Experimental Study of Detonation Waves in a Reactive Supersonic Flow

Nalivaichenko D.G.
Laboratory of Hypersonic technologies
Khristianovich Institute of Theoretical and Applied Mechanics, Siberian Division,
Russian Academy of Sciences, 630090, Novosibirsk, Russia

1 Introduction

As the fuel-burning velocity in a supersonic detonation wave (DW) is greater than that in regimes of the classical low-velocity combustion and results in tremendously powerful output of energy, practical implementation of detonation combustion has undoubted advantages in the development of new efficient aeronautic and astronautic vehicles. Detonation has recently attracted attention of researchers in many countries owing to the problem of creating a pulsed detonation engine (PDE).

Currently available numerous DW studies have been normally performed in the traditional formulation with the DW propagating over a motionless combustible mixture. No problems could be expected in converting the results from a motionless reference system into a moving (inertial) one in accordance with the classical principle of relativity. Few studies of DW formation and propagation in a moving combustible mixture, however, revealed noticeable differences of DW behavior in a flow from DW propagation in a quiescent mixture.

As simple transfer of the phenomenon from a motionless to a moving fluid is invalid, it is necessary to study all issues associated with DW excitation and propagation in moving combustible mixtures almost from the very beginning (both for subsonic and supersonic flows). In the present paper, the process of DW excitation and propagation in a reactive supersonic flow is considered in a comprehensive manner with allowance for gas-dynamic aspects of the flow. Moreover, almost all previous investigations on DW propagation were performed in hydrogen–oxygen flows; therefore, a distinctive feature of the present study is replacement of oxygen by air, which is important for applications.

2 Experimental setup

To study detonation in a supersonic flow of a combustible mixture and to obtain information on characteristics of processes observed, an experimental setup based on a hotshot wind tunnel was designed and manufactured.

The setup consists of the following basic elements: settling chamber 1 with quiescent high-pressure air (up to 200 atm), air heater 2 (up to 650 K) for increasing the initial reserve of enthalpy in generating a supersonic air flow, a system 3 for injecting hydrogen (or another fuel) with a mixing chamber, a nozzle 3 for forming a supersonic flow of the mixture, a working channel 7 (tube 100 mm in diameter and 2000 mm long), an output nozzle 9 connecting the working channel with a vacuum

Correspondence to: denis@itam.nsc.ru

tank 200 m3 in volume for exhaustion of combustion products, an initiation system 8, a measurement rake 5 with probes for measuring the pressure distribution over the cross section of the working channel, a fast-response multichannel measurement system, and sets of piezo- and inductive pressure sensors 6 at various points of the channel. In each operation cycle, the setup ensures high parameters of the supersonic flow: Mach number M = 3–7 and duration of the test regime up to 1 sec. Fuel injection and mixing are provided at the input of the supersonic nozzle, in its “subsonic” part, which ensures a uniform supersonic flow of the combustible mixture in the working channel in terms of species concentrations. Detonation was initiated in the working channel by an additional initiator: detonation tube with an equimolar acetylene–oxygen mixture.

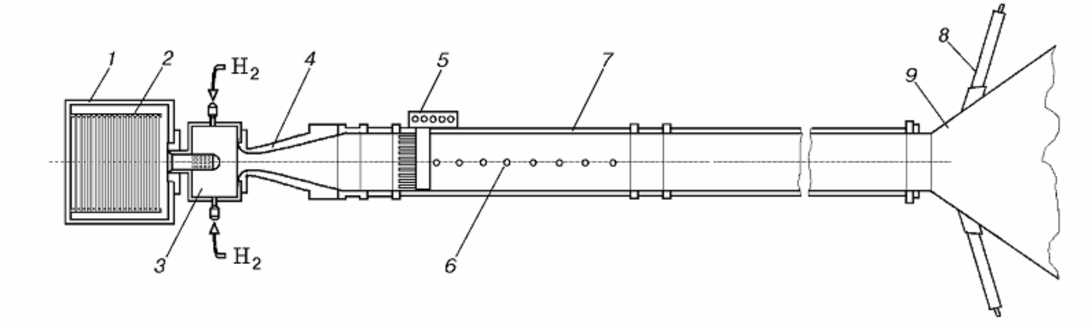

Fig. 1. Experimental setup: 1)initial settling chamber, 2) air heater, 3) fuel-injection system, 4) nozzle for forming a supersonic flow of the mixture, 5) rake of pressure probes, 6) set of piezo- and induction pressure sensors, 7) channel, 8) initiation system, and 9) output nozzle.

To find the details of the influence of numerous factors (flow structure, mixing and homogeneity of the flow of the combustible mixture, combustion and detonation in the flow, etc.) and quantify the characteristics at each point of the flow, the study was divided into several consecutive stages:

1) study of the gas-dynamic structure of the supersonic flow in the channel (with pure air used as a test gas);
2) study of mixing characteristics and flow homogeneity (air flow with injection of helium);
3) DW initiation and propagation in a controlled supersonic flow of the mixture.

3 Investigation of the gas-dynamic structure of a supersonic flow

To identify the specific features of the flow structure, capable of exerting a significant effect on detonation formation and propagation, we carefully studied the gas-dynamic structure of the flow in the setup duct. A rake of probes of the total pressure *p** and probes of static pressure *p* were used to measure the pressures at different points in different cross sections. The measurement results and their processing produce an array of data on the main gas-dynamic parameters of the flow (pressure, temperature, and velocity) at all points of the examined region, including the boundary-layer zone.

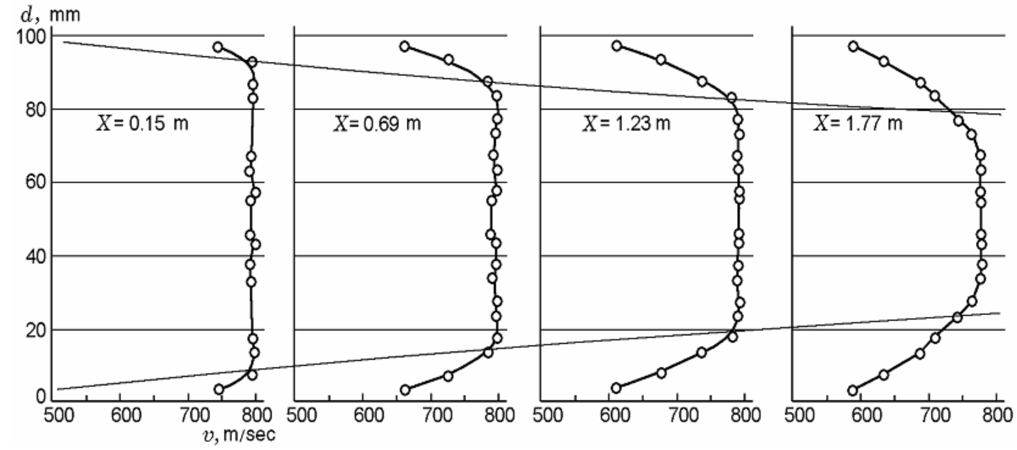

Fig. 2. Flow velocities in different cross sections of the setup duct.

4 Study of chemical homogeneity of the supersonic mixture flow

The experimental procedure included generation of an air flow and injection of helium into the air flow to form an air–helium mixture in the mixing chamber upstream of the supersonic nozzle. Gas samples were taken from the supersonic flow by a special device. The mixture samples were examined for the volume concentration of oxygen.

All experiments were performed under identical conditions: the pressure of air in the settling chamber and the pressure of helium were chosen to be identical. To check repeatability of results, gas samples were taken three or four times in each cross section.

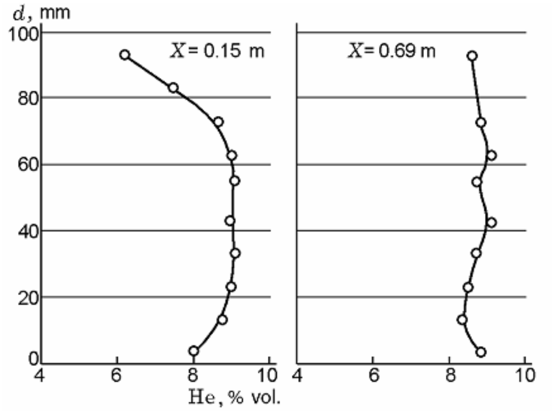

Fig. 3. Typical profiles of helium concentration across the channel.

5 Experiments with detonation combustion

After careful inspection of the gas-dynamic structure and chemical homogeneity of the flow, the final set of experiments (with detonation combustion) was performed. The experiments were performed in a wide range of hydrogen concentrations in air.

Three sets of experiments were performed:

1) with initiation of the mixture near the nozzle of the test section and propagation of the wave upstream in the supersonic flow of the hydrogen–air mixture;

2) with initiation of the mixture at the beginning of the test section (immediately behind the supersonic nozzle) and downstream propagation of the detonation wave;

3) investigation of the DW front profile by a rake of probes.

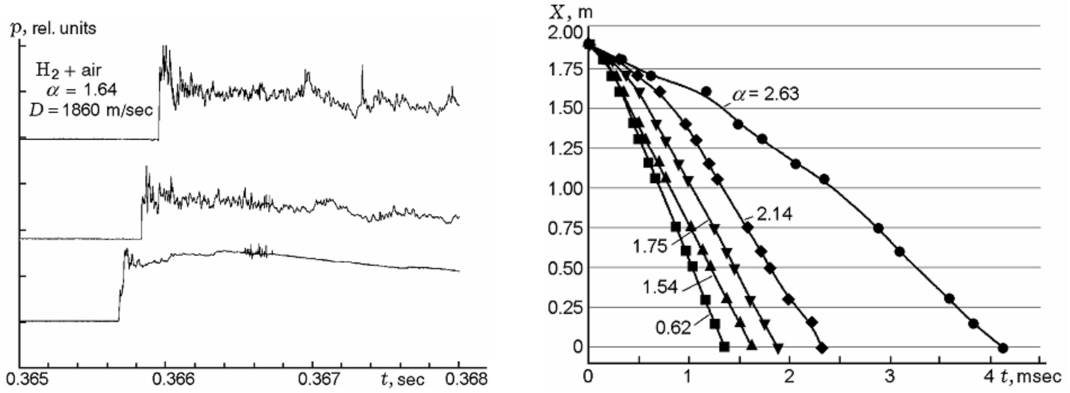

Fig. 4. Left:Typical experimental oscillograms of pressure. Right: Trajectories of the wave propagating upstream.

Thus, the research results demonstrate the possibility of formation of self-sustaining detonation combustion in a supersonic flow of a hydrogen–air mixture in a wide range of concentrations α = 0.5–2.5 for detonation waves propagating both upstream and downstream. If the composition of the mixture deviates from the stoichiometric fuel–to–air ratio toward the flammability limits, regimes of unstable detonation and extended formation of the detonation front are observed.

Detailed information on flow parameters over the channel cross section and length allows us to recalculate this velocity in the system fitted to the moving gas and to determine the DW velocity with respect to the mixture. Figure 5 shows the composite graph of the DW propagation velocity with respect to the incoming gas flow versus the air-to-fuel ratio. Results for the case of detonation propagation upstream (upper experimental points and approximating curve) and downstream (lower points and curve) are compared with the calculated Chapman–Jouguet velocity for a motionless mixture (points and curve in the middle). The experimental values are higher than the calculated ones for the upstream propagating DW and lower for the downstream propagating DW.

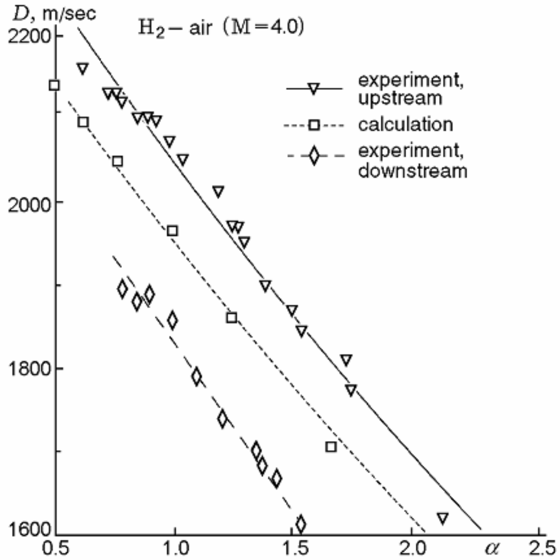

Fig. 5. Composite graph for DW velocity in a supersonic flow of the hydrogen–air mixture.

An important feature of detonation propagation in a supersonic flow is the difference in velocities of the mixture in the core flow and at the periphery (and also along the path), which “shifts” the DW front. To find the real DW shape in a supersonic flow of the mixture, we used a rake of piezoelectric transducers (14 probes), which registered the time of arrival of the wave front.

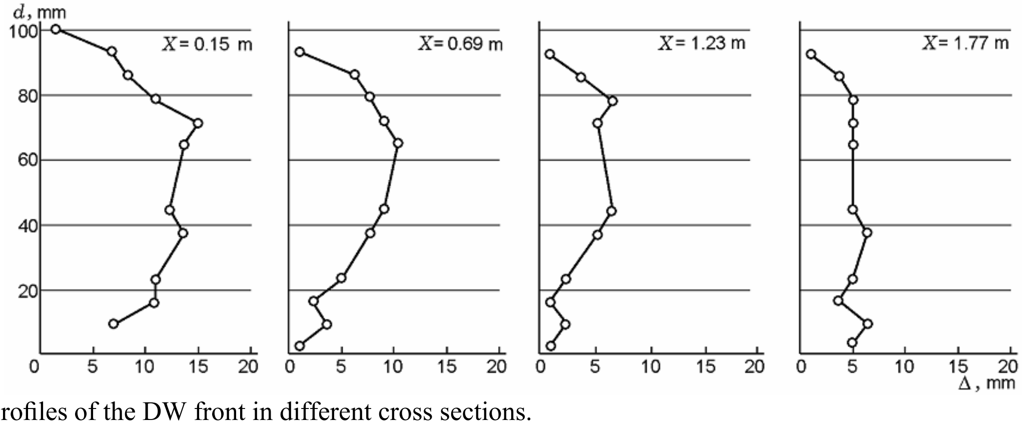

Fig. 6. Profiles of the DW front in different cross sections.