Auto-ignition at Shock-Wave Collisions in Hydrogen-Air Detonation

Oleg. G. Penayzkov[a], Kirill L. Sevrouk[a], Khaled Alhusan[b]
[a] *A.V. Luikov Heat and Mass Transfer Institute, Minsk, Republic of Belarus, 220072*
[b] *Space Research Institute, King Abdulaziz City for Science and Technology, Saudi Arabia*

1 Introduction

Realistic modeling of energy release and reaction length scales associated with a cellular structure of gaseous detonation is important from theoretical point of view and practical applications. Besides, three-dimensional phenomena and interactions are also extremely important under considerations of reacting flows accompanied with shock waves at complex flow and boundary conditions. In this study we attempted to investigate the influence of 2D and 3D shock-wave collisions on auto-ignition in the induction zone of hydrogen/air detonations.

Different collisions and, subsequently, reactive hot spots were produced at interaction of the incident shock wave (ISW) [1-3] with wedge and conical walls. Induction times and auto-ignition modes of the mixture (strong, transient and weak) [4-7] were measured by means of pressure, ion current and emission observations. Particular attention has been paid in experiments to determining the critical ISW intensity required for initiation of different auto-ignition regimes. The results were compared with a reference data obtained behind normally reflected shock waves [8].

2 Experiments

The used experimental configurations and drawings of the test sections are illustrated in Fig. 1. Stainless steel shock tube of 76 mm in diameter was used in experiments. The tube length is 5.5 m. The high-pressure valves with a forced electropneumatic start were used for shock wave intiations. Mixtures were prepared by the method of partial pressures and kept for two days before use. Prior to the experiment, the tube was pumped out twice to the pressure of ~ 10^{-2} mm Hg. To lower an effect of parasite impurities, the tube was flushed with the test gas before the secondary pumping. The initial pressure of the mixture was controlled by pressure meter with accuracy of ± 0.3 mm Hg.

Two-dimensional wedge (apex angle 90^0) and similar conical profile were used for generation of 2D and 3D shock-wave collisions near cavity bottom. Pressure variations in different cross-sections were recorded by piezoelectric pressure gauges with a 1.5-mm spatial resolution (Fig.1). The pressures at the cavity bottom were measured by high-frequency PCB pressure sensors Model 113A24 with rise time less than 1 μs. To fix the arrivals times of reaction front a set of ion current sensors was installed along the test volume upstream the cavity. Stainless steel test section was mated to the end flange of the shock tube.

To measure ignition times in the hot spot vicinity, 5-mm transparent glass rod was passed through the cavity bottom (Fig.1). The end face of the rod has been polished and coincided with profiles of

Correspondence to: penyaz@dnp.itmo.by

reflecting walls. The rod provided a complete overview of the inner cavity and tube volumes. The flame emission in selected spectral band was registered by means of the photo-multiplier having the maximal sensitivity in the selected spectrum. For all tests in hydrogen/air mixtures the luminosity of OH radicals (λ=306.5 nm) was detected using a narrow-band interferometric filter ($\Delta\ \lambda$ = 2 nm). Experimental results were recorded and processed by an automatic 10-bit data acquisition system and a central computer.

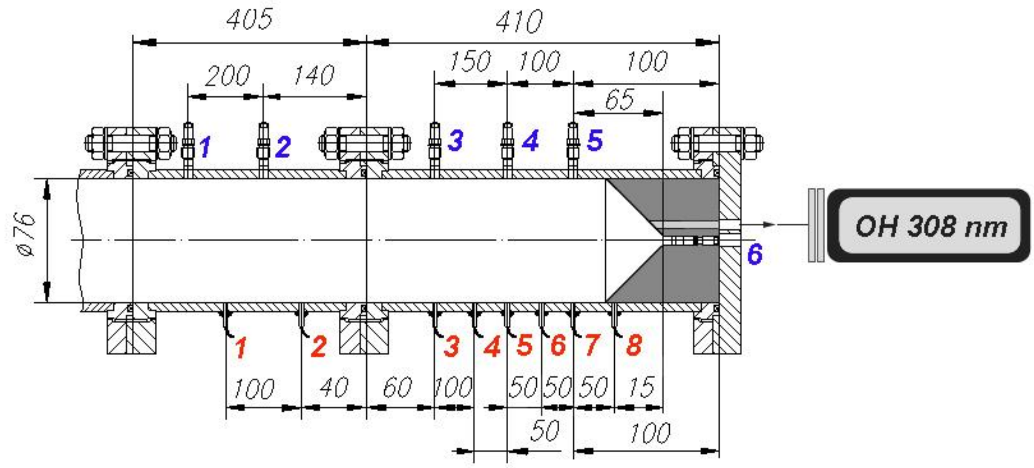

Figure 1. Drawing of the test section: 1- 6 (blue) - high-frequency PCB pressure sensors; 2 - 1- 8 (red) – ion current sensors

The identification of auto-ignition modes at shock-wave collisions was performed by comparing velocities of reflected shock waves and post-reflected shock pressure at different locations from the cavity bottom. The additional ion probe measurements provided the data on propagation velocity of reaction zone. We have categorized four different auto-ignition regimes: no ignition, weak ignition (deflagration), transient ignition resulting in DDT upstream the hot spot and strong ignition (detonation). The strong auto-ignition corresponded to direct initiation of detonation in the vicinity of reactive hot spot. The formed detonation propagated upstream the hot spot through the complex flow field behind the incident shock wave. The reflected shock wave velocity in this part of the tube was defined as $V_R = V + u$, where V is the measured velocity of reflected shock outside the reflector, and u is the flow velocity behind ISW. Measured velocity calculated by processing shock-arrival times at pressure sensors along the tube. If defined reflected shock wave velocities are compared with the calculated CJ velocity for conditions behind ISW, the direct detonation initiation occurred at shock wave collisions.

There was a range of ISW Mach numbers in which transient modes of ignitions were realized. The specific feature of this regime was the presence of powerful pressure spikes behind the reflected shock wave. The source of these spikes was the localized explosion taking place anywhere between reflected shock wave and the cavity bottom. Usually, this explosion is caused by collisions of bow shocks heading transverse flow structure behind reflected shock wave. These bow shocks are accompanied by flame and promote the combustion. This mode of detonation initiation was an example of DDT in post-shock flow.

If the gas parameters in reactive hot-spot is lower, and the mixture precondition at early stages of ISW reflection is not enough for supporting the acceleration of shock wave–reaction zone complex, then weak ignition occurs. The reaction zone lags the reflected shock wave. Small-scale turbulence as well as diffusive phenomena control further combustion developments. In these cases, the visible velocity of reflected shock wave V is the same as for the reflection in inert medium.

Gas parameters behind incident and reflected shock waves were computed by using shock adiabatic curve assuming the frozen chemistry and temperature dependence of heat capacity on the basis of shock wave velocity measurements at different locations along the tube. The Chapman-Jouguet detonation velocity V_{CJ} in preheated gas flow behind incident shock wave was calculated by means of laboratory developed thermochemical equilibrium codes.

Figure 2 shows typical dependencies of the reflected shock wave velocity at different locations along the tube on the ISW Mach number. It is evident from the graphs that, for auto-ignition of the mixture, 3D shock-wave collisions are much more efficient. The critical Mach numbers required for direct initiation for cone reflection case were 2.75 at post-shock density of 0.1 kg/m^3, 2.29 at 0.4 kg/m^3, 2.01 at 0.73 kg/m^3, 1.96 at 1.392 kg/m^3, 1.94 at 1.86 kg/m^3, and 2.01 at 2.79 kg/m^3 respectively. The corresponding values for wedge reflection case were 2.32 at 0.73 kg/m^3, 2.29 at 1.37 kg/m^3, and 2.13 at 2.1 kg/m^3, respectively.

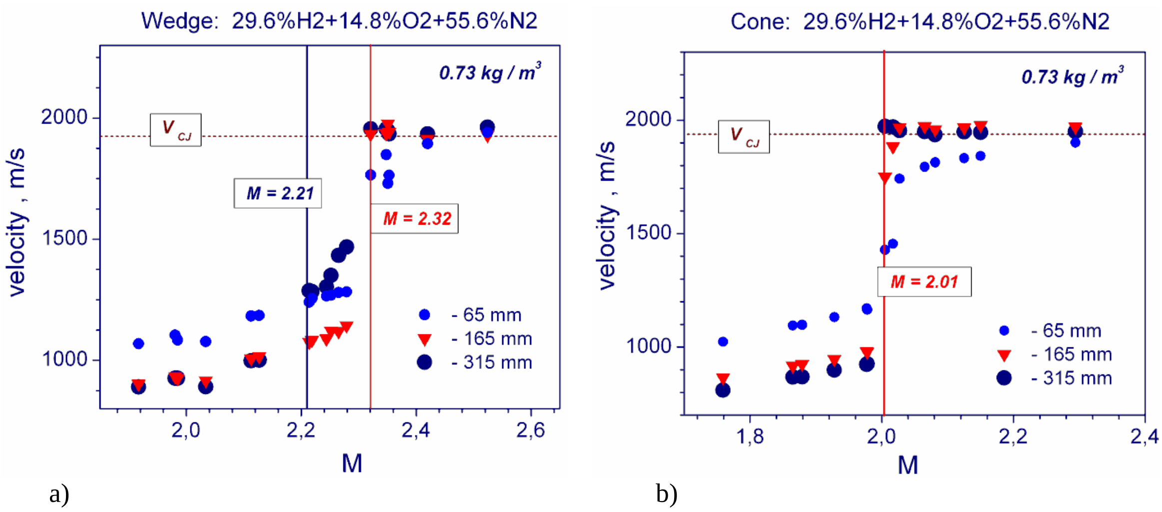

Figure 2. Absolute velocity of reflected shock wave propagating upstream the wedge (a) and cone (b) at different locations along the tube vs. ISW Mach number Red vertical line – the critical Mach number required for strong auto-ignitions; Navy vertical line- the critical Mach number required for transient auto-ignitions

3 Results

For normalized pressure–temperature plane Figure 3 shows positions of different auto-ignition domains at 2D and 3D collisions in comparison with a reference data obtained for the normal reflection from the plane wall. All indicated data points correspond to the average post-shock conditions behind the normally reflected shock wave of the same intensity. As is seen in the figure, the 3D (cone) and 2D (wedge) shock-wave collisions result in the significant decreasing of mean post-shock temperature and pressure required for direct detonation initiations. It is obvious because of much higher local temperature and pressure in the vicinity of hot spot after collisions. The axial 3D collisions can provide the local hydrogen auto-ignition of at extremely low level of average temperature of the mixture (≈ 500 K).

In comparison with a wedge reflection case at similar post-shock conditions 3D collisions suppress significantly the occurrence of transient auto-ignitions. For 2D collisions the DDT upstream the hot spot were detected at M = 2.21 - 2.32 for 0.73 kg/m^3, M = 2.17 - 2.29 at 1.37 kg/m^3. At higher densities for cone and wedge reflections experiments reveal only strong and weak auto-ignitions. In contrast to 2D collisions the cone reflections indicate the transient auto-ignitions only at low post-shock densities of 0.1 – 0.4 kg/m^3.

Figure 3 demonstrates also normalized post-shock parameters behind the fast deflagration wave in porous media [9] and in induction zone of hydrogen /air detonation at ambient pressure. The initial gas conditions in induction zone of hydrogen/air detonation were calculated for velocity of the leading shock front V = 0.6 V_{CJ} before the termination of the cell cycle. As it is seen from the graph, for single two-dimensional collisions the reasonable conditions released in fast deflagration and normal detonation waves are out of the strong auto-ignition domain (I). For single axisymmetric collision case (fig.1b) the gas parameters in induction zone of normal detonations are close to those for strong auto-ignition domain (I) and correspond to the area of transient auto-ignitions.

It means that in both cases single two- and three-dimensional shock wave collisions are not efficient as initiation mechanisms for propagation of porous and normal detonations.

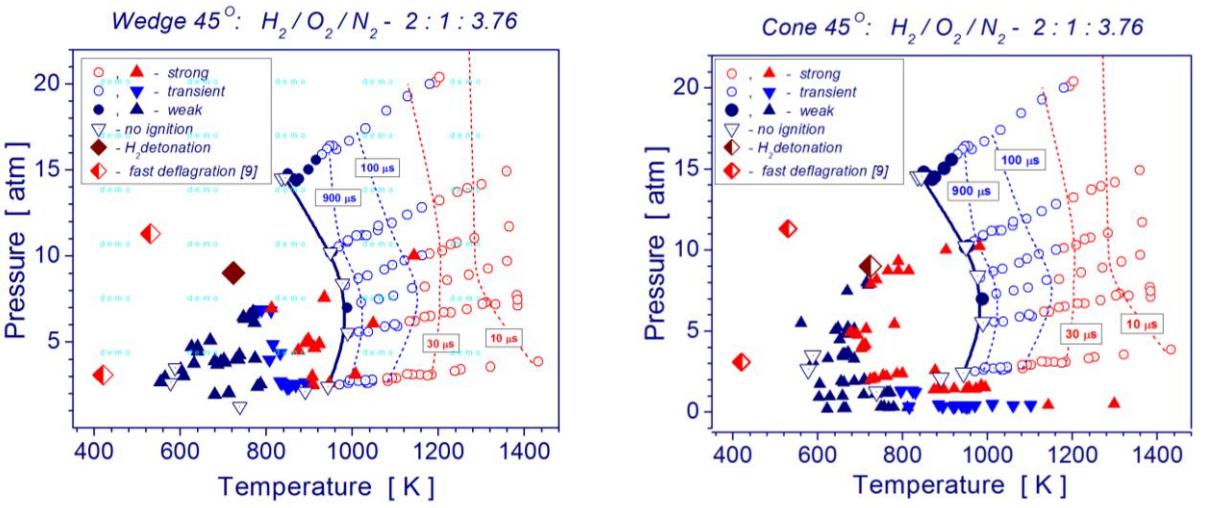

Figure 3. Auto-ignition domains (strong, transient, weak and no ignition) of stoichiometric Hydrogen/Air mixtures in normalized Pressure –Temperature plane behind incident shock wave reflected from the plane wall (circles), wedge (a) and cone (b) (tiangles).

Conclusion

It was shown that 2D and 3D shock wave collisions in two-dimensional and axisymmetric profiles significantly decrease the ignition thresholds of the mixture as compared with the case of the normal reflection. Parametric diagrams, characterizing auto-ignition of hydrogen/air mixture at shock wave reflection from a plane wall, similar two-and axisymmetrical profiles show the significant influence of three-dimensional effects and interactions on the transformation local and integral regimes of combustion. It was demonstrated that in comparison with a normal reflection case the shock wave focusing can provide the auto-ignition of hydrogen at extremely low level of mean temperature of the mixture ($\approx$ 500 K). The normal and porous detonation mechanisms appear to be more efficient at shock focusing than the present experiment. It is likely this is due to the distributed nature of these focusing mechanisms, in comparison to the single focal region associated with a single reflector.

Acknowledgments

These works were sponsored by Research Program "Hydrogen" (Belarus) and by Space Research Institute of the King Abdulaziz City for Science and Technology (Saudi Arabia).

References

[1] Borisov AA, Gelfand BE, Skatchkov GL et al. (1988) Ignition of gaseous combustible mixtures in focused shock waves. *Sov J. Chem. Phys.*, 7(12): 1387.

[2] Chan CK, Lau D, Tibault P, Penrose JD (1990) Ignition and detonation initiation by shock focusing, AIP Conf. Proc., v.208, p.161.

[3] Achasov OV, Labuda SA, Penyazkov OG and Ragozin DS (1995) Shock wave and jets initiation of gaseous detonation. *Archivum Combustionis*, 15(3-4): 253.

[4] Saytzev SG, Soloukhin RI (1962) On autoignition of the adiabatically heated gas mixture, Proc. Combust. Inst., 8: 344.

[5] Voevodsky VV, Soloukhin RI (1965) On the mechanism and explosion limits of hydrogen-oxygen chain self-ignition in shock waves, *Proc. Combust. Inst.*, 10: 279.

[6] Meyer JW, Oppenheim AK (1971) On the shock induced ignition of explosive gases, *Proc. Combust. Inst*., 13: 1153.

[7] Penyazkov OG, Ragotner KA, Sevrouk KL, Tangirala VE, Dean AJ and Varatharajan B (2006) Autoignition of Propane/Air Mixture at Shock Wave Focusing in Three-Dimensional Ducts. Pulse and Continuous Detonation Propulsion. Eds. G. Roy, S. Frolov. Moscow: TORUS PRESS, pp. 43-60.

[8] Martynenko VV, Penyaz'kov OG, Ragotner KA, Shabunya SI (2004) High-temperature ignition of hydrogen and air at high pressures downstream of the reflected shock wave. *J. Eng. Phys. Thermophys.*, 77: 785.

Lyamin GA, Pinaev VA (1986) Combustion regimes in an inert porous material. *Combustion Explosion and Shock waves*, 22: 553.