Detonation Waves in Supersonic Stream of Homogeneous Reacting Mixture

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Abstract. In supersonic stream of Mach number M=4.0 and 5.0 the profiles of pressure, flow velocity and concentration are tested carefully in different cross-sections. Investigations in hydrogen-air mixtures of detonation wave (DW), propagated upstream and downstream, are carried out. It was established that experimental values of DW-velocity at upstream propagation exceed the calculated values of Chapman-Jouguet DW for whole range of investigated values of excess air coefficients, but at downstream propagation the DW-velocity is lower in compare with CJ-velocity.

Introduction. The detonation regime ensures the maximum fast burning of a combustible mixture and, therefore, it can be used effectively in perspective hypersonic flying apparatuses (detonation engines), where traditional low-velocity burning modes are appeared ineffective. However the realization of detonative burning is delayed now because of practical difficulties in solution of some fundamental tasks.

At experimental investigation of DW propagation only motionless mixture is researched as a rule. The forming of DW in stream of homogeneous combustible mixture, driven in the channel with a supersonic velocity, is a low-investigated task. Here, in conditions of the limited supersonic stream with developed turbulent boundary layer, the propagation of DW is defined by a flow gas dynamics. The aim of this investigation is the new knowledge about the influence of gas-dynamic structure of flow on processes of mixture ignition and stabilization of combustion front. The process of origin and propagation of DW in supersonic stream of reacting mixture is considered. The realization of detonation burning in supersonic stream and an extensive information gaining about peculiarities of observable processes are the basic task of the given experimental investigation.

The practical interest to detonation regimes is stipulated by the principal possibility of creation of the supersonic pulsing detonation ramjet engine (SPDRE) [1]. The simplest

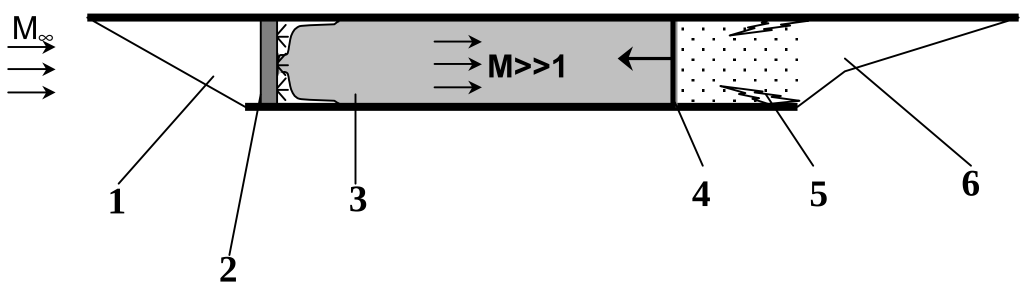


Fig. 1. The schema of supersonic pulsing detonation ramjet engine: 1 – air inlet, 2 – fuel injection system, 3 – combustible mixture, 4 – DW, 5 – ignition system, 6 – nozzle.

schema of such engine is demonstrated schematically on Fig.1. Basic elements of such engine are the next: inlet, system of fuel injection, combustion chamber, ignition system, and nozzle.

The physical process of creation of the tractive force in such engine includes some stages:

- Braking of incident flow in engine air inlet;
- Injection of fuel on an exit from inlet;
- Mixing of fuel in the combustion chamber;
- Ignition of combustible mixture on an exit from the combustion chamber, with the purpose of creation of zone with increased pressure both temperature, and formation of detonation wave;
- Propagation of detonation wave upstream of reacting mixture.

While DW is gone upstream to air inlet, the high pressure behind DW produces the tractive force, formed in nozzle of an engine. With DW approaching to air inlet, the fuel feeding decreases also, and DW damps. Then, the circumscribed cycle repeats.

The initiation and propagation of DW downstream of supersonic mixture flow has a special interest of such schema. This case was investigated in given paper also.

Experimental device. For realization of detonation burning in supersonic stream (Fig.2) the experimental device was designed and created on base of impulse aerodynamic tube [2].

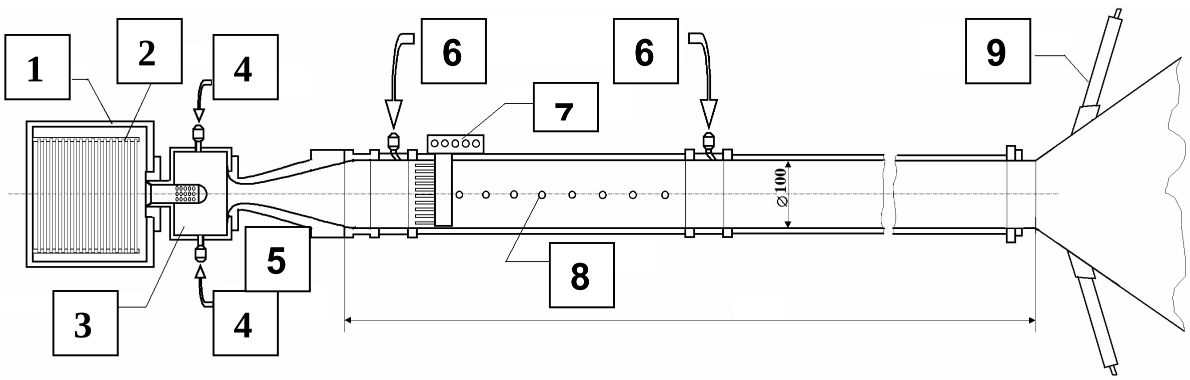


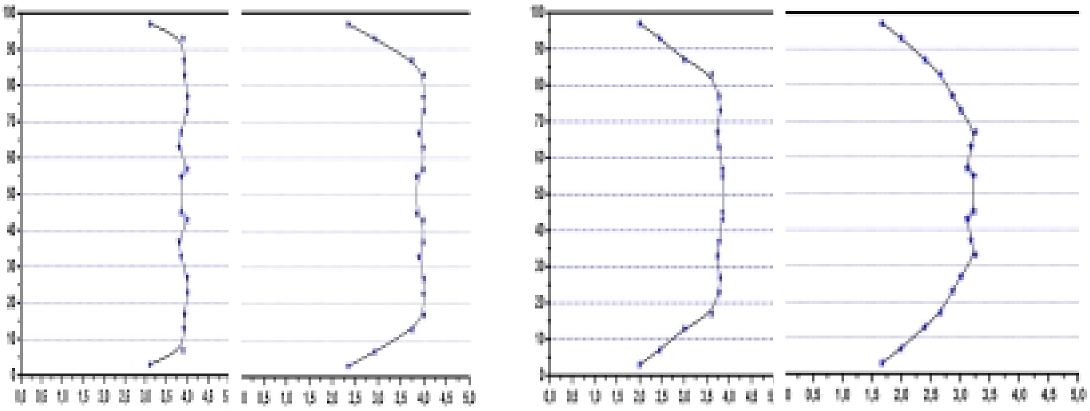
Fig. 2. The schema of experimental device: 1 – prechamber, 2 – gas heater, 3 – mixing chamber, 4 – injection of hydrogen, 5 – supersonic nozzle, 6 – gas heater, 7 – measure system for impact pressure, 8 – measure system for static pressure, 9 – ignition system

The supersonic stream of reacting mixture in channel of round cross-section (diameter 100 mm and length 2000 mm) is realized with the help of impulse aerodynamic device, which allows to ensure on each working cycle the high parameters of a supersonic stream (Mach numbers M = 3÷7, pressure in prechamber $P_{pc} \leq 200$ atm, temperature in prechamber $T_{pc} \leq 700^0$ K, regime duration $t_{reg} \leq 1$ sec). The original schema of fuel injection and mixing on an input in supersonic nozzle ensures a homogeneous stream of combustible mixture in the working channel. The DW initiation in the basic channel is carried out on each cycle with the help of additional initiator (detonation tube). With the purpose of prevention of DW propagation on a boundary layer the slot-hole injection of inert gas in a boundary layer is stipulated.

The registration of high-velocity processes is carried out with the help of high-speed multi-channels measuring system consisted piezo- both inductive pressure transducers and photo-cells. The luminescence of combustion products behind DW is fixed with the help of high-speed digital video-camera through transparent windows of a small size placed on all length of the channel.

Investigations of basic parameters and gas-dynamic structure of flow. Before experiments with mixture combustion, the careful study of flow parameters in flowing tract of experimental device was carried out. The purpose of this investigation has become of detections of singularities of flow structure, capable to render a severe influence on process of forming and propagation of detonation.

With the help of combs of impact pressure and transducers of static pressure (see Fig.2) the fields of pressure (velocities) distribution in various cross-sections along length X of flowing tract of device were investigated. The results of measurements demonstrate the known profiles of pressure and flow velocity with high homogeneity in main flow and typical changes near walls in boundary layer – Fig.3. The profile of Mach number distribution in different cross-section of a flowing tract of experimental device presents the approximate constant line with small decreasing with distance from nozzle exit –Fig.4.



X=0,15 m X=0,69 m X=1,23 m X=1,77 m

Fig.3.

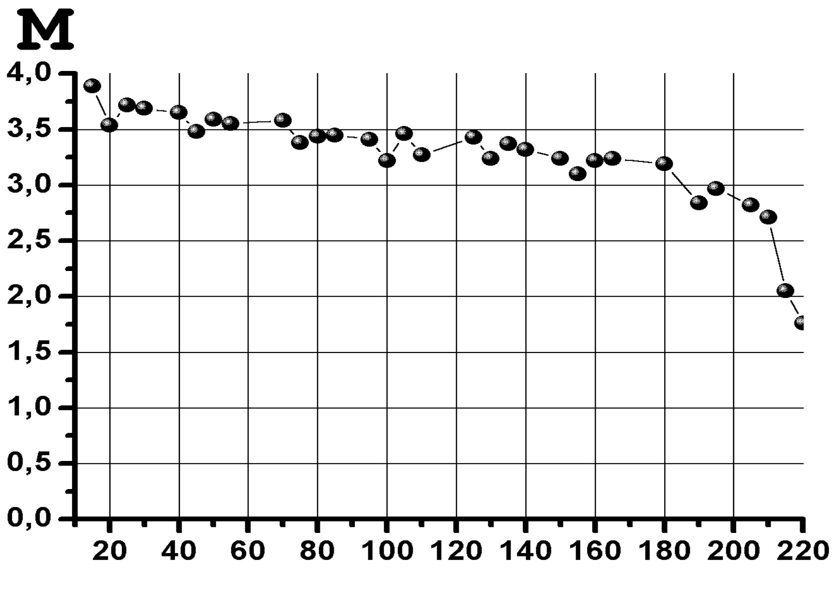


Fig.4.

Investigation of homogeneity degree of fuel-oxidizer stream. The analysis of homogeneity degree of concentration of mixture flow is one of investigation procedure.

During operating regime of device the selection of gas tests from stream with the help of combs of impact pressure was produced. The caught mixture was investigated on volumetric content of oxygen with the help of transducer-sensor «Oxic-3» of firm «PRACTIC-NC» Moscow. The main characteristics of transmitter are the next: range of measured concentration of oxygen – (0 – 30)%; output signal at air feeding in a converter – (350 – 450) mV; basic error - ± 0,3%.

Air was used as working gas in the pre-chamber of impulse device. In the mixing chamber the helium is added to an air. The helium (instead of hydrogen) was chosen in these experiments from reasons of safety and as closest gas to hydrogen on physical performances.

The volumetric concentration of helium in the tests, selected from a stream, was determined in the posterior investigations.

All experiments were carried out under identical conditions: initial pressure in pre-chamber -–70 atm, initial pressure of helium in a fuel tank -–70 atm, initial temperatures of working gas and helium – 290^o K. Time of reception of gas tests in all experiments made ~ 70 ms.

For check of recurrence of results, the selection of gas tests was carried out 3-4 times in each cross-section. The difference of the observations obtained in different experiments, in each point did not exceed 2%.

Already on length of 690 mm from nozzle exit the concentration profile is practically homogeneous (Fig.5: left – l=150 mm, right – l=600 mm), that allows to conclude about sufficient effectiveness of used mixing system and chemical homogeneity of created supersonic stream, suitable for realization of researches of homogeneous combustion.

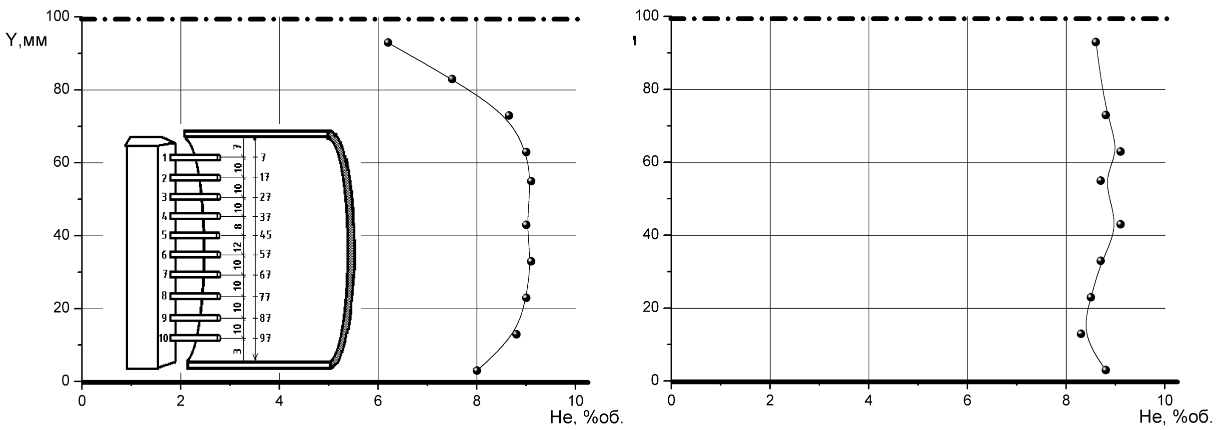


Fig.5.

Experiments with detonation. After carefully investigations of flow and concentration parameters the experiments were carried out in supersonic flow of reactive mixtures, in which detonation was initiated and then was propagated upstream to supersonic flow of hydrogen-air. The (x,t)-diagram of wave propagation at different excess air coefficient α is demonstrated on Fig.6. The corresponding profiles of detonation velocity are presented on Fig.7. One can see, that detonation regimes in supersonic flow was realized in quite broad range of α=0.5 - 2.5, and moreover – DW forming observes quite quickly, on small distance from initiation point. At removing from stoichiometric ratio up to concentration limit the only high velocity

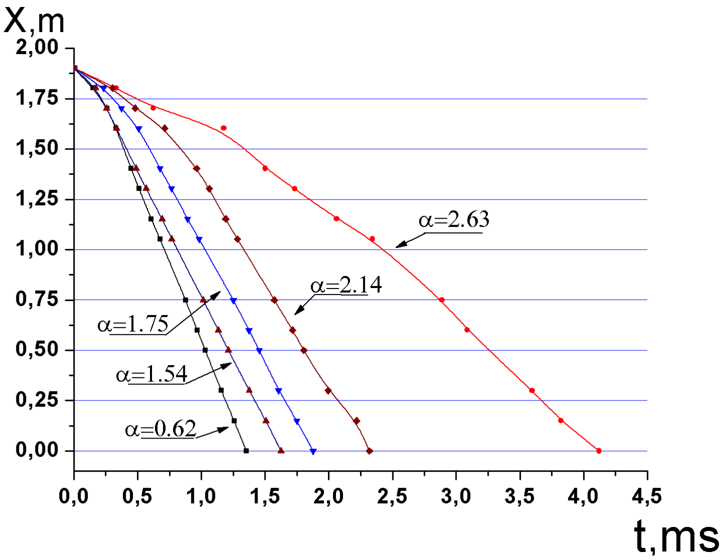

X,m
2,00
1,75
1,50
1,25
1,00
0,75
0,50
0,25
0,00
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5
4,0
4,5
t,ms
α=2.63
α=2.14
α=1.75
α=1.54
α=0.62

Fig.6.

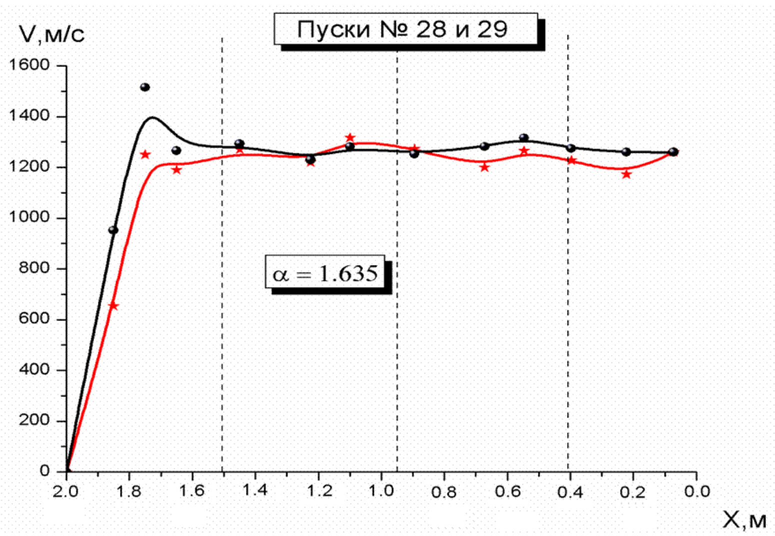

V,м/с
Пуски № 28 и 29
1600
1400
1200
1000
800
600
400
200
0
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
X,м
α = 1.635

Fig.7.

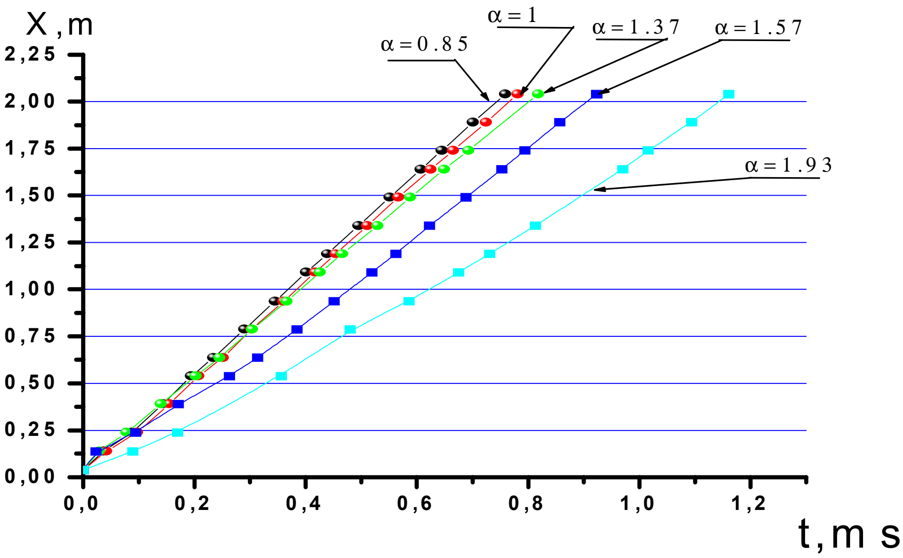

X,m
2,25
2,00
1,75
1,50
1,25
1,00
0,75
0,50
0,25
0,00
0,0
0,2
0,4
0,6
0,8
1,0
1,2
t,ms
α = 1
α = 0.85
α = 1.37
α = 1.57
α = 1.93

Fig.8.

combustion process was observed without forming of DW (line α>2.6 on Fig.6, for example). Similar tendencies are typical and for case, when DW propagates downstream – Fig.8.

Dependence of detonation velocity D (m/s) on excess air coefficient α is demonstrated on Fig.9 for cases of upstream and downstream propagation. The calculated data on Fig.9 about velocity of Chapman-Jouguet DW were received with the help of Code SAFETY [3]. One can see, that experimental velocity exceeds calculation value for any α for case of upstream propagation and is understated for case of downstream propagation.

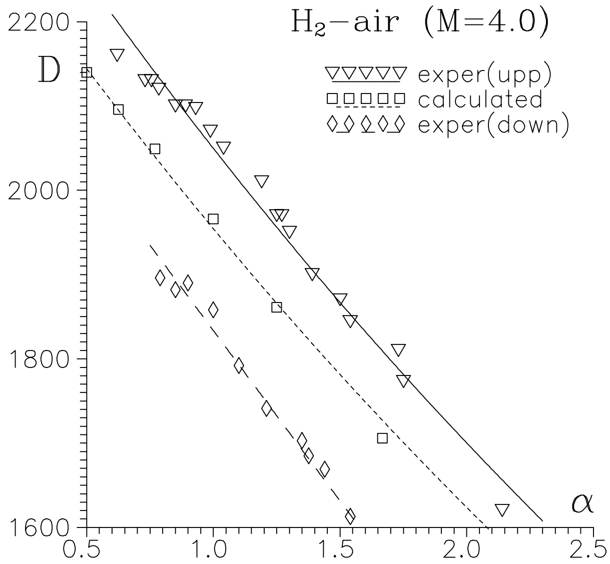


Fig.9.

The profiles of typical DW parameters were determined also: for example, profile on Fig.10 for DW velocity W (m/s) in immovable frame of reference (wall) in flow kernel and in boundary layer on distance X (m) from exit cross section of supersonic channel – velocity W in boundary layer is higher then in central flow kernel (case of upstream propagation).

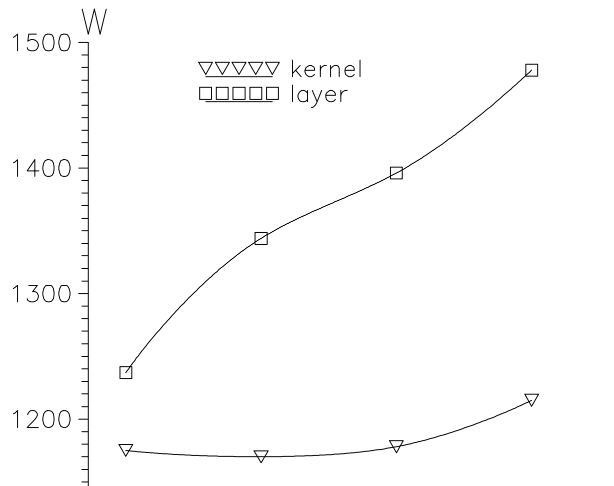


Fig.10.

Conclusion

In supersonic stream of Mach number M=4.0 and 5.0 the profiles of pressure, flow velocity and concentration are tested carefully in different cross-sections.

It was established that experimental values of velocity of DW, propagated upstream, exceed the calculated values of Chapman-Jouguet DW and understate at downstream propagation for whole range of investigated values of excess air coefficients.

The boundary layer plays important role in unusual surface of DW front in supersonic flow of combustible mixture in comparison with immovable mixture.

References

1. Alexandrov, V.G., Vedeshkin, G.K., Kraiko, A.N., Ogorodnikov, D.A., Reent, K.S., Skibin, V.A. and Cherniy G.G. Supersonic pulsed detonation ramjet engine (SPDRE) and the way of operation of SPDRE//Patent of Russian Federation No. 2157909. Priority from 26.05.1999.
2. Vasil'ev A.A., Zvegintsev V.I., Nalivaichenko D.G. Research of a detonation in a supersonic stream of a homogeneous reacting mixture//in "Materials of the Reports" V.2, International scientific - practical conference "Third Okunev's Reading ", St.-Petersburg, June 24-29, 2002.
3. Vasil'ev A.A., a.o. Methoda and calculation code «SAFETY» for determination of detonation hazards// In «Proceedings of the Second Asia-Pacific Conference on Combustion (ASPACC-99)». National Cheng Kung University, Tainan, Taiwan, May 9-12, 1999. P.594-597