Numerical Investigation of the Effect of Ignition Area on the Subsequent Flame Propagation Behavior*

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Abstract
In this paper, the effect of ignition area on the propagation of a laminar premixed flame is investigated numerically in a two-dimensional channel. A single-step irreversible overall exothermic chemical reaction is applied to model combustion chemistry. The time-dependent system of governing equations for reacting flows is discretized using the finite volume method (FVM) on the hexahedral structure grid cells. The discretized system of equations is solved by adopting Front Flow Red, a multi-scale and -physics computational fluid dynamics (CFD) solver. The computed results show that the flame oscillates during the propagation owing to the strong roll-up of the vortices generated by the strong shear layer originating from the sudden high gas expansion flow at the large ignition area. The instantaneous acceleration of the vortices increases the flame surface area which gives rise to higher propagation speed; consequently, combustion time is shortened. These results suggest that the rapid increase in flame surface, caused by the large ignition area induced strong vortices, could be one of the potential methods in improving combustion efficiency by reducing the burning time in the internal combustion devices.

Key words: Ignition Area, Oscillation, Vortex, Multi-Scale and -Physics

1. Introduction
The ignition process and its accompanying phenomenon in a combustion tube/channel are the subject of fundamental combustion research due to the importance of this process in developing energy conversion devices such as internal combustion engine. The successful initiation of flame is a pre-requisite to maintain the combustion with low emission and high efficiency in the practical devices. The combustible gas can be ignited successfully with the addition of a local ignition energy sources such as heat, chemically active molecules or radicals and an electric spark into the chambe r of premixed gas [1]-[3] provided that the minimum ignition energy (MIE) [4] requirement is satisfied. Many combustion scientists/engineers have paid their attention to the ignition process as it affects the vital issues in combustion processes including engine performance as well as the emission of pollutants. In this regard, the non-conventional ignition technique such as laser-induced ignition [5]-[9] is widely used due to its huge advantages over conventional ignition systems for the reliable and stable operation of combustion devices. It is observed in the above studies [5]-[9] that the initiation of flame in many points through the mixture can be
done almost simultaneously by using laser-induced ignition technique in the multiple locations inside the combustion chamber. Besides, it is found that the total burning time is reduced significantly with the adoption of multi-point laser-induced ignition technique which enhances the combustion efficiency as well.

The successful ignition of a combustible mixture, either by multi-point laser ignition or other conventional ignition techniques, not only initiates the combustion event but also influences the subsequent combustion process [9], and the multi-point laser-induced ignition produces spatially extensive ignition [10]. In most of the researches on ignition process, utilize conventional ignition techniques such as electric spark ignition, it is examined whether the supplied MIE intensity is capable of achieving successful ignition event to initiate the self-sustained propagating flame or not. But once the laser or radical induced ignition technique is applied, ignitable area becomes one of the key parameters in addition to their MIE. Motivated by these issues, it is intended to examine the influence of spatial dimension of ignition zone on the propagation character of a flame. In this paper, we have investigated the effect of ignition area on the subsequent flame propagation behavior numerically in a two-dimensional channel under zero-gravity environment where no buoyancy-driven influence is expected.

2. Mathematical formulations for reacting flows

2.1 Governing equations

In this study, we have performed the unsteady numerical simulation of the two-dimensional governing equations for chemically reacting flows, which includes a system of transport equations that describes the conservation of mass, momentum, enthalpy, and chemical species as well as the equation of state. By neglecting the bulk viscosity, Soret and Dufour effects, pressure gradient diffusion, gravity and radiation effects, the two-dimensional \((i,j = 1, 2)\) system of governing equations for combusting flows under low Mach number approximation can be written as follows according to Day and Bell [11]:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0
\]

\[
\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \rho \left[ \frac{u_i}{x_j} + \frac{u_j}{x_j} - \frac{2}{3} \frac{\partial u_i}{\partial x_j} \right] \right)
\]

\[
\frac{\partial (\rho Y_k)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j Y_k) = \frac{\partial}{\partial x_j} \left( \rho D_k \frac{\partial Y_k}{\partial x_j} \right) + \omega_k, \quad (k = 1, ..., N)
\]

\[
\frac{\partial (\rho h)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j h) = \frac{\partial}{\partial x_j} \left( \lambda \frac{\partial h}{C_p \partial x_j} \right) + \frac{\partial}{\partial x_j} \left( \frac{1}{M_k} \sum_{k=1}^{N} \left( \frac{1}{L_{ek}} - 1 \right) \frac{h_k}{C_{pk}} \frac{\partial Y_k}{\partial x_j} \right)
\]

\[
p_{eq} = \rho RT \sum_{k=1}^{N} \frac{Y_k}{M_k}
\]

where \(\rho\) is density, \(u_i\) is velocity in the \(x_i\) direction, \(p\) is dynamic pressure, \(Y_k\) is the mass fraction of species \(k\), \(h\) is the mass-weighted enthalpy of the gas mixture, \(\omega_k\) is the mass of the species produced per unit volume and unit time for species \(k\), \(\delta_{ij}\) is the Kronecker delta, \(\mu\) is the dynamic viscosity, \(\lambda\) and \(C_p\) are the thermal conductivity and specific heat of the gas.
mixture, respectively, $D_k$ and $Le_k$ are the diffusion coefficient and Lewis number of species $k$, respectively, $M_k$ is the molecular weight of species $k$, $N_k$ is the number of chemical species, $T$ is the temperature, and $R$ is the universal gas constant. In the equation of state (Eq.(5)), we assume that the mixture gas behaves as an ideal gas and constant thermodynamic pressure $p_0$ is treated as the total pressure according to the low Mach number approximation.

2.2 Combustion reaction model

The premixed gas for the present investigation is a mixture of $C_2H_4$, $O_2$, and an inert gas consisting of $CO_2$ and $N_2$. For simplicity, a single-step irreversible chemical reaction between ethylene and oxygen ($C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O$) is chosen to investigate the influence of ignition area on the subsequent propagation of a laminar premixed flame. The reaction rate of a single-step reaction is estimated using an Arrhenius-type of formulation and is given by

$$\omega = AT^n \exp(-E/RT)\left[C_2H_4\right]^a\left[O_2\right]^b$$  \hspace{1cm} (6)

where the pre-exponential factor, $A$, activation energy, $E$, and exponents $n$, $a$, and $b$ are referred by Westbrook and Dryer [12]. The chemical source term in Eq. (3) is obtained as $\omega_k = \nu_k M_k \omega$ following Peters [13], where $\nu_k$ is the stoichiometric coefficient of species $k$ in a chemical reaction.

3. Numerical simulation

3.1 Calculation domain

The calculation domain for the present study is considered to be a two-dimensional channel, as shown in Fig. 1. The spatial dimensions of this calculation domain and ethylene ($C_2H_4$) are chosen as a fuel on the basis of the three-dimensional experimental investigation [14]. The three-dimensional reacting flow simulation in a tube of experiment [14] with fine grid resolution involving the chemical reaction model requires massive computing resources in terms of CPU cost and time. In order to reduce the massive calculation load to the affordable range of computing resources, we chose to use a 2D analysis for the present investigation. In Fig. 1, $AB = LK = 150$ mm, $AL = 50$ mm, $BC = JK = 10$ mm, $CJ = 30$ mm, $CD = JI = 14.5$ mm, $DE = HI = 11.5$ mm, $EF = HG = 36.5$ mm, and $HE = GF = 7$ mm. It should be noted here that we have treated ‘GF’ as the only open end of the channel.

The structured computational grid system is generated by decomposing the calculation domain (Fig. 1) into a collection of hexahedral cells with the help of the commercial grid generation software: gridgen [15]. It is composed of 819050 hexahedral cells, the total number of grid points is equal to 1643122, and the size of each grid is 0.1 mm in both $x$- and $y$-directions.
3.2 Numerical conditions and their implementations

The entire calculation domain (Fig. 1) is filled up initially with a working premixed gas involving the species \( \text{C}_2\text{H}_4, \text{O}_2, \text{CO}_2, \text{and} \text{N}_2 \) with 9%, 19%, 48.2%, and 23.8% by volume, respectively, a standard pressure of 0.1MPa, and a temperature of 300 K.

Non-slip conditions for velocity and zero flux for scalars such as temperature and mass fraction are used at the wall boundary. The Neumann condition is applied on the outlet boundary. The premixed gas is ignited at a constant temperature of 1400 K in the center of the domain based on the XY cross-section located 10 mm away from point ‘B’ in the direction of point ‘A’ (Fig. 1) along the horizontal axis.

The governing equations for reacting flows are discretized by using the finite volume method (FVM) on the structured grid cells. The discretized equations are solved with the help of Front Flow Red [16], a parallel multi-scale and -physics computational fluid dynamics (CFD) solver based on the SMAC/SIMPLE algorithm with low Mach number approximation. Note that the present numerical simulation is carried out without using any turbulent flow model. The convective terms as well as temporal terms for all transport equations are discretized by using first order upwind scheme and Euler implicit method, respectively. In addition, a 2\textsuperscript{nd}-order central difference scheme is applied for all other spatial derivatives, except convective derivatives, in all equations for all cases, and a constant time increment of \( 10^{-6} \text{ sec} \) is used in all cases for the time integration of all equations. The influence of the numerical schemes on the results is examined [17] by executing the simulation with higher order schemes for both space and time. The transport coefficients and thermo-chemical properties are estimated by using the approaches described in Smooke [18] and Gardiner [19], respectively.

The present simulation is accomplished with the adoption of the super computing resources of Hokkaido University. This computing facility is equipped with the super computer (Hitachi SR11000/K1) of 5TB memory which consists of 40 high performance nodes, and each node has 16 CPUs. The overall peak performance of this super computer is 5.4TFLOPS which enables the users to perform large-scale and high-precision numerical analysis in their field of interests. Sixty four CPUs are assigned in running the calculation for the ignition area of 9 mm\(^2\) and one-hour execution of these CPUs simulates the physical time of about 0.5 ms of the targeted phenomenon.

4. Results and discussion

The effect of ignition area on the propagation of a premixed laminar flame in a two-dimensional one-sided open channel has been obtained with the prescribed numerical model. The computed results, obtained by using the numerical schemes and the calculation conditions described in the preceding sections, are displayed graphically in Figs. 2 to 9.

The instantaneous distribution of temperature for the ignition area of 4 mm\(^2\) at the different times is depicted in Fig. 2. It is observed in Fig. 2 that the flame front changes its shapes rapidly with the variation of time; of course it is obvious event in flame dynamics. However, at the early stage, a weak pair vortex is seen in Fig. 2 which is generated by the shear layer originating from the sudden gas expansion at the ignition zone. The apparent propagation speed is not too high in both radial and axial directions in the channel. With the progress of time, the shapes of the flame displayed in Fig. 2 are turned into the shapes of flame exhibited in Fig. 3. It is clear in Fig. 3, when the unburnt gas behind the flame front is
Fig. 2  Instantaneous temperature [K] distribution at different physical times with ignition area of 4 mm².

Fig. 3  Instantaneous temperature [K] distribution at different physical times with ignition area of 4 mm².
burnt out then the shape of flame front is converged to a constant shape, for instance, at time of 0.1 sec. It is observed that this converged constant shape of flame is also maintained in the later time of 0.15 sec which means that the sudden gas expansion effect driven by the ignition zone is almost diminished.

The instantaneous distribution of vorticity for the ignition area of 4 mm$^2$ at the different times is shown in Fig. 4. It is clear in Fig. 4 that the vortex structures are strong at the early stage of time 0.001 sec. But these vortices are attenuated rapidly with the advancement of time as the magnitude of gas expansion driven by the ignition area of 4 mm$^2$ is very low. This tendency suggests that the lower ignition area of 4 mm$^2$ would be a suitable condition for the investigation of weak oscillation process such as the laser induced flame oscillation [14].

The instantaneous temperature distribution for the ignition area of 25 mm$^2$ at different physical times is displayed in Fig. 5. It is clear in Fig. 5 that the shapes of the flame front are completely different from the corresponding shapes as showed in Fig. 2. This difference in the shapes of the flame front is the consequence of higher ignition area. In addition, it is
seen in Fig. 5 that the flame oscillates during the propagation due to the acceleration of vortices generated through the high-level gas expansion driven by the higher ignition area.

![Image]

Fig. 5  Instantaneous temperature [K] distribution at different physical times with ignition area of 25 mm².

The sudden gas expansion flow is caused by ignition generates a strong outward flow towards the open end of the channel which collides with the wall ‘DE’ and ‘HI’, and originates strong shear layer at the zones around the corners of ‘I’ and ‘D’ in Fig. 1. Consequently, vortices are formed near at these corners. The generation of vortices in immediate vicinity at these corners enhances the evolution of counter vortices at the ignition area due to maintaining the conservation of vorticity into the domain. Once the vortices are generated from ignition, they are convected through the premixed gas towards the closed end of the channel by their self velocity. The rotational motion of these vortices pushes flame tip forward towards the closed end of the channel which gives rise to a higher apparent propagation speed. It is also observed that the counter-rotating large vortex pair, located behind the flame tip, tries to entrain the gas in between their center axis owing to the strong rotary motion. But at the time of entrainment, the gas with slight lower temperature prevails just behind the leading edge of the large vortex pair. At this location,
these gases impinge on the gas of a higher temperature which is carried by the rotational motion of the large vortex pair from very close vicinity of the flame zone. This impingement causes a little reduction in temperature locally, generates a stagnation point on the center axis between the large vortices at their leading edge, and divides the flow of burnt gas into two directions at the stagnation point. Locally, some fraction of burnt gas is blown out towards the outlet (GF in Fig. 1) of the channel, and some fraction goes towards the flame tip along the center line between the large vortices. The consequence of this periodical process is the oscillation of flame during its propagation in the channel.

The instantaneous distribution of vorticity for the ignition area of 25 mm$^2$ at the different times is shown in Fig. 6. The structures of vortices are very much clear and strong in nature which differ from the vortices as depicted in Fig. 4 for the lower ignition area of 4 mm$^2$. It is also clear in Fig. 6 that the large-dominating vortex pair as well as the small pairs of vortices is distributed symmetrically with respect to the center line of the channel. The main periodical thrust, for exhibiting oscillatory behaviors, comes from the strong vorticity of the dominating counter-rotating large vortex pair to move the flame front.
forward towards the closed end of the channel. Further inspection of Fig. 6 reveals that the strong rotational motion of the counter-rotating large vortex pair generates a small pair of vortices behind the leading edge of the large vortices by the radial deformation of the flame surface. These small pairs of vortices travel towards the upstream of the channel and finally blow out at the open end (GF in Fig. 1) of the channel.

The distribution of maximum vorticity at the center of the large vortex is displayed in Fig. 7 for different ignition area against time. In Fig. 7(a), it is observed that the vorticity at the early stage increases with increasing ignition area. This increment in vorticity, at early stage for the higher ignition areas, strongly affects the subsequent flame propagation character (e.g. Fig. 5). In addition, it is seen in Fig. 7(a) that when the ignition area is increased from 4 to 9 mm\(^2\), the vorticity at early stage is increased around 15% and when it is increased further from 9 to 25 mm\(^2\), vorticity is increased nearly 50% at the same stage of time. Furthermore, a significant dissipation in vorticity is found at time of 10 ms for the lower ignition area of 4 mm\(^2\) which facilitates the flame to be propagated freely by keeping their shapes as in Fig. 3. But for the larger ignition area of 25 mm\(^2\), remaining vorticity after dissipation at 10 ms is around 12 times larger than that of the vorticity remained for the lower ignition area of 4 mm\(^2\) at the same time. This higher vorticity maintains the

Fig. 7(a) The distribution of maximum non-dimensional vorticity (\(\omega/\omega_{25\text{mm}^2,2\text{ms}}\)) versus time for different ignition area.

![Graph](image)

Fig. 7(b) The distribution of maximum normalized vorticity (\(\omega/\omega_{25\text{mm}^2,2\text{ms}}\)) versus time for different ignition area.
oscillatory behaviors (e.g. Fig. 5) even after 10 ms and accelerates the propagation speed as well.

It is clear in Fig. 7(b) that the vorticity is decaying faster for the ignition area of 4 mm$^2$ compared to the ignition areas of 9 and 25 mm$^2$. It means that the vortices generated from the ignition area of 4 mm$^2$ are weaker than that of the vortices developed from the ignition areas of 9 and 25 mm$^2$. In addition, it is observed in Fig. 7(b) that the decaying tendency of vorticity is almost similar for the ignition areas of 9 and 25 mm$^2$ while for the ignition area of 4 mm$^2$, it is quite different. Consequently, the mode of flame propagation is found as smooth and stable for the lower ignition area (e.g. Fig. 3).

![Diagram](image)

**Fig. 8** Instantaneous flame front location versus time along the center line ($y = 25$ mm) of the channel for different ignition area.

The instantaneous flame front location against time along the center line, $y = 25$ mm, of the combustion channel is exhibited in Fig. 8 for three different sizes of ignition area. It is found in Fig. 8 that the large ignition area generated a flame whose propagation is very fast compared to the flames originating from the small ignition areas of 4 and 9 mm$^2$. Obviously, the shapes of the flame for these three cases are totally different from one another. This higher propagation speed is the result of the higher flame surface area generated by the movement of strong vortices evolved from the larger ignition areas. Furthermore, it is observed that the propagation speed is always faster at the early stage of

![Diagram](image)

**Fig. 9** Correlation between flame surface area and magnitude of central blowing velocity of burnt gases at the open end (GF, Fig. 1) of the channel for different ignition area.
time for all cases (sizes of ignition area) compared to the later stage due to the strong effect of the vortices evolved from expansion flow at the ignition areas. As time increases, vorticity decays (e.g. Fig. 7) for all cases and consequently, the lines followed by the movement of flame front in Fig. 8 are deviated slightly from its initial directions towards horizontal axis.

Figure 9 represents the correlation between the flame surface area, calculated by field-view [20] on the basis of the temperature iso-surface, and magnitude of central blowing velocity of burnt gases at the open end for different sizes of ignition area. It is clear in Fig. 9 that the surface area increases linearly with the increasing values of the blowing velocity except a few apparent deviations in the values of flame surface area for the ignition areas of 4 and 25 mm², which are due to the existence of errors in tracing the aforementioned iso-surface during calculation. The increment in flame surface area is the consequence of the interaction between flame and strong vortices with high intensity induced by the larger ignition areas. The large flame surface area always enhances propagation speed which is demonstrated in the preceding sections.

5. Conclusions

In this study, we have investigated the effect of the ignition area on the propagation of a premixed flame in a two-dimensional one-sided open channel using low Mach number approximation under zero gravity environment. The following conclusions can be derived from the present investigation.

- The larger ignition area strongly dominates the shapes of flames, the generation of vortices, and the oscillatory behavior of the flame front during its propagation in the channel.

- The flame propagation speed becomes very high due to the enlargement of flame surface area caused by the larger ignition area induced strong vortices, and consequently, flame propagation time in the prescribed channel is reduced.

The results of the present investigation suggest that the higher ignition area aided strong vortex-driven flame oscillation process should be taken into account when analysing other types of weak oscillation such as laser-induced flame oscillation [14]. Moreover, in most of the engineering and practical applications, the combustion is accompanied by a strong turbulent environment where the interactions between flame and vortices are inevitable. At an elementary level, this inevitable interaction process is very much similar to the interaction of a laminar flame with an isolated vortex or a pair of vortex. In this regard, the results of our present study of higher ignition area induced vortex-aided flame oscillation may have significant utility in determining the ideal operating conditions for improving combustion efficiency by reducing the burning time through the rapid expansion of flame surface in the internal combustion devices.

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