

Geometric Effect of 3D Turbulent Field on Cyclic Variability

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ABSTRACT

Many studies, conducted by different researchers, have shown that in a carefully controlled engine almost all of the cyclic variability, observed in one cylinder, can be attributed to the flame kernel initiation and evolution. The authors have shown that variations in the flame kernel effective area can successfully explain a significant portion of observed cyclic variability. In the search of causes of this variation in effective area, the authors simulated the flame wrinkling in a 2D kinematically simulated turbulent field. That study had shown that flame wrinkling can explain between 5% - 53% of observed variability, depending on the operating conditions. This study explores the effect of adding the third dimension, which in turn allows the addition of flame stretch and curvature effects. Eight of the torque-speed operating points of the previous study are simulated using G-Equation and a 3D kinematically simulated turbulence. The results show that while the geometries of 2D and 3D flames look different the statistics behave quite similarly. The 3D flame shows slightly less variability and can only explain between 3% - 41% of observed variability. Studying the images suggest that this can be attributed to smoothing effects of flame propagation, which is enhanced by incorporating the third dimension. Similar correlation coefficients between flame wrinkling and laminar flame speed and turbulence intensity suggest that the conclusions made for a 2D flame will still be valid for the 3D flame.

INTRODUCTION

Cyclic variability puts severe limits on the charge dilution, which in turn limits the efficiency improvement and NOx

reduction that can be achieved by charge dilution. Different in-cylinder and out-of-cylinder processes can contribute to variability. Events such as cycle by cycle variations in spark or cyclic variations in injected fuel quantity or mixing can significantly contribute to variability. Although most of such variations may seem to stem from control issues, previous research [1] has shown that even in a carefully controlled engine, the stochastic nature of turbulent combustion can produce considerable variability. A good review of literature on the subject can be found in [2]. Since emission reduction and efficiency requirements are pushing the engines to operate more and more in the lean region, understanding and predicting cyclic variability has become increasingly important. There are many different methods for modeling cyclic variability. The interested reader is referred to [3], [4], [5] and [6] to name a few. Such models try to simulate cyclic variability based on a combination of phenomenological modeling and experimental correlations. This approach provides not only specific variability models for specific applications but also provides a better understanding of possible roots of cyclic variability. As such the models can be used as means of researching and understanding cyclic variability [5, 6, 7 and 8].

This study uses such a combination of modeling and experimental correlations as a means of understanding of cyclic variability. The aim is to gain better understanding of the contributions of flame wrinkling to cyclic variability. When the effects involving the displacement of the flame kernel in the combustion chamber [8] are neglected, flame wrinkling is a major source of cyclic variability. The authors have shown that in the absence of flame stretch and flame curvature effects, the interactions of a 2D flame with a

kinematically simulated turbulent field can explain between 5% - 53% [9] of the cyclic variability observed in one cylinder of a carefully controlled LPG-dedicated Ford Falcon engine, where cyclic variations in the mixture composition and homogeneity are well managed [1, 6]. This study extends the previous work on flame kernel modeling to three dimensions.

Ideally, simulation of flame-turbulence interaction requires LES (Large Eddy Simulation) of the flow field, which resolves all the turbulence length scales longer than Gibson length scale. Such simulations can incorporate all the different phenomena involved in flame propagation but they are costly. The computational cost of simulations can be reduced significantly by using kinematic simulation. Kinematic simulation of turbulence is successfully used to simulate the transport of material in the turbulent fields [10] but it does not allow accounting for flame generated turbulence and distortion of turbulent structures by the flame. Since the focus of this study is flame wrinkling caused by an already present flow field and flame generated turbulence is usually considered separately, this does not seem to be a disadvantage.

It has been shown that flame propagation can be simulated using G-Equation [11], where formulation of flame propagation as transport of a higher dimensional field quantity, usually the signed distance. Such representation is suitable for use in conjunction with the kinematic simulation of turbulence. The laminar flame speed in its simplest form will represent the mixture composition effects. It can also be corrected for flame strain [11] but this extension is not considered here. Because kinematic simulation provides a constant density flow field, the laminar flame speed should be corrected for gas expansion.

Assumptions applied to this study are:

- In line with the assumptions of studies reported in [6] and [9] it is assumed that effective flame-turbulence interactions are limited to the period of time, when the flame kernel is smaller than twice the size of integral length scale. This is based on the observation that cyclic variability is mainly caused by the variation in the flame kernel [6].
- The flame modeled here using G-Equation and kinematic simulation does not represent all the effects leading to cyclic variability but it tries to isolate the effects of kinematics of turbulence on the geometry of the flame kernel. Such abstractions of real flames will help to gain better understanding of the capacity of different phenomena in causing cyclic variability and mechanisms by which they affect flame. The authors appreciate that the interaction of these effects with each other deserves separate study.
- Any variations in spark discharge and heat losses to the spark plug are ignored.

The results of this study are compared with the observed variability and 2D simulations reported in [6] and [9] respectively. The results are corrected in order to eliminate the variability introduced by flame displacements.

THE MODEL

KINEMATIC SIMULATION

Kinematic simulation of turbulence is based on the procedures presented in [10]. The velocity field is calculated as a partial sum of the Fourier expansion.

$$\vec{u}(\vec{x}, t) = \sum_{n=0}^{N_k-1} \vec{A}_n \cos(\vec{k}_n \cdot \vec{x} + \omega_n t) + \vec{B}_n \sin(\vec{k}_n \cdot \vec{x} + \omega_n t)$$

$\vec{A}_n$ and $\vec{B}_n$ are two vectors with randomly selected directions. In order to satisfy the equation of continuity the wave number vector $\vec{k}_n$ should be perpendicular to both $\vec{A}_n$ and $\vec{B}_n$. To satisfy this condition the unit vector along the wave number vector is selected to be

$$\hat{k}_n = \frac{\vec{A}_n \times \vec{B}_n}{|\vec{A}_n \times \vec{B}_n|}$$

The magnitudes of wave number vector represent turbulence length scales.

$$\frac{2\pi}{L} = k_0 \leq k \leq k_{N_k} = \frac{2\pi}{\eta}$$

L is the integral length scale, which is taken to be half of the combustion chamber height [9] and η is the Kolmogorov length scale. The magnitude of the n -th vector is calculated using the following equation.

$$k_n = k_0 \left(\frac{L}{\eta} \right)^{\frac{n}{N_k-1}}$$

The magnitudes of $\vec{A}_n$ and $\vec{B}_n$ are determined from turbulence energy distribution.

$$E(k_n) = E_0 L (k_n L)^{-\frac{5}{3}}$$

$$\frac{3}{2} \vec{A}_n^2 = \frac{3}{2} \vec{B}_n^2 = E(k_n) \Delta k_n$$

E_0 is the energy of the largest eddy, calculated from turbulence intensity. Δk_n is calculated as:

$$\Delta k_n = \frac{k_{n+1} - k_{n-1}}{2} \quad n = 1, \dots, N_k - 2$$

$$\Delta k_n = \frac{k_1 - k_0}{2} \quad n = 0$$

$$\Delta k_n = \frac{k_{N_k-1} - k_{N_k-2}}{2} \quad n = N_k - 1$$

ω_n is calculated using the following equation.

$$\omega_n = l_T \cdot \sqrt{k_n^3 \cdot E(k_n)}$$

l_T is the Taylor micro-scale of turbulence.

G-EQUATION

G-Equation approach [11] models the flame propagation problem as a transport process. It uses a higher dimensional field, usually a signed distance function to track the development of the flame. It is based on the following equation.

$$\frac{\partial G}{\partial t} + (S_l \hat{n} + \bar{u}) \cdot \bar{\nabla} G = 0$$

G is the signed distance function, S_l is the corrected laminar flame speed, $\bar{u}$ is the fluid velocity and $\hat{n}$ is the unit vector normal to the iso-surfaces of G . The reader should note that S_l can potentially account for the effects of flame stretch, characterized by Karlovitz number (Ka), and flame curvature, characterized by Markstein number (Ma) [11] but in this study these effects are not considered. Since the experimental results used for comparison are obtained from an LPG engine the fuel used for all of the simulations is LPG and the laminar flame speed is calculated from a van-Tiggelen [6] model calibrated for LPG and corrected for gas expansion based on the mixture composition.

The G equation is discretized on a mesh with cell size of one-tenth of Gibson length scale using central difference. The mesh is a cube with the edge size of twice the integral length scale. A third order TVD Runge-Kutta method [12] is used for time marching. The time steps are selected so that the CFL number of 1 is maintained. The CFL number is calculated using the sum of corrected laminar flame speed and turbulence intensity as the characteristic velocity.

STRUCTURE OF THE RESULTS

Figure 1 shows the development of area for the simplest case possible. There is no turbulence and the flame speed is not corrected for gas expansion. The laminar flame speed is arbitrarily taken to be 40 cm/s. The flame will be spherical

with radius expanding with laminar flame speed. Figure 2 shows the radius of the flame. The numerical results predict a constant radius evolution speed of 39.73 cm/s with COV of 1.00%, which is very close to the exact value.

Figure 3 and Figure 4 show two of operating points considered in this study. The results show that a second order curve represents the area evolution with high degree of accuracy. Being able to represent the area as a quadratic function of time is compatible with the assumption of spherical flame propagation used in quasi-dimensional models [13]. In the quadratic representation, the coefficient of second order term is larger than the other terms by several orders of magnitude, which means that the area evolution can reasonably be approximated as $A(t) = c \cdot t^2$, where c is a constant. This conclusion is important for correcting the statistics of area.

In order to calculate the statistics of area variations, 50 iterations (cycles) are simulated. Figure 5 shows the variation of COV of area with the number of iterations for two operating points shown in Figure 3 and Figure 4. The COV of area becomes almost steady after about 30 iterations. The number of iterations (50) corresponds to those used in [9] and [6].

Figure 6 shows the perspective view of a typical flame at the same operating conditions as the point shown in Figure 4. Figure 7 shows the front view of a section of the flame. In comparison to the flames reported for the 2D case in [9] the section is smooth and is not highly distorted. It keeps its ellipsoid shape. This seems to be because of the extra dimension, which enhances the smoothing effect of flame propagation. The shape of the flame is compatible with the quadratic form mentioned earlier. Note the pockets of unburnt gas in Figure 7 that are left behind.

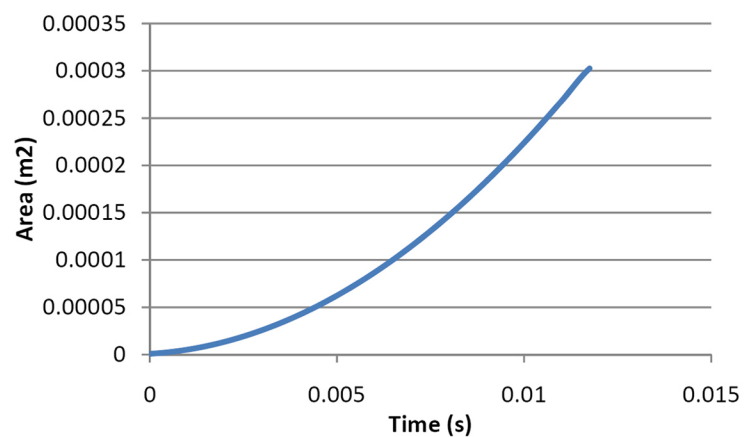


Figure 1. Development of area with time for a case with laminar flame speed of 40 cm/s, no turbulence and no correction for gas expansion.