numbers of C, H and O, respectively.
 58

59 3. SAGE MODEL

60
 61 The SAGE model is a combustion model based on a detailed chemical reaction dynamics
 62 solver [6], which is the most central combustion model in the CONVERGE software. SAGE
 63 calculations are performed using chemical reaction mechanisms in CHEMKIN format. The
 64 model can simulate turbulent combustion of any fuel as long as the chemical reaction
 65 mechanisms are available. The prediction of detonation, self-fire, and emissions is more
 66 accurate than the traditional empirical and semi empirical models. If the reaction mechanism
 67 is provided with sufficient accuracy, then SAGE will be able to solve for very accurate
 68 results.

69 When using the SAGE combustion model, the quality control equations for the computational
 70 unit are:

$$\frac{d[X_m]}{dt} = \dot{\omega}_m$$

71
 72 The energy control equation is:

$$\frac{dT}{dt} = \frac{V \frac{dP}{dt} - \sum_m (\bar{h}_m \dot{\omega}_m)}{\sum_m ([X_m] \bar{c}_{p,m})}$$

73
 74 For fixed-volume combustion, the energy control equation is:

$$\frac{dT}{dt} = \frac{\dot{Q} - \sum_m (\bar{h}_m \dot{\omega}_m)}{\sum_m ([X_m] \bar{c}_{p,m})}$$

75
 76 In the above three equations, X_m is the molar concentration of component m , denotes the
 77 exothermic rate, V denotes the volume, T denotes the temperature, p denotes the pressure,
 78 denotes the molar specific enthalpy of component m , and denotes the molar constant pressure
 79 specific heat capacity of component m .

81 4. G-EQUATION MODEL

82

83 The G-Equation model, or G-equation model, is a combustion model based on the Level-set
84 method. The model can be used to simulate premixed combustion and can better reflect the flame
85 propagation development in the cylinder. The G-equation describes the chemical reaction
86 between the region inside the flame surface and the region outside the flame surface with the
87 flame surface as the boundary, and the calculation solves the propagation development of
88 turbulent flame through the flame surface without solving the flow field region inside the flame
89 surface [7-8]. However, at large variations in the mixture equivalence ratio, the G-equation
90 prediction of laminar flame propagation differs significantly from the experimental values [9-10].
91 In CONVERGE, which can be used alone or in conjunction with SAGE, the G-equation when
92 used alone does not need to solve the detailed chemical reaction mechanism and thus is faster
93 than the SAGE model, and the G-equation when used in conjunction with SAGE needs to solve
94 the detailed chemical reaction mechanism but is computationally faster than the SAGE model
95 alone. However, the G-equation requires more parameters to be calibrated when used, which
96 requires a higher level of experience and knowledge from the user.

97 98 **5. FGM MODEL**

99
100 The FGM (Flamelet Generated Manifold) model is a simplified generalized combustion
101 model [11] that reduces the reaction mechanism to two scalars. The model captures kinetic
102 phenomena such as ignition, flame extinguishing and flame quenching and provides
103 accurate flame dynamics, fuel effects and emissions for both premixed and diffusion
104 combustion. The FGM model has a high prediction accuracy in both the high and low
105 temperature regions and allows for natural diffusion of premixed combustion to non-
106 premixed combustion models.

107 The FGM model decomposes the complex chemical reaction process into global variables
108 that can characterize the complex chemical reaction, which greatly reduces the amount of
109 computation while taking into account the detailed chemical reaction mechanism [12]. The
110 FGM can calculate the detailed reaction mechanism and transfer the results in the form of a
111 table to the three-dimensional CFD software for the simulation of combustion process, and
112 this kind of combustion computation can reduce the computation time significantly.
113 The principle is that before the 3D calculation, the chemical reaction mechanism is first
114 calculated in one dimension and made into a table, and the results of the one-dimensional
115 calculation are interpolated into the 3D calculation, which makes FGM easy to use the
116 chemical kinetic reaction mechanism containing thousands of steps, which is almost
117 impossible to realize in the SAGE combustion model, however, FGM is currently applicable
118 to fewer models, mainly because of the difficulty of simulating the gas exchange process.

119 120 **6. SUMMARIZE**

121
122 An internal combustion engine combustion model is a mathematical model used to describe
123 the combustion process of an internal combustion engine, which mainly involves fuel
124 injection, mixing, ignition, combustion, and emissions. The development of combustion
125 models for internal combustion engines has important theoretical and practical significance,
126 which can help engineers better understand and optimize the combustion process of internal
127 combustion engines, thus improving the performance and efficiency of internal combustion
128 engines [17].

129 In general, the main advantages of combustion modeling for internal combustion engines
130 include the following:

131 1. internal combustion engine combustion modeling can predict the nature and
132 characteristics of combustion and emissions. Parameters such as combustion efficiency,
133 types of combustion products and their contents, temperature and pressure can be predicted

134 by the model for a variety of different scenarios, as well as emission properties such as NOx
135 and particulate content.

136 2. Internal combustion engine design and control can be optimized. Using combustion
137 models, the effects of various factors on the combustion process and emissions can be
138 investigated, thus helping to optimize the design and operational control of internal
139 combustion engines to improve their efficiency and reduce pollution [18].

140 3. Combustion modeling can improve the design and analysis capabilities of internal
141 combustion engine engineers by helping them to better understand the thermodynamic,
142 hydrodynamic, and chemical reaction aspects of the internal combustion engine and thus
143 better design and analysis.

144 Although combustion modeling for internal combustion engines has many advantages, there
145 are also some challenges and limitations:

146 1. The combustion process of an internal combustion engine is too complex. The
147 combustion process in an internal combustion engine involves a variety of physical and
148 chemical mechanisms, and it is very difficult to construct an accurate mathematical model.

149 2. The model requires high computational resources and data input. The establishment and
150 operation of the model requires massive data and computational power, which requires a lot
151 of time and computational resources.

152 3. The accuracy and validity of the model depends on the accuracy and sufficiency of
153 experimental data. Environmental, fuel and other factors in the actual combustion process
154 may also affect the accuracy and reliability of the model.

155 In conclusion, combustion modeling for internal combustion engines is a very complex and
156 challenging study that still requires further research and development. However, the
157 development of combustion modeling can provide internal combustion engine engineers with
158 new ideas for thinking and analyzing combustion problems and promote the development
159 and innovation of internal combustion engines.

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161 **COMPETING INTERESTS**

162

163 Authors have declared that no competing interests exist.

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165 **AUTHORS' CONTRIBUTIONS**

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167 This work was carried out in collaboration among all authors. All authors read and approved
168 the final manuscript.

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