A Theoretical Study on the Effects of Thermal Stratification on the Operating Range of HCCI Engines

Ramanan Sankaran* and Hong G. Im†
Department of Mechanical Engineering
University of Michigan
Ann Arbor, MI 48109

Abstract
The characteristics of auto-ignition in HCCI engines in the presence of charge stratification is studied theoretically using activation energy asymptotics. Some preliminary results on the effects of mixture stratification on the duration of burning and the sensitivity of ignition delay to initial temperature are presented. The analysis accounts for the effects of pressure rise due to piston motion and heat release, and the consequent compression heating of the charge. The results of this theoretical study can be used for extensive parametric studies of the effects of different temperature and composition distributions on HCCI combustion.

1 Introduction
Homogeneous charge compression ignition (HCCI) engines are considered a potential alternative to the conventional SI or CI engines for their promising advantages in efficiency and emissions. In an HCCI engine, fuel and air are well mixed and induced into the engine cylinder. This charge is then compressed to a high pressure and temperature which ignites the mixture without any external ignition system. If the charge was truly homogeneous, the entire charge would ignite at the same instant leading to very high rates of heat release and knock. This has been found to limit the maximum load realizable on the HCCI engines.

In real engines, however, the presence of wall heat transfer and residual exhaust gas will lead to a thermal and composition stratification of the charge. Such a stratification is not undesirable, since it reduces the rate of pressure rise in the cylinder and prevents knock. In fact, a mixture stratification by exhaust gas recirculation has been considered a viable means to a smoother heat release and lesser tendency to knock, thereby increasing the achievable load. However, the nature of combustion in the presence of mixture stratification is very complex and difficult to characterize.

The ignition and combustion characteristics in a nonuniform scalar field are fundamentally different from those expected for a homogeneous charge. The local peaks in temperature can create “hot spots” or kernels which are more reactive and thus lead the initial ignition events. Therefore, ignition at any given location is strongly affected by the neighboring mixture conditions, and hence depends on flow, mixing, compression heating, and other factors. Of these, compression heating is considered the most significant factor in the HCCI engine conditions. During the ignition event, the combustion and heat release in any part of the reactant gas leads to an overall pressure rise in the rest of the mixture. The temperature rise due to this compression will significantly increase the reactivity of the unburnt mixtures and cause them to ignite earlier. Therefore, the ignition delays in a stratified system depend not only on the local initial temperature, but also on the amount of compression heating it would receive prior to ignition. Consequently, the overall duration of burning is strongly influenced by the statistical nature of the distribution in temperature or the composition. A parametric study on these effects will provide valuable insights for the development of the HCCI engines.

Results from two-dimensional DNS studies [1, 2] of the auto-ignition of a stratified mixture in the presence of turbulence indicate a strong dependence of ignition behavior on all of the factors mentioned above. However, due to the high cost of simulating the combustion event along with the in-cylinder fluid dynamics, most of the modeling approaches used in HCCI engine studies neglect the effects of flow and mixing. One such approach for modeling the HCCI combustion event is the multi-zone model [3–5], which subdivides the mixture into a number of zones based on their temperature and composition, and then describes each of them as a well-stirred reactor.

While there is no mixing between these zones, work interaction is allowed, thereby capturing the effects of compression heating on ignition. Despite its simplicity, this model is still computationally expensive for an extensive parametric study of various temperature distributions. A simplified analytical description of the stratified charge combustion will be of great use in performing such parametric studies.

Activation energy asymptotics has been used to study the ignition of a constant volume system with a non-uniform temperature [6, 7]. In particular, Liñán and Williams [7] used an entropy-like variable to isolate the temperature rise due to chemical reaction from that due to compression heating. In this paper, we follow a similar approach and perform an asymptotic analysis to obtain a closed-form solution to describe the auto-ignition of a stratified mixture, including the compression heating effects. Using this analytical model, a parametric study is performed to understand the effects of statistical variables of the unburnt gas temperature distribution, such as the standard deviation or skewness. Quantitative measures are obtained for the change in duration of burning and sensitivity of ignition delay, which are expected to provide valuable insights for addressing the knock reduction and ignition control challenges in HCCI engines.

*Present address: MS9051, Combustion Research Facility, Sandia National Labs, Livermore, CA 94551
†Corresponding author: hgim@umich.edu
2 Formulation

In the HCCI mixture conditions, the effects of molecular mixing and scalar dissipation during the ignition event is considered of secondary importance and are neglected in the present study. The energy equation governing the thermal runaway of the stratified charge system is then given by,

\[
\frac{dT}{dt} = \frac{1}{\rho C_p} \frac{d\dot{P}}{dt} + \dot{\omega}.
\]

where \( \dot{T} \) and \( \dot{P} \) denote the dimensional temperature and pressure, respectively, \( \rho \) is the mixture density, and \( C_p \) is the specific heat. A one-step irreversible chemical reaction with an activation energy \( E \) is used to obtain the following expression for the chemical heat release term:

\[
\dot{\omega} = \left( \frac{Q}{\rho C_p} \right) AY_f \exp \left[ -\frac{E}{RT} \right].
\]

Using the above expression, the energy equation (1) is rewritten as

\[
\frac{d\dot{T}}{dt} = \frac{1}{\rho C_p} \frac{d\dot{P}}{dt} + \left( \frac{Q}{\rho C_p} \right) AY_f \exp \left[ -\frac{E}{RT} \right].
\]

In order to non-dimensionalize time(\( t \)) in the above equation, a reference homogeneous ignition delay time, \( t_{i, \text{ref}} \) is obtained by considering the thermal runaway of a constant volume system whose initial temperature is equal to the mean initial temperature, \( T_0 \), of the stratified system under study. For such a constant volume system, the ignition delay is given by [8]

\[
t_{i, \text{ref}} = \frac{\rho C_p T_0}{\gamma A Q Y_{f,0}} \frac{RT_0}{E} \exp \left( \frac{E}{RT_0} \right)
\]

where subscript 0 denotes the mean condition at TDC of the engine at motored condition. Defining nondimensional variables, \( P = \dot{P}/P_0, V = V/V_0, T = T/T_0 \), and \( \tau = t/t_{i, \text{ref}} \), equation (3) then becomes

\[
\frac{d\dot{T}}{d\tau} = \frac{\dot{P}_0}{\rho C_p T_0} \frac{dP}{d\tau} + \frac{\epsilon Y_f}{\gamma A Q Y_{f,0}} \exp \left[ -\frac{1}{\epsilon} \left( \frac{1}{T} - 1 \right) \right],
\]

where \( \beta = Q Y_{f,0}/\rho C_p T_0 \) and \( \epsilon = RT_0/E \). Assuming constant molecular weight, the ideal gas equation of state gives

\[
R = \frac{P}{\rho T} = \frac{\dot{P}_0}{\rho T_0} \frac{P}{T}.
\]

Furthermore, since we are studying the ignition behavior, fuel consumption prior to thermal runway is negligible \( (Y_f \approx Y_{f,0}) \). Therefore,

\[
\frac{d\dot{T}}{d\tau} = \frac{RT}{C_p P} \frac{dP}{d\tau} + \frac{\epsilon}{\gamma} \exp \left[ -\frac{1}{\epsilon} \left( \frac{1}{T} - 1 \right) \right]
\]

or

\[
\frac{d\ln T}{d\tau} = \frac{\gamma - 1}{\gamma} \frac{d\ln P}{d\tau} + \frac{\epsilon}{\gamma T} \exp \left[ -\frac{1}{\epsilon} \left( \frac{1}{T} - 1 \right) \right].
\]

Following the approach of the earlier work [7], we define an entropy-like variable \( S = T/P^\alpha \), where \( \alpha = (\gamma - 1)/\gamma \), such that the energy equation reduces to a simpler form,

\[
\frac{d\ln S}{d\tau} = \frac{\epsilon}{\gamma S^{\alpha}} \exp \left[ -\frac{1}{\epsilon} \left( \frac{1}{S^{\alpha}} - 1 \right) \right].
\]

While \( T \) can increase both due to compression and chemical heat release, \( S \) increases only through chemical heat release. Writing the energy equation in terms of \( S \) is advantageous because it isolates the chemical heat release from compression heating effects and hence allows the determination of the ignition delay. Equation (9) has to be solved along with a relationship for the pressure evolution to obtain the ignition characteristics of a stratified charge system. As a reference case, we first study the auto-ignition in a homogeneous charge engine.

3 Homogeneous Charge Ignition

In this section, we study the ignition characteristics of a homogeneous charge engine, where compression of charge is achieved by the piston motion. To analyze the thermal runaway of this system using equation (9), an additional equation is required for the pressure. Since we are interested in the evolution of the system prior to thermal runaway and the ignition delay, the effect of heat release during this period can be neglected and the system treated as adiabatic. Therefore, \( PV^{\gamma} = P_0 V_0^\gamma \) or \( PV^{\gamma} = 1 \), which relates the pressure as a function of volume during compression.

Since \( V_0 \) is the clearance volume of the engine, the instantaneous volume is given by the crank-slider relation [9],

\[
V = \frac{\dot{V}}{V_0} = 1 + \frac{(r - 1)}{2} \left[ L + 1 - \cos \theta - (L^2 - \sin^2 \theta)^{1/2} \right].
\]

Close to the TDC, where the value of crank angle \( \theta \) is small, the above equation reduces to \( V = 1 + g^2 \theta^2/4 \), where \( g^2 = (r - 1)(1 + 1/L) \) depends on the crank slider geometry of the engine. If \( t_c \) is the time period of crank rotation and \( t_0 \) the time at TDC, then \( \theta = 2\pi(t - t_0)/t_c \), and

\[
V = 1 + g^2 \pi^2 (t - t_0)^2/t_c^2.
\]

Then the pressure is given by,

\[
P = \left( 1 + g^2 \pi^2 \left( \frac{t - t_0}{t_c^2} \right) \right)^{-\gamma}.
\]

To understand the ignition of this system, equations (9) and (12) are solved using asymptotic expansions. Temperature and pressure are expanded about their TDC values in terms of the small parameter \( \epsilon = RT_0/E \) as \( S = 1 + \epsilon s + O(\epsilon^2) \), \( P = 1 + \epsilon p + O(\epsilon^2) \), and also, since \( P = V^{-\gamma} \), \( V \) has to be of the form \( 1 + \epsilon v + O(\epsilon^2) \). Equation (11) can be rewritten to satisfy this form as

\[
V = 1 + \epsilon \left( \frac{t - t_0}{t_c} \right)^2.
\]
where $\tau$ and $\tau_0$ are non-dimensional times and $\tau_c = \frac{t_c\sqrt{\tau}}{\rho \pi t_{i,ref}}$ is the non-dimensional time period of crank rotation. Substituting equation (13) in $P = V^{-\gamma}$ gives

$$p = -\gamma \frac{(\tau - \tau_0)^2}{\tau_c^2}. \quad (14)$$

Substituting the expansion for $S$ and $P$ in equation (9) yields the following equation at leading order in $c$:

$$\frac{ds}{d\tau} = \frac{1}{\gamma} \exp\left[ s - (\gamma - 1) \frac{(\tau - \tau_0)^2}{\tau_c^2} \right] \quad (15)$$

or,

$$\exp(-s)\,ds = \frac{1}{\gamma} \exp\left[ -(\gamma - 1) \frac{(\tau - \tau_0)^2}{\tau_c^2} \right] d\tau. \quad (16)$$

The above equation needs to be integrated to determine the time when $s$ has grown from zero to infinity marking thermal runaway. Therefore,

$$\int_0^\infty \exp(-s)\,ds = \frac{1}{\gamma} \int_{-\infty}^{\tau_c} \exp\left[ -(\gamma - 1) \frac{(\tau - \tau_0)^2}{\tau_c^2} \right] d\tau, \quad (17)$$

and then,

$$1 + \text{erf}\left[ \sqrt{\gamma - 1} \frac{(\tau_i - \tau_0)}{\tau_c} \right] = \frac{2\gamma\sqrt{\gamma - 1}}{\tau_c \sqrt{\pi}}. \quad (18)$$

For TDC ignition, $\tau_i = \tau_0$ and the equation simplifies to $\tau_c = 2\gamma\sqrt{\gamma - 1}/\sqrt{\pi}$ or,

$$t_{i,ref}^h = \frac{\tau_c\sqrt{\pi}}{2\pi g\gamma\sqrt{\gamma - 1}}. \quad (19)$$

The above equation implies that, in order for ignition to occur at TDC, the TDC motored conditions, $T_0$ and $P_0$, should be such that the reference ignition delay at those conditions is equal to the right hand side of equation 19. The superscript $h$ has been used to denote that this ignition criterion for TDC ignition has been derived for a homogeneous charge engine. Note also that when $\tau_c < \sqrt{\gamma - 1}/\sqrt{\pi}$, equation (18) has no solution implying that the reactivity was not high enough to overtake the expansion following TDC and hence ignition does not occur.

4 Stratified Charge Ignition

The analysis of ignition in a stratified charge system is more complicated due to the compression heating effects. The analysis can be simplified using the following assumptions:

(i) For the first point in the system to auto-ignite, which is the mixture at the hot end of the temperature spectrum, the pressure rise is only due to piston motion and hence can be modeled using the same approach as in the previous section.

(ii) For the bulk of the mixture that ignite later, the pressure rise due to heat release from combustion in other parts of the system is much more significant than the effect of piston motion. Hence, their ignition delays can be determined by treating them as a stratified charge igniting in constant volume conditions.

The ignition delay of the hot end of the system can be determined by substituting the expansions for $S$ and $P$, $S = T_{0,\text{max}}(1 + \epsilon s + O(\epsilon^2))$ and $P = 1 + \epsilon p$, into equation (9) and integrating the equation as before. Note that, since pressure is uniform, $P_0 = 1$ and therefore $S_0 = T_0$. This yields the expression:

$$1 + \text{erf}\left[ \sqrt{\frac{1}{\tau_c}} \frac{(\tau_{i,\text{max}} - \tau_0)}{\tau_c} \right] = \frac{2\gamma\sqrt{\gamma - 1}}{\tau_c \sqrt{\pi}} \exp\left[ \frac{1}{\epsilon} \left( \frac{1}{T_{0,\text{max}}} - 1 \right) \right], \quad (20)$$

where the $T_{0,\text{max}}$ has been omitted except in the exponential term, since its value is close to unity. Equation (20), like equation (18), can be used to determine $\tau_c$ and thereby the $t_{i,\text{ref}}$ required to obtain the desired ignition delay $\tau_{i,\text{max}}$ at the hot end of the spectrum.

In the rest of this section, we study the ignition of the bulk mixture that follows the ignition at the hot end. An analytical model for the ignition delay is developed for a given temperature distribution, assuming constant volume conditions. Let $f(T_0)$ be the temperature distribution at TDC of a motored engine. Since all mixing and flow effects are being ignored in this analysis, the ignition of a mixture is a unique function of its $T_0$ and hence all mixtures with equal $T_0$ will ignite at the same instant, irrespective of their spatial location. (Note: since the dependence of ignition delay on temperature is much stronger than composition, the effects of inhomogeneities in composition can be neglected at this point. However, they will influence the extent of heat release and pressure rise, and will be taken into account for those purposes.) Therefore, $\tau_i = \tau_i(T_0)$. This relation can also be used to obtain an inverse mapping $T_{0,i}(\tau)$, such that $T_{0,i}$ is the temperature of the mixture that is igniting at a given instant of time $\tau$.

The first step in obtaining a model for $\tau_i$ is to determine the evolution of pressure in time. At any time, $\tau$, the pressure of the constant volume system under consideration can be determined by evaluating the pressure rise due to heat release from all mixtures that have ignited prior to that instant, namely

$$P(\tau) = 1 + \int_{T_{0,i}}^{\infty} \beta(T_0)\, f(T_0)\, dT_0, \quad (21)$$

where $\beta = QY_{\text{i,}0}/\rho C_p T_0$ is the non-dimensional heating value of combustion. When the composition of the mixture is uniform throughout, $\beta$ is a constant. However, when inhomogeneities in composition are present, $\beta$ can be evaluated as the mass-weighted average heating value of all mixtures at a given $T_0$, thereby accounting for inhomogeneities in composition. Note that differentiating equation (21) gives $dP/dT_{0,i} = -\beta f$.

To determine the ignition delay for a mixture whose initial temperature was $T_0$, we expand its entropy variable $S$ as $S = T_0(1 + \epsilon s + O(\epsilon^2))$ and substitute in equation (9) to obtain:

$$\exp\left[ \frac{-s}{T_0 P_0 s} \right] ds = \frac{1}{\gamma T_0 P_0 s} \exp\left[ -\frac{1}{\epsilon} \left( \frac{1}{T_0 P_0 s} - 1 \right) \right] d\tau. \quad (22)$$
When this mixture ignites at time $\tau_i$, the pressure at that instant is given by equation (21). Since this pressure, $P$, is higher than the initial pressure, it led to compression heating of the mixture to a temperature higher than $T_0$ and then to its ignition. This is seen from the exponential term in the RHS of the above equation. Due to the exponential dependence of the reactivity on the pressure, the reactivity of the mixture will be negligible until the pressure has risen close to

$$P = P(\tau_i) - k\epsilon,$$

where $k$ is an $O(1)$ constant, and then starts increasing. It rapidly grows to reach infinity when the time $\tau = \tau_i$. Therefore, the appropriate limits for integrating equation (22) are $s \to 0$ as $\tau = \tau_i - k\epsilon(dP/d\tau)^{-1}$ and $s \to \infty$ as $\tau = \tau_i$. Using the limits we obtain,

$$\int_{0}^{\tau_i - k\epsilon(dP/d\tau)^{-1}} \frac{1}{\gamma T_0^\alpha} \exp \left[ -\frac{1}{\epsilon} \left( \frac{1}{T_0^\alpha} - 1 \right) \right] d\tau$$

Neglecting the variation in $P$ during the short duration of time $k\epsilon$ and treating it as a constant,

$$\gamma(T_0^\alpha)^2 = \exp \left[ -\frac{1}{\epsilon} \left( \frac{1}{T_0^\alpha} - 1 \right) \right] k\epsilon \left( \frac{dP}{d\tau} \right)^{-1},$$

where

$$\frac{dP}{d\tau} = \left( \frac{dP}{dT_0, i} \cdot \frac{dT_0, i}{d\tau} \right)^{-1} = \frac{1}{\beta f T_0^2 / k} dT_0^{-1}.$$  

Combining equation (23) and (24) we obtain,

$$\frac{dT_0}{dT_0^{-1}} = \frac{\beta f T_0^2 / k}{\gamma(T_0^\alpha)^2} \exp \left[ \frac{1}{\epsilon} \left( \frac{1}{T_0^\alpha} - 1 \right) \right]$$

All the terms in the leading coefficient $\beta f T_0^2 / k$ are of $O(1)$ and are approximately constant when compared to the exponential dependence on $T_0$ and $P$. This unknown constant is chosen here to be unity. Then,

$$\frac{dT_0}{dT_0^{-1}} = \frac{\gamma(T_0^\alpha)^2}{\epsilon} \exp \left[ \frac{1}{\epsilon} \left( \frac{1}{T_0^\alpha} - 1 \right) \right]$$

is an equation for the time at which ignition occurs in different parts of the mixture and needs to be integrated with respect to $T_0$ to obtain an explicit relation. Equation (25) is integrated numerically for a given distribution of $f$.

The analytical model is verified by comparison against numerical results obtained using a multi-zone model. The initial temperature distribution is chosen to be a gaussian function, given by

$$f = \frac{1}{\sigma \sqrt{2\pi}} \exp \left[ -\frac{(T_0 - 1)^2}{2\sigma} \right]$$

where $\sigma$ is the standard deviation of $T_0$ non-dimensionalized by $\bar{T}_0$. Since $\bar{T}_0 = O(1000K)$, $\sigma = 0.04$ would imply a standard deviation of 40K in temperature. The analytical model agrees very well with the computed results, as seen in figure 4 where the choice of parameters was $\epsilon = 0.04$, $\sigma = 0.04$ and $\beta = 1.0$. The composition of the mixture was treated as uniform everywhere. Good agreement was obtained for other choices of these parameters as well, thereby validating the analytical model.

A brief analysis of the ignition delay result shown in figure 4 is given here to aid subsequent discussion. The two dashed lines indicate the ignition delays in a homogeneous constant pressure (CP) and a constant volume (CV) reactor, respectively. The ignition delays in a CV reactor are shorter than a CP reactor by a factor of $\gamma$. When the hot end of the stratified mixture ignites, the conditions are close to constant pressure, which explains the respective ignition delays falling close to each other. However, as the ignition progresses through the bulk of the mixture the pressure starts rising, and the resultant compression heating leads to shorter and shorter ignition delays, as seen from the ignition delay curve deviating from the dashed lines at lower temperatures. Due to the enthalpy gain from the compression heating effect, all the mixture pockets that follow the hottest spot ignite earlier than the equivalent homogeneous mixture at the same initial temperature. For a reference, the ignition delay of a homogeneous charge with same mean temperature is shown as a square symbol in the figure. The results in figure 4 implies that, to obtain a constant TDC ignition, the mean temperature of a stratified charge system has to be lower than that of a homogeneous charge system. This fact is considered in our further analysis in determining the combustion characteristics.

5 Results and Discussion

5.1 Ignition criterion

The main objective of the analysis herein is to determine the mean temperature $\bar{T}_0$ required in order to obtain TDC ignition for a stratified charge, such that most of the heat release
occurs close to TDC and that the heat release profile is centered at TDC. For the gaussian temperature distribution considered, the hot end of the spectrum should ignite at some instant prior to TDC such that 50% of the total heat release is complete at TDC. We define the hot end of the spectrum as the point where the temperature is given by $T_{0 \pm 5\%}$ and the point at 50% of heat release by $T_{0 \pm 50\%}$. Knowing these two temperatures, the ignition criterion for the hot end to be used in equation (20) would be

$$\tau_{i,\text{max}} - \tau_{0} = - (\tau_{i,50\%} - \tau_{i,5\%}),$$

where the ignition delays on the RHS are obtained using the integral of equation (27). Using this criterion, an expression is obtained for the required reference ignition delay, $t_{i,\text{ref}}$, as was done for the homogeneous charge engine. The superscript $\sigma$ is used to denote that this criterion is for a stratified charge with a standard deviation of $\sigma$. Figure 5.1 shows the ratio $t_{i,\text{ref}}^\sigma/t_{i,\text{ref}}^h$ as,

$$\delta = (\exp(-\beta) + \tau_{i,95\%} - \tau_{i,5\%}) \times \frac{t_{i,\text{ref}}^\sigma}{t_{i,\text{ref}}^h}$$

which is shown in figure 5.2 for different values of the standard deviation $\sigma$.

It is seen in figure 5.2 that the duration of burning is sensitive to both the extent of stratification and the load conditions. An important observation is that the exponential decrease in duration of burning as $\beta$ increases is seen to be as valid for the stratified mixtures as for the homogeneous mixtures. Incidentally, an extremely long duration of burning predicted by the present model may, in reality, lead to incomplete combustion, if the effect of downward piston motion is to be accounted for. It can be seen that, in order to maintain the duration of burning within a fixed range, the level of stratification of the charge will have to be varied any time there is a change in the load, $\beta$. A highly stratified charge at low load conditions can lead to incomplete combustion, while a close to homogeneous mixture at high load will lead to knocking.

5.3 Sensitivity of ignition delay

An important issue in HCCI combustion is that the ignition is very sensitive to the temperature of the unburnt mixture.
Figure 4: Sensitivity of ignition delay as a function of the extent of thermal stratification.

Unless the intake charge temperature is closely controlled a misfire or incomplete combustion can result. Therefore, we study the sensitivity of the ignition delay to the mean temperature. Let $S$ denote the sensitivity of the ignition delay to the mean temperature $T_0$. Differentiating equations (19) and (20), the following expression can be obtained for the ratio of sensitivities.

$$\frac{S^\sigma}{S^h} = \exp \left[ (\gamma - 1) \left( \frac{\tau_{i,\text{max}} - \tau_0}{\tau_c^2} \right)^2 \right] \cdot \exp \left[ \frac{1}{\epsilon} \left( \frac{1}{T_{0,\text{max}}} - 1 \right) \right] \left( \frac{dT_{i,\text{ref}}}{dT_0} \right) \left( \frac{dT_{h,\text{ref}}}{dT_0} \right).$$

(31)

Substituting the derivative of equation (4) to the above equation, we obtain at leading order:

$$\frac{S^\sigma}{S^h} = \exp \left[ (\gamma - 1) \left( \frac{\tau_{i,\text{max}} - \tau_0}{\tau_c^2} \right)^2 \right] \cdot \exp \left[ \frac{1}{\epsilon} \left( \frac{1}{T_{0,\text{max}}} - 1 \right) \right] \left( \frac{t_{i,\text{ref}}}{t_{i,\text{ref}}} \right) \left( \frac{t_{h,\text{ref}}}{t_{h,\text{ref}}} \right).$$

(32)

Figure 5.3 shows the ratio of the sensitivity for a stratified mixture to that for a homogeneous mixture. The results show a significant reduction in sensitivity for a stratified mixture compared to a homogeneous mixture, which will lead to a more stable engine operation.

6 Conclusions

Asymptotic analysis was used to obtain an analytical model for the ignition of a stratified charge under HCCI engine conditions. The analytical model is simple and suitable for performing extensive parametric studies of the influence of thermal stratification. It was validated using numerical results obtained from a multi-zone model. Preliminary results obtained using a gaussian function for the initial temperature distribution show that although thermal stratification increases the duration of burning, it continues to decrease exponentially as the load is increased even at highly stratified conditions. The results also show that the sensitivity of ignition delay to the initial temperature is much lower for a stratified mixture than for a homogenous mixture.

Acknowledgements

This work has been sponsored by the Consortium on Homogeneous Charge Compression Ignition Engine Research, directed by the University of Michigan, and funded by Department of Energy under agreement DE-FC04-01AL67611.

References


