Computational Study of the External Shock-wave Impact on the Combustion Regime.

Alexey D. Kiverin, Mikhail F. Ivanov, Viktor A. Galburt,

Joint Institute for High Temperatures
of Russian Academy of Sciences, 125412, Moscow, Russia

1 Introduction

It is known, that deflagration-to-detonation transition (DDT) in gaseous combustible mixtures accelerates sufficiently in presence of external impact. It induces studies of the combustion processes sensibility to external influences. Most prevalent of such influences is a shock-wave impact. Under certain physical conditions such an impact causes DDT acceleration [1]. Shock interaction with the developing flame launches non-linear gasdynamic processes. Evolution of these non-linear processes strongly affects flame evolution. As a result a highly perturbed flame structure is generated, energy-release rate increases, flame accelerates and transition to the detonation regime occurs [2, 3].

This paper examines shock-flame interaction by the means of two-dimensional numerical simulations. The problem corresponds to the conditions of the shock-tube experiments [1-3]. A flame is ignited at a distance from a reflecting wall. A shock is released at the opposite end of the tube (open end). Shock-flame interaction distorts flame surface, increasing the energy-release rate in the system and accelerating the combustion. Consequence of the interaction is determined by the characteristics of the shock wave and the flame. This paper examines scenario of the system evolution due to the shock-flame interaction in hydrogen bearing mixtures. The main results are related to the less intensive (“slow”) and more intensive (“fast”) regimes that are realized in the hydrogen-air and hydrogen-oxygen mixtures correspondingly. The characteristic velocities (normal velocities of the laminar flames) of these regimes differ approximately on the order. Consequently, flame acceleration and DDT caused by shock interaction with the “slow” flame are determined mainly by the non-linear processes of hydrodynamic mixing. It differs from the shock interaction with the “fast” flame. In this variant the impact of the same intensity may cause DDT already behind the incident shock.

2 Numerical results and analysis

Computer simulations of the combustion process, shock-flame interaction and DDT is based on gasdynamic model of hydrogen combustion. The model includes gasdynamic transport of viscous gas, oxidation kinetics of hydrogen, multi-component diffusion and heat conduction. For multi-component mixture and combustion products the equations of state for real gases were used. The reduced model of chemical kinetics includes nine reactions and describes process sufficiently detail. Chosen model was widely used by authors and described for example in [4]. To solve problem a Lagrange-Euler numerical method was used [4].

Correspondence to: alexeykiverin@gmail.com

The computational domain represents a planar semi-closed channel width of L with smooth adiabatic walls and uses non-slip boundary conditions on the walls. The spherical laminar flame is ignited by the additional temperature increase in the area on the axis.

For a start the dynamics of the flames propagating in absence of the shock-wave impact is examined. The evolutions of the integral (flame surface) and differential (velocity of the leading point) characteristics are used to describe dynamics. The following stages of the flame evolution stand out (Fig. 1):

1) Ignition center develops until reaching the walls (points 1 and 2). The stage is similar in both variants (hydrogen-oxygen and hydrogen-air mixtures) except larger elongation along the axis of the hydrogen-oxygen flame due to higher velocity.

2) Quasi-steady stage of flame evolution (hydrogen-air flame doesn't overcome this stage on the considered scales).

3) Accelerating regime.

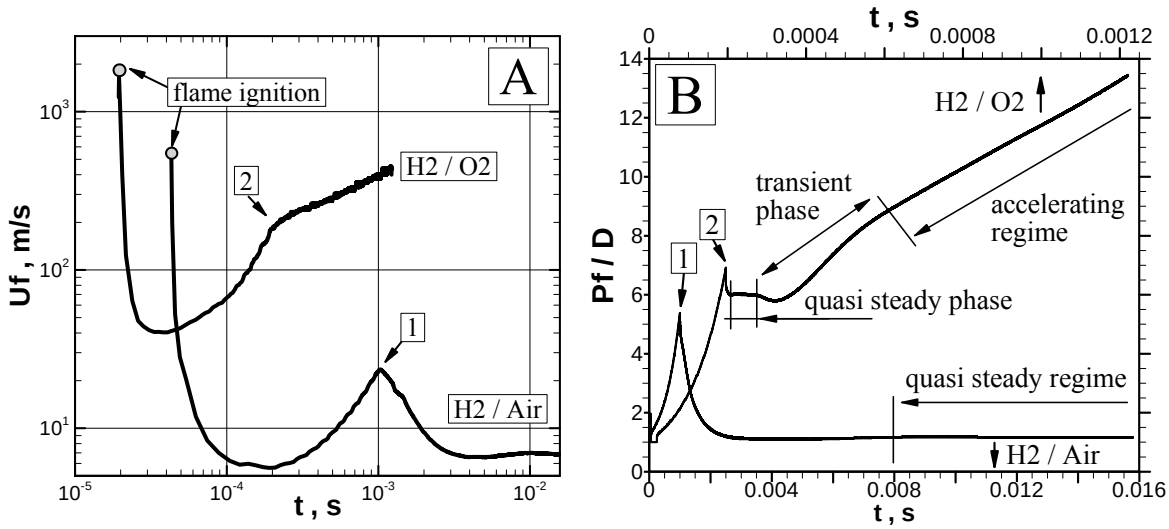

Figure 1. Velocity of leading point (A) and perimeter of 2D flame front (B) histories in hydrogen-oxygen and hydrogen air mixtures in channel width of L=0.005m.

Time scales of the shock-flame interaction problem are linked with relatively short time of shock wave propagation from the opened end to the flame surface. On these scales the perturbations generated by the non-stationary flame have no time to reflect from the closed end wall and to return. In turn, the flame doesn't achieve the walls. Therefore, one obtains the first stage that is similar in both variants. It allows solving the problem in similar conditions for two different mixtures.

During the computational experiments the series of calculations of the shock-flame interaction in channel of width L=0.010m took place. Ignition was initiated at a distance of 0.130m from a reflecting wall. A shock was placed near the open end boundary. The initial conditions behind the shock were set as a uniform flow with post-shock parameters determined from the Rankine-Hugoniot conditions for a shock with Mach number M. The following variants were calculated: M=1.9; 1.4; 1.1 in hydrogen-oxygen and M=1.9 in hydrogen-air.

In Fig. 2 the evolution of the shock-flame system at different time instants is represented. Incident shock (IS) propagates from right to the left. Due to the interaction, flame diffracts the shock with pressure increase in the front (frame 1 in Fig. 2A and Fig. 2C). The rarefaction wave, formed in the opposite direction, enters fuel mixture. Rarefaction of the compressed (due to the IS) fuel mixture promotes fuel's penetration into combustion products. It causes mixing of the burned and fresh mixtures according to Richtmyer-Meshkov instability scenario. In hydrogen-air mixture the mixing process is more intensive and causes temporal quenching of the flame (frame 2 in Fig. 2C). Secondary

ignition occurs in the surface among hot products and cold fuel after shock has passed through. Shock propagation through the flame causes intensity decrease. But shock intensity increases due to the interactions with oblique shocks generated by the reflections on the walls and flame surface. In case of hydrogen-oxygen burning, the flame has larger surface and corresponding shock intensity increase is higher. In case of IS with initial Mach number M=1.9 such an increase generates a local explosion behind IS on the flame front (frame 2 in Fig. 2A) (evolution of pressure in the shock front is showed in Fig.3). When the shock emerged from the opposite side of the flame, shock intensity decreases (in case of local explosion, the overdriven explosion regime transits to detonation (frame 4 in Fig. 2A). Consequently the shock reflected from the surface (retonation wave (R) – in case of explosion) propagates in opposite direction. The reflected waves are supporting more intensive mixing. The retonation wave passes through the flame according the same scenario as IS and generates second explosion on the other flame surface leading to detonation.

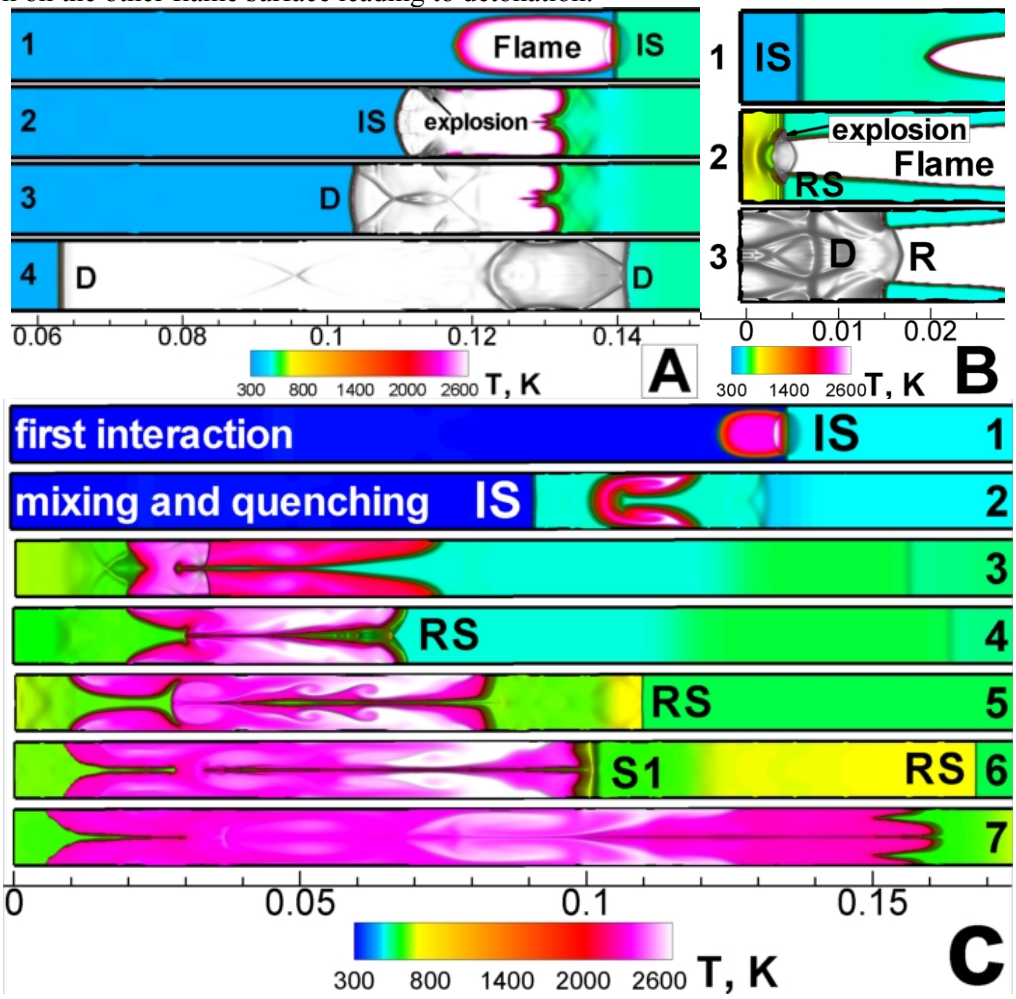

Figure 2. Evolution of shock-flame system in channel width of L=0.010m at different time instants. A – hydrogen-oxygen mixture, M=1.9, frames: 1 – 0.1600ms, 2 – 0.1750ms, 3 - 0,1775ms, 4 – 0,1887ms. B - hydrogen-oxygen mixture, M=1.4, frames: 1 – 0,2987ms, 2 – 0,3800ms, 3 – 0,3850ms. C – hydrogen-air mixture, M=1.9, frames: 1 – 0,2350ms, 2 – 0,2900ms, 3 – 0,4750ms, 4 – 0,5100ms, 5 – 0,5850ms, 6 – 0,6800ms, 7 – 0,8950ms. Scale represents distance from the reflecting wall in meters. IS – incident shock, RS – reflected shock, S1 – secondary reflected shock, D – detonation wave, R – retonation wave.

In case of smaller Mach number (M=1.4) explosion take place in the shock reflected from the closed end due to it's interaction with developed accelerating flame (frames 1 and 2 in Fig. 2B). Then the wave of overdriven detonation enters the flame (frame 3 in Fig. 2B), the mixing practically isn't

observed. Most vividly vortex structures caused by mixture are observed after the shock reflected from the closed end wall passes through the hydrogen-air flame (frames 3 – 5 in Fig. 2C). Besides the shock reflected from the closed end wall (RS), the secondary reflected shocks (for example S1 in frame 6 of Fig. 2C) pass through the flame. Mixing is gradually quenching and pressure increase rate slow down. Established regime (frame 7 in Fig. 2C) is similar to the regime caused by Darieus-Landau instability evolution [5]. In case of the reviewed spatial scales and Mach numbers (M≤1.9) the DDT in hydrogen-air mixture doesn't take place. Thus, even for such energetic mixtures like hydrogen-air, relatively strong shocks (M=1.9) are still not enough to generate DDT. Thereby gaseous flame non-interacting with the walls (except the most energetic mixtures) is a highly stable to pulse perturbations. This result is in agreement with the recent results received by authors [5]. On the other hand, even a weak impact may induce DDT in the flame additionally perturbed due to interaction with the walls.

Paper's results denote important differences between consequences of the shock-flame interaction in mixtures of various composition. One emphasizes necessity to use more detailed chemical kinetics models in computer simulations. Primarily, it is determined by the dependency of the process dynamics and it's sensibility to external influences on the combustible mixture composition.

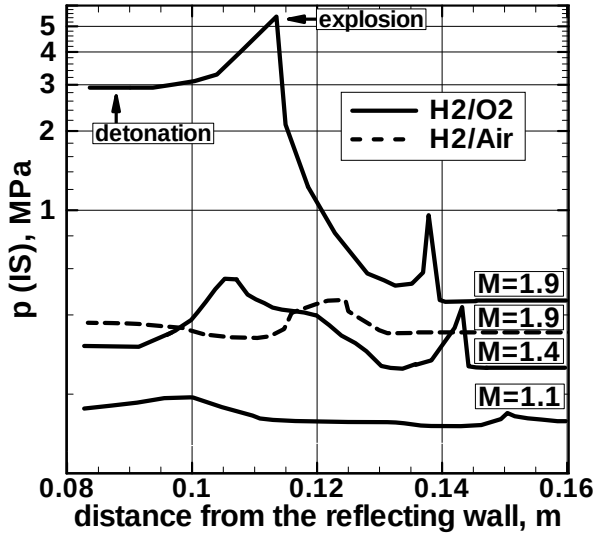

Figure 3. Evolution of pressure in the shock front propagating through the flame.

References

[1] Markstein GH. (1964). Nonsteady Flame Propagation. Macmillan. 1964. Chapter D.

[2] Utriew PA, Oppenheim AK. (1966). Experimental observations of the transition to detonation in an explosive gas. Proc. R. Soc. Lond.. A295: 13.

[3] Oran ES, Gamezo VN. (2007). Origins of the deflagration-to-detonation transition in gas-phase combustion. Combustion Flame. 148: 4.

[4] Galburt VA, Ivanov MF, Petukhov VA. (2008). Mechanisms of Development of Superhigh Pressures under Conditions of Propagation of Explosion Waves in Conical Cavities. High Temperature. 46: 867.

[5] Ivanov MF, Kiverin AD, Galburt VA. (2008). On one method of deflagration-to-detonation transition acceleration in gaseous combustible mixtures. Vestnik MGTU im. N.E. Baumana. 4: 38. (Rus)