Investigation of ignition dynamics in a H2/air mixing layer with an embedded vortex

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Numerical simulations are carried out to study the effect of a vortex on the ignition dynamics of hydrogen/air in a mixing layer. The problem has direct implications on the auto-ignition behavior and stabilization mechanism in turbulent non-premixed flames. This complicated auto-ignition behavior is simplified by isolating a single mixing layer of fuel and air with an embedded vortex and studying the effect of different parameters. Similar problems have been studied in the past using different approximations like infinitely fast and single-step chemistry. While useful insight is obtained, the role of multi-step reaction chemistry is neglected. More recent work utilizing detailed chemical kinetics has been limited in its scope due to computational requirements. These difficulties are overcome in the present study by utilizing a tabulated approach that incorporates detailed reaction chemistry into the fluid dynamic simulations in a computationally efficient manner. Chemistry tabulations are generated utilizing steady-state solutions of the non-premixed flamelet equations. The fluid dynamic simulations are carried out using a lookup table approach to obtain various mixture properties during the course of the calculations. Similar calculations are also performed with detailed chemistry to demonstrate the accuracy of the tabulated approach. Preliminary work has been conducted in a mixing layer with air at 2000 K and H2 at 300 K. The large temperature difference also means that temperature driven diffusion (Soret effect) could play an important role. A considerable reduction in computational time when compared to detailed chemistry has been observed that allows for a wide-ranging parametric study. The parameters explored include vortex strength, characteristic size, center location, and fuel/air temperatures. The effect of these parameters on ignition delay time and location are correlated to the scalar dissipation rate which has been shown to play a key role. Finally, a regime diagram showing the influence of key parameters on delay time and ignition behavior is developed using the simulation results.

1 Introduction

The interaction of chemistry with turbulence is a key area of combustion research being actively pursued using computational methods. The understanding of this process is inherently linked to a wide variety of applications (internal combustion and gas turbine engines, industrial burners, supersonic combustors, etc.) where turbulent combustion drives energy release from liquid/gaseous hydrocarbon fuels. The complexity of this process is obvious given the variety of physical phenomena such as fuel/air mixing, reaction chemistry, ignition, flame propagation, turbulence interaction etc. which often occur simultaneously in complex geometrical configurations and flowfields. The existence of a range of length and time scales makes it increasingly difficult to understand phenomena taking place at the smallest scales. One such process is the auto-ignition behavior believed to be responsible for stabilization of turbulent lifted jet flames.

Turbulent lifted jet flames form a key component in direct-injected SI engines, Diesel engines and commercial boilers. Further it is widely considered to be a building-block in understanding
auto-ignition in turbulent combustion. The configuration which consists primarily of a co-flow of heated air with fuel and a lifted flame base has been explored experimentally by Dec [1], Pickett [2], Cabra [3] and Mastorakos [4]. Numerical simulations have been conducted by researchers using a variety of techniques including RANS, LES and DNS [3], [5], [6] with the inclusion of chemical kinetics using single-step, detailed or tabulated approaches. The results of these various analyses increasingly point to auto-ignition of pockets of fuel-air mixture near the flame base in a turbulent flowfield to be responsible for flame stabilization, simultaneously determining the lift-off height of the flame. The complexity of this configuration however, precludes a more basic understanding of the auto-ignition process itself. At the core of this process, one could imagine a packet of fuel and heated air subjected to turbulent flow structures undergoing an ignition process. The simplest flow structure in this regard would be an isolated vortex. An attempt to understand this basic phenomenon provides the motivation for the current work.

The ignition process taking place in a coflow of heated air and fuel in the presence of a vortex has also been addressed in numerical studies using different approaches to model reaction chemistry. A study conducted by Macareg et al. [7] attempted to study the structure of the ignition process for a case with equal fuel and oxidizer temperatures in a quiescent flowfield using asymptotic theory. This study was later extended to include the effect of shear flow motion between the fuel and air streams [8]. Thevenin and Candel [9] performed a similar calculation with varying air and fuel (H2) temperatures assuming constant density, unity Lewis number and one-step reaction chemistry. Zheng et al [10] conducted a similar calculation with the oxidizer at 2000K and fuel (H2) at 300K incorporating detailed reaction kinetics. The increasingly sophisticated treatment of reaction chemistry has shown finite-rate chemistry to be an important factor governing the ignition process. However, the added computational requirements and complexity has limited the range of parameters that can be studied as experienced by Zheng et al [10].

This work attempts to use tabulated chemistry to conduct studies similar to those by Zheng and Candel, so as to incorporate multi-step reaction chemistry into the fluid dynamic simulation in a computationally efficient manner. This work extends on the study conducted by Zheng et al by investigating the effect of oxidizer temperature on the ignition process by varying it in the same range as studied previously by Candel using one-step chemistry. As part of this effort, it is also desired to obtain a better understanding of tabulated approaches for ignition in a non-premixed environment especially at lower oxidizer temperatures where flamelet solutions are seen to be inherently unstable.

The first section of the paper presents a brief discussion of the physical problem being modeled in this work. The next sections describe the governing equations, the reaction mechanism, tabulation details and the solution approach used to solve the coupled fluid-dynamic combustion problem. The next section describes simulation results following which conclusions are presented and discussed.
Figure 1: Schematic of the configuration investigated computationally in this work.

get insight into the purely diffusion driven ignition process. Next the 2-D problem is solved with a vortex present. The fuel is purely hydrogen whose temperature is maintained at 300K in all the test cases. The hot air consisting of oxygen and nitrogen is subject to different temperatures in the range between 800–2000K.

3 Simulation details

3.1 Governing equations

The governing equations of fluid motion for the simulations performed here are the variable density low-Mach number Navier-Stokes equations. The governing equations for laminar flow are presented as follows:

Mass conservation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0$$ (1)

Momentum conservation

$$\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho uu) = -\nabla p + \nabla \cdot \tau + \rho g$$ (2)

3.2 Initial conditions

The initial conditions consist of a uniform profile for mixture fraction on either side of the mixing layer with a hyperbolic tangent function used to smooth the jumps across the layer. The transition in $Z$ going from pure fuel(1) to pure oxidizer(0) was represented by 10 grid points. The progress variable is set to a very small initial value(1e-10). As will be shown later, this is necessary because the chemical source term for a zero value of the progress variable is identically zero and no ignition can occur. Varying the initial value of the progress variable for values less than 1e-8 was found to produce no significant effect on the ignition delay time or location. Specifying the initial mixture fraction profile and progress variable simultaneously determines the temperature and species mass fraction profiles in the tabulated approach. The data file generated by this step is used to initialize the simulations.
A quiescent mean velocity field is assumed at the initial time. At the same time, for the cases where the effect of a vortex is investigated, a velocity field for the vortex is prescribed using the stream function for an incompressible, inviscid vortex given by [11],

$$\psi = C \exp \left( \frac{-x^2 + y^2}{2R_c^2} \right)$$  \hspace{1cm} (3)

where $R_c$ is the characteristic vortex radius and $C$ is the vortex strength. The velocity field prescribed by the stream function $\psi$ can be written as [10],

$$\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} \frac{\partial \psi}{\partial y} - \frac{\partial \psi}{\partial x} \\ \psi \end{bmatrix} = \frac{C}{R_c^2} \exp \left( \frac{-x^2 + y^2}{2R_c^2} \right) \begin{bmatrix} -y \\ x \end{bmatrix}$$  \hspace{1cm} (4)

The vortex strength, radius and center location are three key parameters that are varied in this study to study their influence on ignition location and timing. Varying the vortex strength essential varies the vortex Reynolds number which can be expressed as,

$$Re = \frac{\Gamma}{2\pi \nu}$$  \hspace{1cm} (5)

where $\Gamma$ represents the vortex circulation.

3.3 Grid and boundary conditions

The 1D simulations are done on a domain 4 cm in length while the 2D simulations are conducted on a domain 4 cm x 4 cm in size. In both cases, a non-uniform grid is used with about half the mesh points concentrated close to the center of the domain. The total number of points in all simulations are 256 in each direction. The size of the domain and distribution of mesh points used imposes an initial value for the scalar dissipation rate ($\chi$) which is described in more detail later. However, it is important to recognize that $\chi$ forms an additional parameter whose effect on ignition dynamics is explored in this work. Finally, non-reflecting boundary conditions are imposed on all four boundaries.

3.4 Chemistry modeling

A reaction mechanism for H2-air combustion consisting of 13 species and 76 reactions is utilized in this work [12].

Two different approaches are used to model the reaction kinetics for the configuration illustrated in Fig. 1, the main difference being the method used to capture finite-rate chemical kinetics. In the first approach, the chemistry is tabulated a priori using solutions to 1D unsteady diffusion flames. The second approach solves the full set of transport equations for each of the reacting species and involves considerably more computational resources as compared to the tabulated approach. The main reason for pursuing these two different approaches is to validate the tabulated approach for ignition calculations. The two approaches are now described in further detail.
3.4.1 Tabulated approach

In this approach, reaction chemistry is modeled using the flame progress variable (FPV) approach as formulated by Knudsen and Pitsch [13]. The FPV approach requires the solution of transport equations for additional scalar variables given by,

Transport of progress variable

\[ \frac{\partial (\rho C)}{\partial t} + \nabla \cdot (\rho u C) = \nabla \cdot (\rho D \nabla C) + \dot{\omega} C \]  

(6)

and transport of mixture fraction

\[ \frac{\partial (\rho Z)}{\partial t} + \nabla \cdot (\rho u Z) = \nabla \cdot (\rho D \nabla Z). \]  

(7)

The progress variable represents the extent of reaction and is estimated as the mass fraction of the major product species, i.e. H\(_2\)O. The mixture fraction is calculated from the mass fractions of fuel and oxygen using,

\[ Z = \frac{\nu Y_F - Y_{O_2}}{\nu Y_{F,1} + Y_{O_2,2}} \]  

(8)

where \(Y_F\) and \(Y_{O_2}\) represent fuel and oxygen mass fractions in the mixture, \(Y_{F,1}\) represents the fuel mass fraction in the fuel stream(1), \(Y_{O_2,2}\) represents the oxygen mass fraction in the air stream(0.232) and \(\nu\) represents the stoichiometric mass ratio(8). The stoichiometric mixture fraction is given by,

\[ Z_{st} = \left[1 + \frac{\nu Y_{F,1}}{Y_{O_2,2}}\right]^{-1} \]  

(9)

and works out to 0.0284. The diffusivity, \(D\) used in equations 6 and 7 is the thermal diffusivity using a constant, unity Lewis number assumption for all species.

Species mass fractions, production rates, mixture transport properties etc., are assumed to depend only on mixture fraction and the reaction progress variable. These properties are tabulated a priori using a chemical kinetic solver - FlameMaster[14]. The tabulation process is described in detail in a following section. The numerical solver utilizes a lookup table procedure to acquire species and mixture properties during the course of the simulation.

3.4.2 Detailed chemistry

In this case, simulations are conducted by solving species transport equations for all the species in the reaction mechanism and an energy equation in addition to the mass and momentum conservation equations. The species transport equations take the form,

\[ \frac{\partial (\rho Y_i)}{\partial t} + \nabla \cdot (\rho u Y_i) = \nabla \cdot (\rho D \nabla Y_i) + \dot{\omega}_i \]  

(10)

where the Soret effect (mass diffusion due to temperature gradients) has been neglected and Fick’s law is assumed with constant, unity Lewis numbers for all species. The energy equation written in
the temperature form is given by,

\[
\frac{\partial (\rho C_p T)}{\partial t} + \nabla \cdot (\rho u C_p T) = \frac{D_p}{Dt} + \nabla \cdot (\lambda \nabla T) - \sum_i \rho C_{p,i} j_i \cdot \nabla T - \sum_i \rho h_i \omega_i \tag{11}
\]

where the Dufour effect (heat diffusion due to species concentration gradients) and radiation heat losses have been neglected and \(j_i\) is the species mass flux.

3.4.3 Chemistry tabulation

The chemistry tabulation forms a vital part of the simulations conducted in this work. The tabulations are generated using solutions for counterflow diffusion flames obtained using FlameMaster. The solutions are generated in the mixture fraction space by solving the steady state version of the flamelet equations given by [15],

\[
\rho \chi \frac{\partial^2 \psi_i}{\partial Z^2} + \omega_i = 0 \tag{12}
\]

where \(\psi_i\) and \(\omega_i\) are the mass fractions and source terms for each reactive scalar. The scalar dissipation rate, \(\chi\), for non-premixed combustion is given by,

\[
\chi = 2 D |\nabla Z|^2. \tag{13}
\]

The Lewis numbers for all species are assumed to be equal to unity and the diffusivity \(D\), in Eqn. 13 is taken to be the thermal diffusivity. For a fixed oxidizer and fuel temperature, a set of solutions are obtained by varying the scalar dissipation rate, \(\chi\), so as to go from a non-burning, pure mixing region (large \(\chi\)) to a burning region (small \(\chi\)) and points in between. Figures 2(a) and 2(b) show the results of a solution obtained for an oxidizer temperature of 2000K, a fuel temperature of 300K and three different initial values of \(\chi\). Temperature is plotted in Fig. 2(a) while the progress variable is plotted in Fig. 2(b). As seen in the figures, for a high value of \(\chi\), no ignition occurs and the temperature varies smoothly going from hot air (\(Z=0\)) to fuel (\(Z=1\)). On
the other hand, the mixture ignites for higher values of \( \chi \) and a corresponding increase is observed in temperature and progress variable. Figures 3(a) and 3(b) show the entire set of solutions obtained for different oxidizer temperatures ranging from 800–2000K and fuel temperature of 300K. Maximum temperature is plotted as a function of \( \chi \) in Fig. 3(a) while the progress variable, \( C \), is plotted as a function of \( \chi \) in Fig. 3(b). Both figures present results for the stoichiometric value of the mixture fraction, \( Z_{st} = 0.0284 \). As seen in Fig. 3(a), for a high oxidizer temperature (eg. 2000K), no unstable solutions between the burning and non-burning branches are found. However, at lower oxidizer temperatures (eg. 800K), an S-shaped curve with unstable points between the burning and non-burning solutions are obtained.

The next step is to generate a unique chemistry tabulation utilizing the steady flamelet solutions shown in Figures 3(a) and 3(b). Since a tabulation generated using \( \chi \) would be non-unique on account of the S-shaped curves, the progress variable in addition to the mixture fraction are chosen as the independent co-ordinates for the chemistry tabulation. Figure 4 shows a result from the
chemistry tabulation for an oxidizer temperature of 1200K where contours of the source term are plotted with the x-coordinate representing the progress variable and y-coordinate representing the mixture fraction. As seen in the figure, the source term is considerably larger in the vicinity of the stoichiometric mixture fraction ($Z_{st} = 0.0284$). To capture this region adequately, a considerable number of points in the table are clustered around $Z_{st}$. Figure 5 shows the source term as a function of the progress variable for different oxidizer temperatures plotted on a log-log scale.

Figure 5: Source term as a function of the progress variable for different oxidizer temperatures plotted on a log-log scale.

function of the progress variable for different oxidizer temperatures at the stoichiometric mixture fraction. The points represent the flamelet solutions obtained from FlameMaster and the lines represent the solutions as represented in the tabulation. Good agreement is obtained between the two which is necessary for accurate representation of finite-rate chemistry. The chemistry tabulation utilizes 200 points in each direction ($C$ and $Z$). Of the 200 points in the progress variable direction, 175 are estimated on a log-scale to accurately capture the evolution of the progress variable from a very small value of about 1e-16 to about 0.1. This ensures a smooth and continuous representation of the ignition process.

4 Results

A set of test cases in a 1D configuration were first investigated to understand the purely diffusion driven ignition process. Additionally the ignition delay times obtained from the 1D calculations serve as baseline values to compare with those obtained in the presence of a vortex. Next, 2D simulations are run with a vortex present, for different initial values of $\chi$ and oxidizer temperature, and the effect of vortex size, strength, and center location on ignition delay time are investigated.

4.1 1D simulations without a vortex

Figure 6 shows a series of plots illustrating the ignition process from a 1D simulation. The oxidizer temperature is 2000K, fuel temperature is 300K, mixture fraction is initialized as described in Section 3.2 and the initial velocity is zero in the domain. The results are obtained using the tabulated
approach described in Section 3.4.1. Figure 6(a) shows the maximum value of the source term in the domain plotted over time. The ignition delay time is identified as 9.3 $\mu$s seconds. Ignition delay in all the test cases presented in this work is determined as the time taken to reach a value for the progress variable equal to 0.05, which roughly estimates to a 20% increase in the progress variable. Diffusion of heat and species decreases the gradient in mixture fraction curve resulting in a corresponding decrease in the value of $\chi$. This can be seen in Fig. 6(b) where the maximum value of $\chi$ in the domain is plotted as a function of time. A better understanding of the local ignition process can be obtained by identifying the most reactive mixture fraction ($Z_{MR}$). $Z_{MR}$ is defined as the value of $Z$ corresponding to the maximum heat release when ignition occurs. For this case $Z_{MR}$ is identified as 0.04 which is slightly higher than $Z_{st}$ which is 0.0284. Figure 6(c) shows the local $\chi$ as a function of $Z$ over time. As seen in the figure, at the point when ignition occurs, the value of $\chi$ corresponding to $Z_{MR}$ is about 400. This gives the value for the most reactive $\chi$ or $\chi_{MR}$. Thus, in the 1D case, ignition can be predicted to occur at the value of $Z = Z_{MR}$ when the local value of $\chi \leq \chi_{MR}$. This result can be further visualized in Fig. 6(c), where the progress variable is plotted as a function of $\chi$ for $Z = Z_{MR}$. As diffusion drives the value of $\chi$ below $\chi_{MR}$, it is possible to move from a non-burning condition to a burning condition leading to ignition of the mixture. The values of $Z_{MR}$ and $\chi_{MR}$ vary with oxidizer temperature. Table 1 summarizes $Z_{MR}$ and $\chi_{MR}$ for different oxidizer temperatures investigated in this study.

4.1.1 Effect of air temperature

Figure 7 shows a plot of ignition delay time calculated for a 1D configuration in a quiescent velocity field as a function of air temperature. The grid spacing is maintained the same for all cases. Inspite of this, there are slight differences in the initial $\chi$ distribution due to differences in the gas
Table 1: $Z_{MR}$ and $\chi_{MR}$ for different oxidizer temperatures investigated in this study.

<table>
<thead>
<tr>
<th>Oxidizer temperature [K]</th>
<th>$Z_{MR}$</th>
<th>$\chi_{MR}$ [1/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0.010</td>
<td>0.5</td>
</tr>
<tr>
<td>1200</td>
<td>0.016</td>
<td>10</td>
</tr>
<tr>
<td>1400</td>
<td>0.022</td>
<td>36</td>
</tr>
<tr>
<td>1600</td>
<td>0.027</td>
<td>102</td>
</tr>
<tr>
<td>1800</td>
<td>0.027</td>
<td>148</td>
</tr>
<tr>
<td>2000</td>
<td>0.040</td>
<td>400</td>
</tr>
</tbody>
</table>

Figure 7: 1D calculations showing ignition delay as a function of oxidizer temperature. Note that the y-axis is on a log scale.

diffusivity, $D$. In each case, the $\chi$ distribution in the domain decreases due to diffusion till at the point corresponding to $Z_{MR}$, the value of $\chi$ goes below $\chi_{MR}$ resulting in ignition. The effect of air temperature can be clearly seen in the figure. There is a rapid increase in ignition delay time with decrease in air temperature. No ignition is seen to occur for an air temperature of 900K and below. Figure 7 also shows similar results obtained from a detailed chemistry calculation as described in Section 3.4.2. The two data sets show good agreement at high temperatures but deviate at lower temperatures below 1200K. Although the validation is not perfect, the trends are correctly predicted, enabling the tabulated approach to be used to investigate ignition dynamics for the 2D test cases in the presence of a vortex.

4.1.2 Heat release rate

Some interesting aspects of the ignition process leading to the development of a flame can be investigated by observing the heat release rate in the 1D domain. The heat release rate is analogous to the progress variable source term ($\dot{\omega}$) which is plotted in Fig. 8. Figure 8(a) shows a plot of source term plotted as a function of the length of the domain at different time intervals during the course of the simulation where the air temperature is set at 2000K. Figure 8(b) shows a similar plot for an air temperature of 1000K. As seen in Fig. 8(a), a single peak in the source term appears at the point
of ignition (9.3 µs) at the location in the domain corresponding to \(Z_{MR}\) and \(\chi_{MR}\) as described in the analysis in the previous section. This peak grows to a considerably larger value corresponding to the peak heat release rate (10 µs). Further on in time, twin peaks appear in the source term of which one propagates to the right (fuel rich side) and establishes a diffusion flame front. The peak to the left which corresponds to a premixed-type ignition travels some distance and then extinguishes. This behavior is more prominent in Fig. 8(b), where the lower air temperature which requires more time to ignite allows for a greater amount of premixing. Similar results are seen in the theoretical analysis by Linan [16] and numerical simulations by Candel [9] and Law [10].

4.2 2D simulations with an imposed vortex

The effect of a vortex on ignition dynamics is now studied using 2D simulations conducted using tabulated chemistry. The sections below report the effects of vortex strength, size and center location on ignition delay.

4.2.1 Effect of vortex strength

The effect of vortex strength is studied by varying the parameter \(C\) in Eqn. 4 over a range 0.005–0.5. This corresponds to a vortex Reynolds number ranging from A–B. Figures 9(a) and 9(b) show the effect of vortex strength on ignition delay time for two different air temperatures (1000K and 1200K) and two different scalar dissipation rates. The ignition delay in each case is normalized by the value obtained from the 1D analysis presented previously. In both figures, the ignition delay time is seen to drop slightly with increasing vortex strength before attaining an almost constant value. The case with \(\chi = 4900\) with an air temperature of 1200K however seems to be an exception where increasing vortex strength does not appear to affect ignition delay. The vortex radius is held constant while increasing the vortex size resulting in an increasingly stronger velocity field.
4.2.2 Effect of vortex radius

The effect of vortex strength is studied by varying the parameter $R_c$ in Eqn. 4 over a range 0.1–4mm. This range is within typical integral length scales of 2–3mm observed in turbulent ignition experiments by Blough and Law [17]. Effects similar to those for vortex strength are seen in Figures 9(c) and 9(d). An initial slight decrease in ignition delay is seen with increasing vortex size which then attains a nearly constant value. The vortex strength is held constant while increasing the size of the vortex resulting in an progressively weaker velocity field.

Figure 9: Effect of varying vortex parameters on ignition delay time.
4.2.3 Effect of vortex center location

The effect of vortex center location with respect to the center of the domain is studied by moving the x co-ordinate of the center of the vortex progressively to the left and right of the domain. Figures 9(e) and 9(f) show the effect on ignition delay with the x axis showing the displacement distance normalized by the vortex radius. As the vortex is moved to the left or the right of the domain center, a ‘W’-shaped behavior is observed in the normalized ignition delay time. The ignition delay decreases on either side to a minimum value before increasing back to the reach close to the 1D ignition delay time. The center of this ‘W’-shaped profile is not aligned with zero displacement of the vortex as can be seen in the figures 9(e) and 9(f).

5 Discussion

The effect of a vortex on ignition delay time and location is visualized by plotting contour plots of various parameters at the point of ignition as shown in Fig. 10. This case corresponds to an air temperature of 2000K, fuel temperature of 300K, vortex strength of 0.2 and radius of 0.5mm. In figures 10(c) and 10(d), iso-contours of the mixture fraction are overlaid on the contour plots. The orange line in all four plots corresponds to an iso-contour of the most reactive mixture fraction ($Z_{MR}$) which for this case corresponds to a value of 0.04. The red dots in figures 10(b), 10(c) and 10(d) correspond to the point of ignition while the yellow dots represent the location with the lowest $\chi$ on the iso-contour of $Z_{MR}$.

Figure 10: Contour plots of various quantities at the point of ignition for an oxidizer temperature of 2000K, vortex strength of 0.2 and vortex radius of 0.5 mm.
As seen in Fig. 10(a), the presence of the vortex has led to considerable mixing of fuel and air in the core of the vortex. The distortion of the mixture fraction field which in the 1D case was purely by diffusion, is now aided by convection resulting in a more rapid decrease in the scalar dissipation rate which is shown in Fig. 10(b). As identified by the analysis in section 4.1, ignition takes place at a point where $Z = Z_{MR}$ when $\chi \leq \chi_{MR}$. Thus ignition would be expected to take place at the location illustrated by the yellow dot on the iso-contour of $Z_{MR}$ in Fig. 10(b). However, it is seen to take place at the location corresponding to the red dot on the iso-contour of $Z_{MR}$. This process can be seen more clearly in Fig. 10(c) where contours of the progress variable are plotted. Accumulation of the progress variable is seen around the iso-contour of $Z = Z_{MR}$ just outside the mixing region generated by the vortex. The reason for this can be attributed to the velocity field shown in Fig. 10(d). The convection dominated field prevents the accumulation of reactive species delaying ignition at the point of lowest $\chi$. At the same time, the velocity field stretches the iso-contours of $Z$ just outside the convection dominated field, locally reducing the value of $\chi$ and allowing sufficient accumulation of reactive species leading to ignition at that location.

![Figure 11: Contour plot of velocity along with iso-contours of mixture fraction for different vortex strengths at the point of ignition whose location is indicated by the red dot. Velocity is in m/s.](image)

The role of vortex strength in affecting the ignition delay time as shown in figures 9(a) and 9(b) is now explained using contour plots shown in Figure 11. The figure shows contour plots of velocity at the point of ignition corresponding to four different vortex strengths overlaid with iso-contours of mixture fraction. As seen in figures 11(a) and 11(b), increasing the strength of the vortex results in a larger and more rapid stretching of the iso-contours of mixture fraction resulting in a decrease in ignition delay time. However, once a critical vortex strength is reached as seen in Fig. 11(d), the velocity field loses all structure due to the large induced velocities. Any further increase in vortex strength results in a rapid breakup of the mixture fraction distribution preventing any further decrease in ignition delay by stretching the iso-contours of $Z$ as seen in figures 11(a), 11(b) and 11(c).
The role of vortex size in affecting the ignition delay time as shown in figures 9(c) and 9(d) is now explained using contour plots shown in Figure 12. The figure shows contour plots of velocity at the point of ignition corresponding to four different vortex sizes overlaid with iso-contours of mixture fraction. When the vortex is very small (Fig. 12(a)), smaller than the thickness of the layer indicated by the iso-contours of $Z$, it takes more time for the velocity field to adequately stretch the iso-contours of $Z$, leading to a decrease in $\chi$ and hence cause ignition. As the size of the vortex increases (Fig. 12(b)), it stretches the iso-contours of $Z$ faster leading to an initial decrease in ignition delay time. However, as the vortex size is increased (Fig. 12(c) and 12(d)) holding the vortex strength constant, the velocity field decreases in magnitude resulting in a slower stretching of the iso-contours of $Z$ leading to a progressive increase in the ignition delay time.

Figure 13 shows contour plots for velocity overlaid with iso-contours of mixture fraction corresponding to different cases presented in Fig. 9(e) earlier. The ‘W’-shaped behavior seen in ignition delay time can be explained on the basis of the plots in Fig. 13. The ‘W’-shaped behavior is centered around the case shown in Fig. 13(a). As the vortex is moved progressively towards the left (Fig. 13(b), Fig. 13(c)), ignition delay decreases due to the effect of the vortex in stretching the iso-contours of $Z$. However, once this reaches a critical value, further displacement of the vortex towards the left (Fig. 13(d), Fig. 13(e)) results in reduced effect of the vortex in enhancing ignition delay. Eventually, the vortex is far enough away that it has no influence on the ignition delay time (Fig. 13(f)) and the 1D value is recovered.
δx = 2 * Rc

δx = 1 * Rc

δx = 0 * Rc

δx = -2 * Rc

δx = -4 * Rc

δx = -6 * Rc

Figure 13: Contour plot of velocity along with iso-contours of mixture fraction for different vortex displacements from the domain center at the point of ignition whose location is indicated by the red dot.

6 Concluding Remarks

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