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NUMERICAL STUDY OF OBLIQUE DETONATION WAVE CONTROL FOR FUEL BLENDS

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ABSTRACT

The current study is motivated to develop control strategies for oblique detonation wave formation on a finite length wedge in a premixed methane-air mixture. The effectiveness of hydrogen blends (0 - 100%) to methane-air premixed mixture (at 300 K) on Chapmann Jouguet (CJ) detonation and oblique detonation wave formation are analyzed for different pressures (20 kPa - 100 kPa) and incoming velocities (2.4 - 3.2 km/s) by using 1-D Zeldovich-von Neumann-Doering (ZND) calculations. It was found that induction length and induction time reduces with higher blends of hydrogen in CJ-ZND analysis as well as oblique detonation wave ZND analysis. Similar effects are observed by adding small amount of reaction promoters (H_2O_2 or O_3) as additives up to 15000 PPM. The two-dimensional numerical simulations for the oblique shock wave (OSW) to oblique detonation wave (ODW) transition for different blends and additions in fuel-air mixtures are performed for wedge at angle $\theta = 26^\circ$ for incoming flow velocity of 2800 m/s, pressure of 20 kPa and temperature of 300 K. The unsteady reactive Navier-Stokes RANS equations are solved with adaptive grid refinement and robust SAGE chemistry solver on CONVERGE platform using reduced version of GRI mechanism along with ozone sub-chemistry. Two-dimensional simulations confirms smooth transition with initiation length 1 cm for stoichiometric hydrogen-air and no ODW formation for methane-air premixed mixtures for 10 cm wedge length. It is also found that 50% hydrogen blending and 10000 PPM of ozone addition to stoichiometric methane-air mixture can establish ODW with initiation lengths of 3.9 cm and 4.0 cm, respectively on a finite length wedge.

1. INTRODUCTION

The hypersonic air-breathing propulsion requires integration of different propulsion system to operate from lower flight speeds to hypersonic flight speeds in efficient manner [8]. Among various propulsion systems, turbojet with afterburner can generate high specific impulse up to Mach 4. Ramjet engine (with subsonic combustion) works with optimum specific impulse between Mach 2 to 5, and beyond Mach 5, the efficiency starts decreasing. The scramjet engines (with supersonic combustion) can become efficient in higher flight regimes (between Mach 5-12). Additionally, the dual mode scramjet can operate over the range of ramjet and scramjet. Turbine based (TBCC) and Rocket based combined cycle (RBCC) concepts offer practical and efficient solution for integrating individual efficient propulsion systems at different flight Mach number regimes (turbojet/rocket with ramjet, scramjet or dual mode scramjet engines). The fuel selection is an important integrating factor for these high-speed propulsion systems, which requires not only efficient fuel-air mixing and optimum combustion in available short residence time (even shorter with increased speed), but also higher energy density, fuel stability and practical fuel management system. Hydrogen is one of the preferred fuel due to combustion and ignition characteristics, but hydrocarbon fuels can be handled better and have higher energy density by volume in comparison to hydrogen. The combined cycle engine with hydrocarbon fuel should work in all flight regime, hence operability of individual propulsion systems with selected fuel (or fuels) remains challenging. Further application of hypersonic air-breathing propulsion for space launch vehicle can benefit in reducing operating cost, mission flexibility, safety, increase in re-usability. The performance of scramjet deteriorates at high speeds near orbital velocities, scramjet alone may not be suitable for space launch vehicle application. One practical solution is to enable "rocket-mode", which can provide thrust beyond Mach 10-12. There can be another possibility to increase scramjet operating range by integrating "detonation" based propulsion system.

Theoretically, detonation based propulsion systems (pulse detonation, rotary detonation (RDE) and oblique detonation (ODWE) engines [10]) can achieve higher heat release rate, higher thermal efficiency than compared to deflagration based propulsion systems[9, 23]. Fundamentally, detonation mode combustion allows the flame to propagate at supersonic speed along with shock wave, causing high pressure increase across the flame front, along with high temperature increase. Among the above three detonation based systems, ODWE has simpler design and it can be easily integrated to scramjet engine configuration with added advantage of shorter combustor length, no requirement of ignition devices, and higher flight operation range, between Mach 6 - 16. The oblique detonation wave engine requires a wedge in a supersonic premixed stream of fuel and oxidiser mixture, which can establish a compression wave as an oblique shock wave (OSW). With sufficient compression, (depends on incoming flow speed & wedge angle), it is desired that fuel-oxidiser mixture ignite itself. The OSW can transition into a standing detonation wave, which can be further accelerated through the nozzle [14]. The fuel-air mixture undergoes shock induced combustion by oblique shock wave (OSW) further transition to oblique detonation wave (ODW) after a certain distance on the wedge, defined as "initiation length", it is highly dependent on fuel composition for a given incoming flow Mach number and wedge angle. Due to various difficulties in performing experiments for oblique detonation wave [21, 25], many researchers had used theoretical and numerical simulation methods to develop understanding of oblique detonation wave formation and optimizing the operating parameters. The numerical simulations for oblique detonation formation are also computationally expensive due to range of resolving space and time scales along with chemistry modelling involved in the process. Hence, most of the theoretical studies assumes frozen flow [14], and numerical studies uses two-dimensional Euler solver and simplified chemistry to develop understanding of ODW formation. However, recent studies suggested that detailed chemistry modelling is important for estimating the initiation length and understanding of OSW to ODW transition [11, 16, 18, 17]. Recently, Vashishtha et al. [20] suggested that ODW initiation length for hydrogen-air premixed mixture can be efficiently reduced maximum up to 80% with addition of 10000 ppm of O_3 and H_2O_2. The control of initiation length with reaction promoters or fuel blends may increase the flight range operability of ODWE for a finite length wedge. The use of hydrocarbon fuel for ODW formation has challenges as it is difficult to ignite pure hydrocarbon fuel, which require very long initiation length. Xi et al.[24] suggested to blend hydrogen to methane-air powered ODWE, which can significantly reduce the initiation length with increase in hydrogen content. The current study aims to investigate the ODW formation control for methane-air premixed mixture at a given incoming Mach number. The objectives of the study can be stated as: 1) Understanding the effects of addition of more reactive fuel (H_2) or reaction promoters (O_3 and H_2O_2) on methane-air ODW formation 2) Utilize the efficient SAGE chemistry solver & robust adaptive grid refinement capabilities in CONVERGE [15] solver to model ODW formation by solving N-S equations.

2. NUMERICAL METHOD

In this study, initially chemistry effects of fuel (H_2) blends and addition of reaction promoters (O_3 and H_2O_2) on detonation wave formation have been analyzed using Chapmann-Jouguet (CJ) analysis and one-dimensional steady Zeldovich–von Neumann–Doring (ZND) model [10]. Later, the two-dimensional numerical simulations for oblique detonation wave formation are carried out using commercial CFD solver including detailed chemistry as well as turbulence modelling.

2.1 CJ and ZND Modelling

To develop understanding of chemistry effects on detonation wave for different fuel-air mixture, Shock Detonation Toolbox [1] and Cantera [5] have been used to perform CJ and ZND analysis. The chemistry effects on detonation wave propagation for different fuel mixture is analyzed by calculating CJ-speed with assumption of equilibrium chemistry. CJ-speed is defined as minimum wave speed for which there is jump condition exist for reactant to equilibrium product travelling at supersonic (sonic) speed. The CJ-Speed is mainly dependent on thermodynamic properties of reacting mixture. Further the chemistry effect on detonation wave structure is analyzed by one dimensional steady ZND model. The detonation wave is supersonic combustion wave in which shock wave and flame front are coupled. ZND-detonation model assume normal shock compression of reactants and compute reaction zone with two length scales: induction zone and energy release pulse width. The induction zone plays important role, where active radical species are generated by thermal dissociation of the shock-heated molecules. Once sufficient active radical species are produced, rapid chain-branching reactions convert the reactants to products. The computation of induction length and corresponding induction time is performed by computing thermicity, which represents coupling between chemical reaction and fluid motion in a inviscid, ideal compressible flow. The induction length (Δ_i) and induction time (τ_i) are defined as distance to maximum thermicity gradient from shock front and time to reach maximum thermicity gradient. The results of induction length and induction time for different fuel-air mixtures are analyzed here with ZND modelling.

2.2 Two-dimensional Modelling

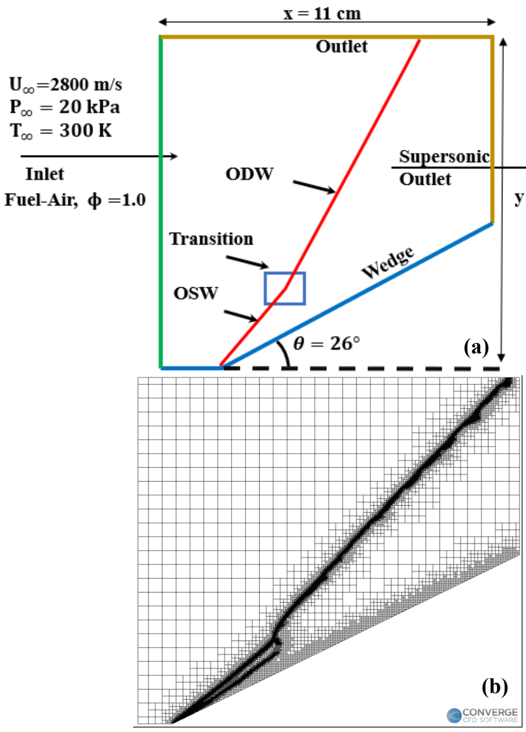


Figure 1: (a) Computational Domain and Boundary Conditions, (b) Adaptive Mesh Refinement for 50 % H_2 blend case

The two-dimensional, reactive multi-species Euler equations with detailed chemical kinetics with adaptive grid refinement have been used in many previous studies to develop understanding of various detonation phenomenon [2, 4, 3, 7, 19]. Recently, adaptive mesh refinement (AMR) capable cfd-solver [12, 13] CONVERGE has been used to simulate complex rotating detonation engine phenomenon by solving Navier-Stokes equations including turbulence modelling in efficient manner. CONVERGE solver utilize efficient SAGE detailed chemistry solver with adaptive zoning [22] to accelerate the chemistry calculations. In the current study, CONVERGE solver has been used to simulate two-dimensional wedge in hypersonic flow of premixed fuel-air mixture for ODW formation as shown in Fig. 1a. The computational domain of $11cm \times 10cm$ was used with wedge at angle $\theta = 26°$. The inflow boundary is considered as fuel-air stoichiometric mixture ($\phi = 1$) with speed of 2800 m/s, free stream pressure of 20 kPa and temperature of 300 K. The slip wall is modelled with zero normal gradient for temperature and the wedge wall is considered with no-slip and adiabatic condition. The outlet is considered as supersonic outlet. The OSW at the wedge tip will transition to ODW after certain distance near wedge.

The unsteady Reynolds Averaged Navier-Stokes equations of mass, momentum, species transport and total energy are solved with realizable $k-\varepsilon$ turbulence model. An ideal gas equation was used for calculating gas properties. The second order spatial discretization with step flux limiter and fully implicit first-order accurate time integration method were used with PISO solver scheme. Variable time-stepping method with minimum time-step of 0.1 ns was employed, which was automatically calculated based on maximum CFL assigned. The simulations are stopped at 200 μs after the stable oblique detonation wave formation. The solver uses cut-cell method and generate grid while simulations as well as uses adaptive mesh refinement (AMR) based on computed parameters. The simulation was initialized with combustion off, once the oblique shock was stabilized on the wedge, the combustion with initiated at 50 μs. The adaptive mesh refinement was controlled with parameters: velocity, temperature and density for gas dynamics effects up to level 3 and with OH, O and H_2O for flame front capturing up to level 5 (with minimum grid size of 0.125 mm). The sample grid for ODW simulation is shown for 50 % hydrogen, 50% methane-air (by volume) blend in Fig. 1b. The chemistry is modelled using reduced version of GRI Mechanism DRM22 (with 24 total species and 104 reactions). In order to incorporate the effect of ozone addition, ozone sub-chemistry from Halter et al.[6] was included into DRM22 mechanism. The final reaction mechanism with 27 species and 119 reaction was used for all the calculations, assuming Nitrogen as inert gas.

3. RESULTS AND DISCUSSION

The oblique shock wave (OSW) to oblique detonation wave (ODW) stable transition on a finite length wedge depends on incoming flow speed, wedge angle, free stream pressure and temperature as well as chemical kinetics. Initially, the effect of the incoming flow speed and pressure are analyzed for different the fuel-air compositions by hydrogen blending and small addition of reaction promoters on detonation wave by analyzing equilibrium chemistry and 1D ZND calculations in following sections. In the later section, results of ODW formation for different optimum blends are presented using two-dimensional numerical simulations for finite length wedge of 100 mm at pressure of 20 kPa, temperature of 300 K with incoming velocity of 2800 m/s.

3.1 Effect of Mixture Composition on ZND - CJ Detonation

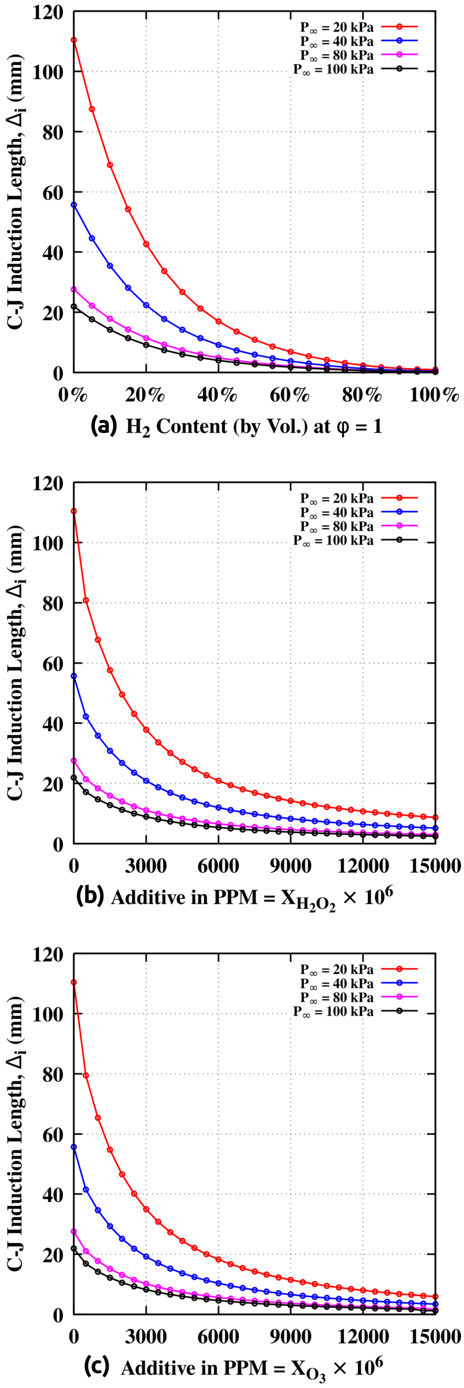


Figure 2: CJ- Induction Length Variation for (a) Hydrogen blending, (b) H_2O_2 and (c) O_3 addition in CH_4-air mixture at equivalence ration $\phi = 1$

The CJ-characteristics of mixture composition analyzed with CJ-speed calculation and induction length and time analysis of CJ-ZND detonation. The gas dynamics parameters such as free stream pressure, temperature and mixture composition decides the minimum detonation wave speed (or Chapmann-Jouguet, CJ speed) for a given fuel-air mixture. The CJ-speed is defined as limiting minimum detonation wave speed behind which the equilibrium reaction products travel at sonic speed.

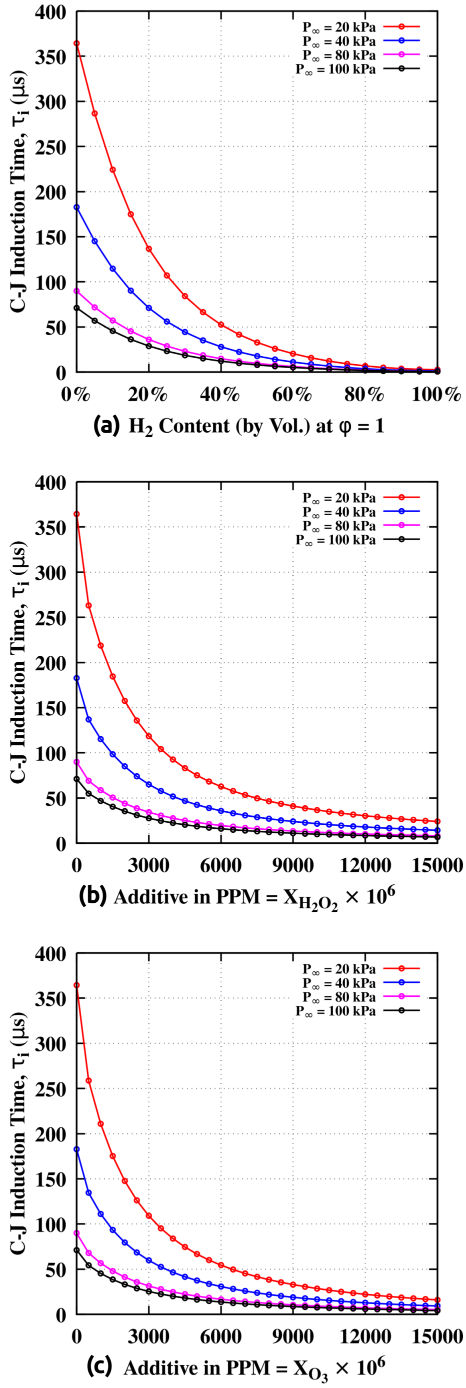


Figure 3: CJ- Induction Time Variation for (a) Hydrogen blending, (b) H_2O_2 and (c) O_3 addition in CH_4-air mixture at equivalence ration $\phi = 1$

With increase in hydrogen content in a given methane-air mixture, the thermodynamic properties of mixture will change, which can result in change in CJ-speed of mixture. The pure CH_4-air mixture at 300 K has CJ-speed between 1781 m/s to 1809 m/s for initial pressure of 20 kPa to 100 kPa. The CJ-speed increases approximately 8% with increase in hydrogen content in the methane-hydrogen-air up to 100% hydrogen-air at all the above pressure levels. On the other hand, the reaction promoters are required to added in the fuel-air mixture in very small amount (in current study analyzed up to 15000 PPM). As the small amount of reaction promoters (H_2O_2 and O_3 does not change the thermodynamic properties of mixture, the CJ-speed varies up to 0.6% with addition of (H_2O_2 and O_3 up to 15000 PPM in methane-air mixture at 300 K temperature and pressure between 20 kPa to 100 kPa.

The CJ-ZND calculations are performed for a given mixture assuming CJ-detonation, where the reaction product travels at sonic speed behind the leading shock wave. The leading shock wave compresses the fuel-air mixture and raises pressure and temperature initiating dissociation of reactants and radical formation in induction zone. After sufficient time-lapse (induction time) within the induction zone, rapid recombination reaction occur with temperature rise by exothermic reaction. The induction zone and induction time are main characteristics of detonation wave formation. The variation of induction length and induction time for different methane-air mixtures (with hydrogen blend and O_3 and H_2O_2 addition) at CJ-detonation conditions are shown in Figure 2 and 3 at different pressures and the temperature of 300 K. As the CJ-speed is dependent on mixture properties (not incoming flow velocity), the CJ-ZND condition is also corresponding to mixture properties with minimum flow velocity requirement for detonation wave formation. It is also to note that CJ-ZND calculation are based on normal shock assumption, but will provide understanding of detonation wave structure. The CJ induction length for pure CH_4 varies from 110 mm to 21 mm with initial pressure variation between 20 kPa and 100 kPa, corresponding CJ induction time varies between 360 μs to 71 μs. Figure 2a and 3a correspond to variation of CJ induction length and time with increasing hydrogen content in methane-air mixture. Both CJ induction length and CJ induction time drops exponentially with increase in hydrogen content in mixture. The induction length halves at 15 % of hydrogen content (by volume) at all pressure levels and reduces to below 1 mm for pure hydrogen-air mixture. The CJ induction time reduces to approximately 15% at corresponding half CJ induction length mixtures at all pressure levels. The addition of reaction promoters (both H_2O_2 and O_3) affects the CJ induction length and CJ induction times in similar manner but with very small amount of addition, without changing CJ-speed of the mixture. Figure 2b,c and 3b,c shows the variations in CJ induction length and time with increasing H_2O_2 and O_3 content up to 15000 PPM. At all pressure levels, the CJ induction length halves approximately with 1500 PPM addition of both reaction promoters, while reduces to 8 mm with 15000 PPM H_2O_2 and 6 mm with 15000 PPM O_3 addition at 20 kPa and to 2.5 mm & 1.2 mm, respectively at corresponding 100 kPa. Similarly, the CJ induction time also approximately halves at 1500 PPM with addition of reaction promoters at all pressure levels and reduces to very lower values with 15000 PPM. Although both reaction promoters affects in similar manner, but O_3 reduces CJ- induction length and time relatively more than H_2O_2 at the same amount of addition in PPM.

3.2 Effect of Mixture Composition on ZND - Oblique Detonation

The 1D ZND calculation for oblique detonation waves are performed in two steps: 1) by computing the oblique detonation wave angle for incoming flow and given deflection angle of wedge ($\theta = 26^\circ$ in current study), with assumption of equilibrium mixture behind the detonation wave, 2) by computing the normal component of incoming flow based on ODW angle and performing 1D ZND calculation for the overdriven detonation. Figure 4 and 5 plot the variations on ODW induction length and time for different incoming inflow velocities 2.4 km/s to 3.2 km/s with wedge angle of $\theta = 26^\circ$ and same free stream pressure of 20 kPa and temperature of 300K. As the overdriven factor (ratio of incoming flow and corresponding CJ-speed for mixture) increases, the induction length and time decreases for all mixture compositions. The overdriven factor corresponds to 1.3 to 1.8 for incoming flow velocities 2400 m/s to 3200 m/s in pure CH_4-air mixture at given pressure and temperature conditions. The blending of hydrogen to methane-air mixture decreases the ODW induction length and time in exponential manner. Figure 4a depicts that ODW induction length reduces to half by blending 20 % hydrogen by volume at incoming flow of 2400 m/s, while halves at approximately 40 % hydrogen blend for 3200 m/s incoming flow. The similar variation are observed in ODW induction time for corresponding hydrogen blending in Fig. 5a. The reaction promoters are more effective with small amount of addition to the methane-air mixtures than compared to higher hydrogen blends at lower velocities. At 2400 m/s, the ODW induction length reduces less than half up to 2000 PPM H_2O_2 or O_3 addition along with ODW induction time. At higher speed 3200 m/s, the corresponding half reduction occur up to 3000 PPM of addition of any of the reaction promoters as shown in Figure 4b, c and 5b, c. The above results provides the fundamental understanding of oblique detonation wave formation at different incoming speeds at given wedge deflection angle,

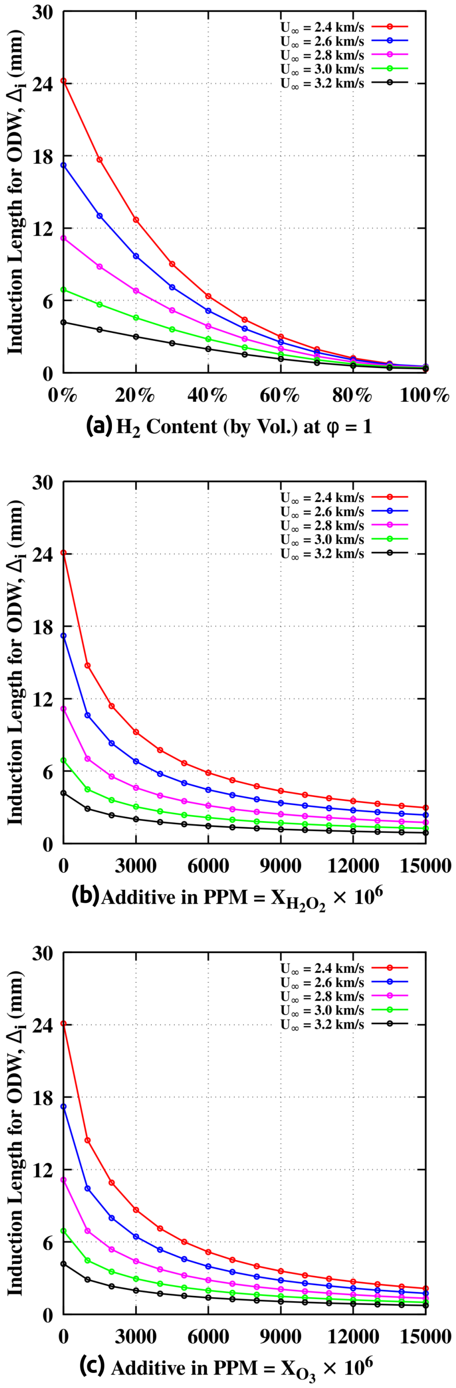


Figure 4: ODW Induction Length Variation for (a) Hydrogen blending, (b) H_2O_2 and (c) O_3 addition in CH_4-air mixture at equivalence ration $\phi = 1$

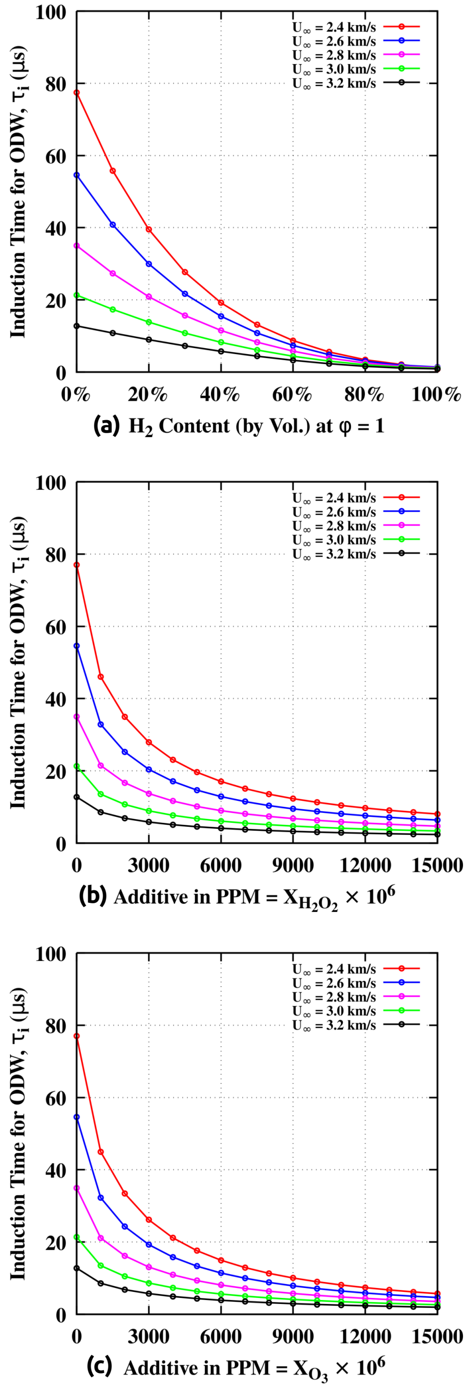


Figure 5: ODW Induction Time Variation for (a) Hydrogen blending, (b) H_2O_2 and (c) O_3 addition in CH_4-air mixture at equivalence ration $\phi = 1$

while details of oblique shock wave to oblique detonation wave transition and formation can be analyzed by two or higher dimensional numerical simulations. The above discussion provides understanding that, it will be difficult to achieve stabilized oblique detonation wave for pure methane-air mixture in comparison to pure hydrogen-air mixture for a given finite size wedge length. The CJ-induction (non-dependent of incoming velocity) and ODW-induction (dependent on incoming flow velocity) length and time vary significantly at different operating conditions (pressure, temperature) and mixture composition. Modifying the wegde length for wide range of flight

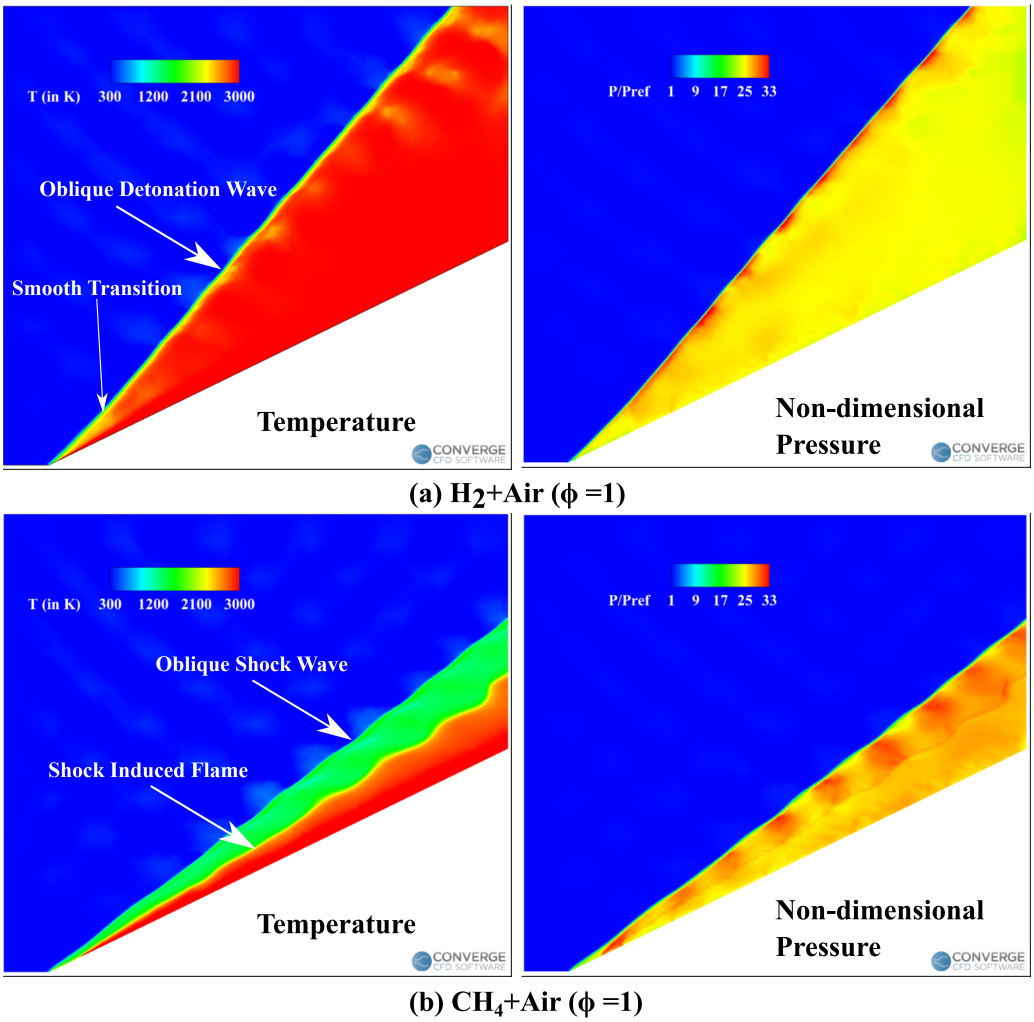
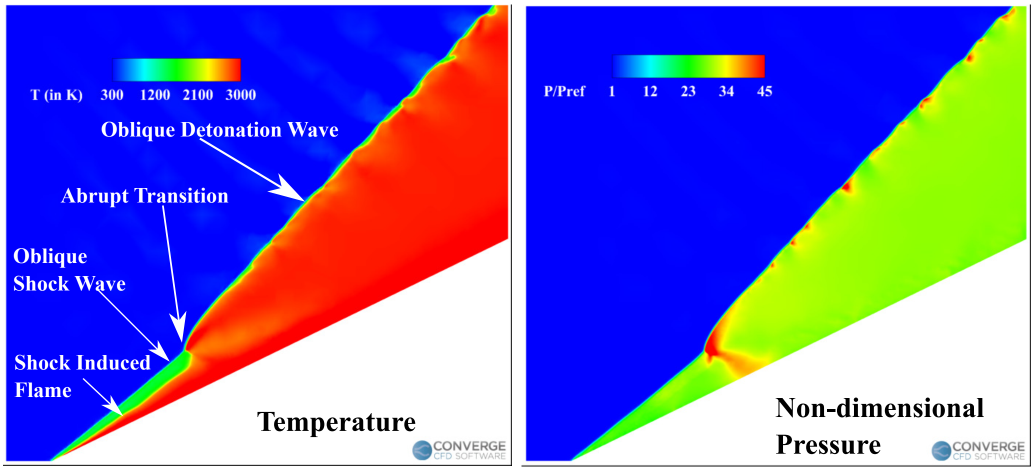


Figure 6: ODW formation for premixed (a) H_2-Air ($\phi = 1$), (b) CH_4-air ($\phi = 1$) mixture

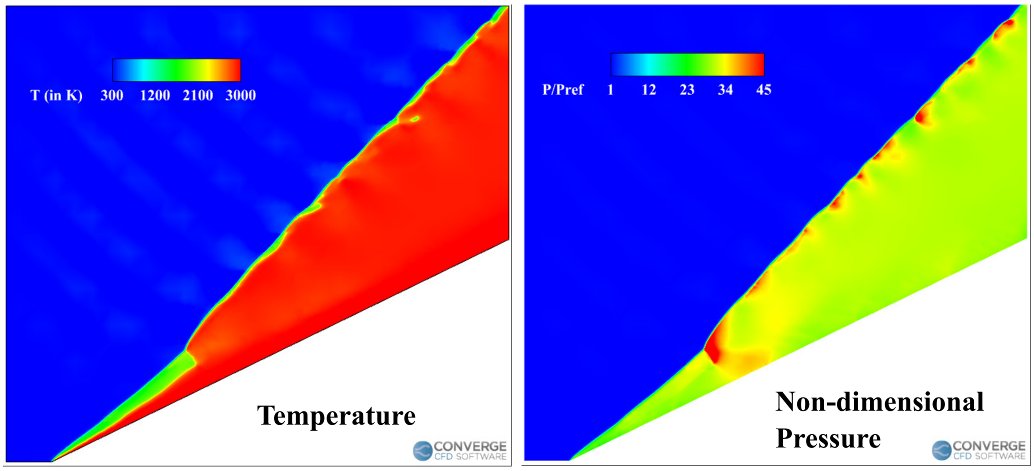
operations cannot be a practical solution. Hence, hydrogen blending or using reaction promoters as additives can be a practical solution to establish ODW on a finite length wegde for methane-air powered ODWE. However, higher hydrogen blends may be required for stabilized oblique detonation wave formation on a finite length wedge, but small amount of reaction promoters may provide similar reduction in induction lengths and time for ODW formation on a finite length of wedge. Both the reaction promoters, H_2O_2 or O_3 affects the CJ-induction and ODW-induction lengths and time similarly with minor enhanced performance for reduction in induction length and times for O_3 at various conditions. It can also be deduced that reaction promoters are effective when added with small quantities, the higher amount (beyond 10000 PPM) may not be helpful to reduce induction lengths and time significantly. The future study can incorporate small amount of hydrogen blending with reaction promoters as additives for optimized ODW control strategy. The next section confirms the above findings and details of ODW formation for few mixture conditions by performing two-dimensional numerical simulations.

3.3 Simulation of ODW Formation

In this section, the two-dimensional unsteady reactive Navier-Stokes RANS simulations are performed for ODW formation on a finite length wedge of 100 mm at angle $\theta = 26°$ for an incoming velocity of 2800 m/s, pressure of 20 kPa and temperature of 300 K. All the simulations are stopped at 200 μs, when the stable detonation wave is formed. Initially, premixed mitures of 100 % H_2-air and 100 % CH_4-air at stoichiometric ratio (ϕ=1) were simulated. The temperature and non-dimensional pressure results of the flow field at 200 μs time, are shown in Fig. 6. The hydrogen-air mixture shows formation of detonation wave near the wedge tip in Fig. 6a, which suggests pattern of OSW to ODW smooth transition with a very small initiation length (1 cm horizontal distance from tip) for the simulated condition. The shock and



(a) 50 % H_2 + 50 % CH_4 + Air (ϕ =1)



(b) CH_4+Air + 10000 PPM Ozone (ϕ =1)

Figure 7: ODW formation for a premixed (a) 50 % H_2 Blend (by Vol) and (b) 10000 PPM O_3 addition, to CH_4 - air mixture at $\phi = 1$

flame are coupled and oblique detonation wave form approximately 45.6° angle. The simulation conditions are similar to [20], but the ODW detonation transition pattern is different than the previous study. The previous study does not account for wall thermal modelling and turbulence effects. In the current study, flame is initiated at wall and couple with shock wave at 1 cm from the wedge tip smoothly. The high pressure and temperature region along the detonation wave reflects the smooth transition of OSW to ODW. In Fig. 6b, the flow field for 100 % CH_4-air mixture at $\phi = 1$ are shown with temperature and non-dimensional pressure contours. It is observed that 10 cm wedge length is not sufficient for detonation wave formation for the mixture and simulated condition. The flame is initiated along the wall near the tip and remains attached to the wall and does not couple with oblique shock wave for the given length of wedge in Fig.6b. In transient simulation, the abrupt transition point of OSW to ODW move downstream and out of the domain at the end of 200 μs. The oblique shock wave compresses the fuel air mixture and initiate combustion near the wall as shock induced flame.

It is understood that the higher compression or longer wedge length will be required to establish a stable oblique detonation wave for methane-air mixture than compared to hydrogen-air mixture for ODW Engine. As the ODW formation on a finite length wedge can be controlled effectively by altering the chemical characteristics of the fuel-air mixture by either blending more reactive fuel or utilizing the reaction promoters. As the previous section explains the effect of hydrogen blending & adding relatively small amount of reaction promoters (H_2O_2 & O_3) in methane-air mixture on ZND detonation structure by analyzing the induction length and induction time. A shorter induction length and time can enable OSW to stable ODW formation on a finite length of wedge. To demonstrate both the approaches, the numerical simulations are performed for 50% hydrogen blend (by vol.) as well as 10000 PPM O_3 addition to stoichiometric methane-air premixed mixture. The temperature and pressure contours for both the fuel-air mixtures, simulated for a wedge of 26° with 2800 m/s incoming velocity, 20 kPa of pressure and 300 K of temperature after 200 μs are shown in Fig. 7. Figure 7a shows the temperature and non-dimensional pressure contours for 50 % hydrogen blend into premixed stoichiometric CH_4-air. The fuel-air mixture gets compressed due to oblique shock formation at the tip and ignite itself near wall boundary layer, with flame remains below the oblique shock wave near the wedge tip region and OSW transforms to ODW at 3.9 cm horizontal distance from tip. The OSW to ODW transition can be characterized as abrupt transition with formation of Mach stem at the transition point. The characteristic cellular structure and triple points are observed in pressure contours beyond the transition point. The horizontal initiation length for 50 % hydrogen blend mixture is observed as 3.9 cm, which has been reduced significantly from the larger than 10 cm for 100 % methane-air mixture. The simulation results for oblique detonation formation by 10000 PPM O_3 addition to stoichiometric CH_4-air mixture are shown in Fig. 7b. The temperature and non-dimensional pressure contours show the similar abrupt transition of OSW to ODW, but with horizontal initiation length of 4.0 cm in this case. The slightly bigger Mach stem is visible with cellular structures and triple points beyond the OSW to ODW transition point. The above results demonstrate that the small amount of reaction promoters can be as effective as higher volumes of hydrogen blending requirements to establish the oblique detonation wave on a finite length wedge. Also, these results confirms the findings of 1D ZND analysis for ODW formation, as the induction lengths for 50% hydrogen blend and 10000 PPM of ozone additions were calculated as 2.8 mm and 2.4 mm, respectively. The unsteady simulation also shows OSW to ODW transition triple point varying between smooth and abrupt with change in interaction of cellular structure.

4. CONCLUSIONS

The control strategies for oblique detonation wave formation on a finite length wedge are analyzed for premixed methane-air stoichiometric mixture. The CJ-ZND and ODW ZND calculations for different operation conditions and fuel-air compositions are performed and two-dimensional CFD simulations for selected cases are performed to demonstrate the ODW formation. From the obtained results, following are concluded:

1. The methane-air fueled ODW Engine operation requires controlling strategies to establish oblique detonation wave on a finite length wedge for operating in the wide range of hypersonic speed.

2. Hydrogen blending is one of the promising strategy to reduce induction length and induction time at different operating pressure and speeds. However, it may require higher amount of hydrogen blending to effectively control the same. 15-20% hydrogen (by vol.) blending is required to reduce the induction length and time to half at different pressure and incoming flow conditions.

3. Both reaction promoters H_2O2 and O_3 controls the oblique detonation wave formation effectively. By adding 2000-3000 PPM, the induction length and time can be reduced to half, for studied conditions.

4. The two-dimensional simulations confirms the effectiveness of reaction promoters and hydrogen blending by simulating OSW to ODW transition for 50 % H_2 blend and 10000 PPM of O_3 addition case, results in 60 % initiation length reduction.

5. The study also concluded that the effective adaptive mesh refinement and SAGE-chemistry solver robustness in CONVERGE solver can be efficiently used by including turbulence modelling and wall effects for oblique detonation wave simulations fired with higher hydrocarbons.

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