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The History of the Study of Detonation

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ABSTRACT

In this article we reviewed the main concepts of detonative combustion. Concepts of slow and fast combustion, of detonation adiabat are introduced. Landmark works on experimental and semi-empirical detonation study are presented. We reviewed Chapman-Jouguet stationary detonation and spin detonation. Various mathematical model of detonation wave have been reviewed as well. Works describinig study of the instability and complex structure of the detonation wave front are presented. Numerical methods, results of parametric and asymptotic analysis of detonation propagation in channels of various forms are reviewed. It is shown that initiation of detonation is the main problem. Its various possible forms have been discussed. Laser ignition of fuel-air mixture was discussed separately and potential advantages of such initiation were demonstrated.

KEYWORDS
Detonation, detonation wave, chapman-jouguet detonation, spin detonation, detonation adiabat

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Introduction

There are two modes of combustion propagation in gas mixtures. In slow combustion mode gas burns in flame front, velocity of which is defined by transition processes: heat conductivity and diffusion (Bulat, 2014; Bulat & Ilina, 2013). During detonative combustion mode compression and heating of combustible mixture, which lead to its ignition, are carried out by shock wave of high intensity. In this case the combustion is localized inside of narrow area behind shock wave, so it has the same as shock wave velocity which can reach

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up to few kilometers per second (Bulat & Prodan, 2013a; Bulat & Prodan, 2013b).

Interest in the detonation combustion has recently increased. This is due to the development of detonation engines, which are superior to all other types of heat engines in terms of thermodynamic efficiency. A lot of reviews of studies of detonation were made, the most interesting of them are the following (Zitoun &Desbordes, 2011; Wolanski, 2010; Wolanski, 2011).

Below we review main concepts of combustion theory and various process models, which occur behind detonation wave front. The main attention is paid to the problem of detonation flow calculation, and modeling of detonation initiation process.

Literature Review

The idea of fuel detonative combustion's energetic use was developed in work of Ya.B. Zeldovich (1940), which shows analysis of detonation cycle's efficiency (Fig. 1).

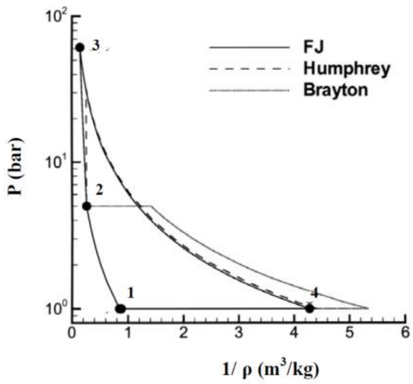

Figure 1. Thermodynamic cycles: FJ – Fickett-Jacobs detonative combustion cycle on stationary CJ detonation mode, Humphrey – combustion at constant volume, Brayton – combustion at constant pressure

The efficiency of thermodynamic cycle is defined by effective work, which can be found by calculating area that is limited by line 1-2-3-4. As you can see, the even on CJ mode the detonative combustion cycle is greatly superior to Brayton cycle.

The experimental study of detonation process application capabilities for engine development has been attempted in work of Nicholls et al., (1957) and can be applied to air-hydrogen mixture. Based on accomplished theoretical calculations and experimental research, the comparison analysis of detonation appearance and detonation in hydrogen-oxygen and acetylene-oxygen mixtures has been carried out and was continued in future (Helman, Shreeve & Eidelman, 1986). with the use of ethylene-oxygen and ethylene-air mixtures, in detonation pipes of various builds and action types.

In order to increase combustion efficiency and to establish continuous detonation mode, the rotating detonation wave have been used in works of T.C. Adamson and G.R. Shen (1967; 1972).

The possibility of standing detonation wave application for ramjets and rocket engines have been studied (Dunlap, Drehm & Nicholls, 1958). For the same purpose, the stationary spin detonation has been studied by B.V. Voitsekhovsky (1959).

The physical nature of detonation appearance and development has not been fully studied. Large gradients of gas-dynamic parameters and complex image of flow behind detonation wave make experimental and theoretical study difficult. The methods and results of experimental research on detonation waves in gas have been reviewed in work of R.I. Soloukhin (1969). He discovered the instability of detonation wave front. It has been established that detonation wave is not a flat surface, but in fact, it is a combination of constantly transforming and morphing into each other triple shock wave configurations (Fig. 2). At certain moments, the triple configurations merge into special points, at which wave structure becomes unstable. At these moments the conditions on detonation wave satisfy Chapmen-Jouguet formula for self-sustainable detonation. The distance between those special points is call length of Chapmen-Jouguet wave (λ in Fig. 2).

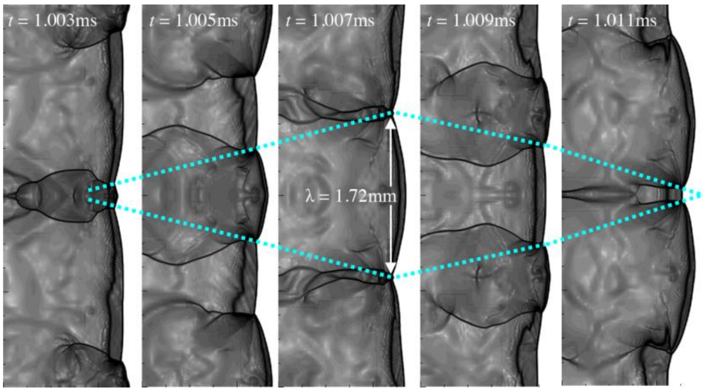

Figure 2 – Transformation of detonation wave's front with flow of time t [19]. t – time

The evolution of configurations in detonation wave and detonation wave instability to minor disturbances is described in detail in fundamental article by K.I. Shchelkin (1967). When studying detonation wave's propagation through a circular tube(Voitsekhovsky, Mitrofanov & Topchiyan, 1963) discovered an interesting phenomenon which he called spin detonation. When back pressure in channel exceed some critical value, the triple configurations of detonation front rearrange in way, that combustion front starts to move azimuthally. As a result the combustion region has a spiral-like trajectory (Fig. 3). In addition, the translational velocity precisely equals to the velocity of plane detonation wave CJ.

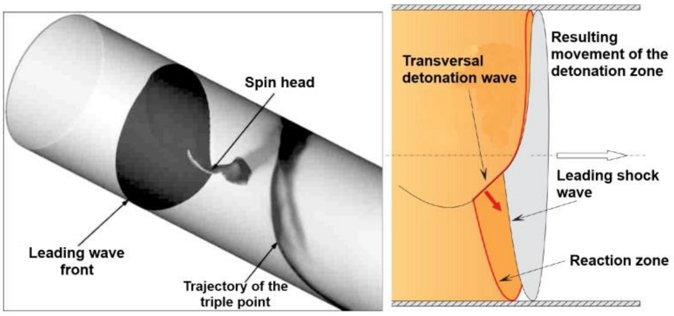

Figure 3. The structure of spin detonation in channel

The discovery of spin detonation, gave B.V. Voitsekhovsky (1960) idea to set up a radial (rotational) detonation in coaxial channel and to express the idea of rotational engine. Spin and circular detonation have been studied experimentally and systematically by F.A. Bykovsky and S.A. Zhdan (2013). The results of their long-lasting research are summarized in the monograph. A review of technical solutions in field of detonation engine design and creation, and also problems, that arise upon their realization, are given in works G.D. Roy et al. (2004) and P. Wolanski (2013).

Use of hydrogen and liquefied natural gas is one of possible development scenarios for transport and energy economics. In USA and European Union the large-scale research on using hydrogen as fuel unwraps. The management structure and infrastructure are being created and finances invested into research. Safety regulations are being developed for systems and devices that are designed to produce, store, transport and utilize hydrogen. The attraction of hydrogen use in detonation engines is wide range of detonation modes of hydrogen combustion.

Aim of the Study

Aim of the work is to highlight history of research on detonation (fast combustion), its initiation methods, and numerical modeling.

Research questions

- To review the main concepts of detonative combustion.
- To review Chapman–Jouguet stationary detonation and spin detonation.
- To review various mathematical model of detonation, numerical methods, results of parametric and asymptotic analysis of detonation propagation in channels of various forms.

Method

Deflagration is a term used to describe subsonic combustion modes. During layer-by-layer (slow) combustion, the reaction region is located in thin layer called flame front. The combustion region that emits visible light is called flame. Flame front velocity relative to initial substance is always subsonic and doesn’t exceed few dozen meters per second. The flame front of normal laminar combustion (Fig. 4, left and middle images) in gas mixtures propagates at velocity range from dozen centimeter to dozen meters per second.

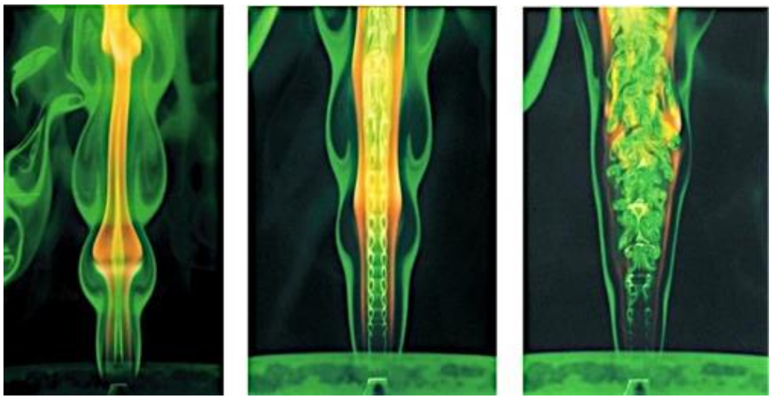

Figure 4. Laminar, transient, and turbulent combustion

During gas flow turbulization its combustion velocity and effective front thickness rises because of convective flame transfer via oscillation flows (Fig. 4, right image). Various combustion engines utilize slow combustion, and formation of shock wave in region of chemical reaction, is viewed as negative and can compromise engine integrity.

Combustion in shock wave front is called fast combustion or detonation. And such wave is called a detonation wave. The velocity of shock wave front relative to fuel components is supersonic. In detonation wave the process of fuel combustion is almost instant (100-1000 time faster than deflagration). This allows increasing pressure by one or two orders inside of semi-closed volume chamber, compared to conventional combustion engines.

The Zeldovich-Neuman-Döring (ZND) model is a basic model of detonative combustion (Fig. 5).

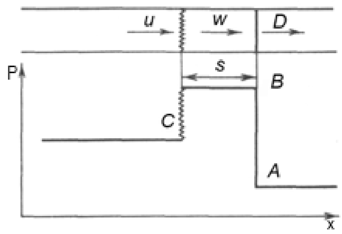

Figure 5. The Zeldovich-Neuman-Döring detonation model

D- detonation wave, w– induction region, u– combustion products, A-B– gas-dynamic discontinuity, s - region of free radical formation, C - rarefaction wave, on which chemical oxidation occurs

ZND assumes that compression of fuel mixture occurs instantly in shock wave front (D in Fig. 5). Stepwise temperature buildup in induction region (W in Fig. 5) leads to mixture ignition. The induction region extension is dependent on characteristic time of free radical formation reaction and velocity of shock wave propagation. Afterwards, the mixture burns until fully transforms into combustion product. The extension of combustion region is defined by characteristic speed of oxidation reaction, which is dependent on pressure and temperature behind shock wave. The extension of chemical reaction region behind shock wave is independent of geometric size of the devise at which detonation takes place. Because of this the region extension can often be assumed to be zero. Thus, the shock wave and infinitely thin chemical reaction region form a single detonation wave – a gas-dynamic discontinuity, on which stepwise increase of pressure/density/temperature and chemical fuel mixture-to-products transformation occurs.

It is convenient to analyze deflagration and detonative combustion in a way, similar to analyzing shocks and shock waves, by using adiabatic plane that binds pressure and specific volume (the value reciprocal to density) in various combustion modes, on assumption that combustion front extension is small and can be changed to a thin exothermic shock.

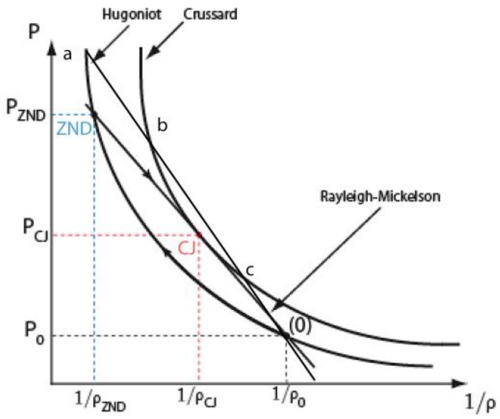

Figure 6. Detonation adiabat

CJ - Chapman–Jouguet detonation, ZND - Zeldovich-Neuman-Döring detonation, p – pressure, ρ – density.

The initial state of substance before shock wave and combustion region is characterized by parameters p_0, ρ_0. The line drawn through point of substance initial state, with parameters p_0, ρ_0,and any other point on Hugoniot adiabat is called Rayleigh-Mickelson line. Movement on Rayleigh-Mickelson line, from initial point to any other point Hugoniot curve corresponds to fuel mixture compression in leading wave. The compression process is shown in Fig. 6 via arrow on Hugoniot curve.

Gas heating and compression result in start of chemical combustion reaction. As reaction progresses, the point corresponding to initial state of fuel mixture, moves downwards on line "a - 0". This reflects linear nature of pressure change dependency on specific volume of substance, which the outcome of flow density, mass, energy and impulse conservation laws. Point "b" on detonation adiabat corresponds to complete burnout of the substance. Point "c" is unreachable.

For any value of p_0, ρ_0 there are two points at which adiabat contacts with Rayleigh-Mickelson lines. There is one point on each branch (the upper one is detonation and lower is deflagration). In addition, the upper contact point corresponds to minimal propagation velocity of upper branch, and lower one corresponds to maximum velocity of lower branch.

At the upper contact point (CJ in Fig. 6), the shock wave front moves at velocity, which is relative to combustion products lagging behind, and equals the velocity of sound. Thus, shock wave conserves its intensity, because disturbances from combustion region do not stack. In such mode the motion of shock wave and detonation region on it is uniform. The established detonation, corresponding to contact point of Rayleigh-Mickelson line and detonation adiabat, is called Chapman–Jouguet detonation (CJ). In this case the detonation model corresponds to ZND model (ZND point on Hugoniot curve).

Thus, the dynamics of Chapman-Jouguet detonation waves can be studied by using same methods that are used in study of conventional shock waves in non-reactant medium. (Bulat & Uskov, 2014; Bulat, 2013). Detonations that correspond to section above Chapmen-Jouguet point are called over compressed (strong), because density of detonation products behind their front is higher than at point. The detonation on section below CJ point is call under compressed. Based on what was said above, two important for practice conclusions can be made:

- the "left at rest" detonation wave aspires to Chapman-Jouguet detonation, i.e. higher parameters of combustion product behind detonation wave front, can only be realized in stable over compressed detonation; in case of over compressed detonation the detonation front can't be self-sustainable because front motion velocity, relative to combustion products, is supersonic.

Data, Analysis, and Results

Numerical study of detonation

The development of computer engineering has made possible to numerically model various naturals and technical occurrences with consideration of fast flowing physical-chemical processes. Numerical computations that utilize model and real kinetics of chemical reactions, has allowed to establish the mechanism of self-maintained detonation wave appearance and propagation at concentrated energy supply (such wave is always non-stationary). In addition, leading shock wave parameters periodically vary under the influence of compression waves, that form in induction region before accelerating flame front (Levin & Markov, 1975).

According to calculations, the self-oscillating process starts to develop when the amount of energy exceeds a certain critical value. Otherwise detonation wave fades, breaking down into shock wave and wave of slow combustion. If explosion energy is close but doesn't exceed critical, the detonation starts to fade after few oscillations.

In research of non one-dimensional structure of detonation wave with use of two-stage kinetics the development process of plane detonation wave disturbance , which leads to formation of visible in experiment cell structure (Fig. 5) of two-dimensional detonation has been examined (Levin et al., 2005).

The existence of minimal and maximal cell size has been established and also the key role of transversal waves during non-one-dimensional wave initiations and propagation, especially during wave transition into expanding channel, has been defined.

The problem of point explosion in combustible gas mixture (Fig. 7) was studied by V.A. Levin, V.V. Markov & S.F. Osinkin (1981) taking into account finite velocity of occurring chemical reactions for flows with plane, cylindrical and spherical symmetry. For motions with cylindrical and spherical waves, the dependency of region minimal radius, at which detonation occurs in environment, on value of pressure inside the region, has been acquired.

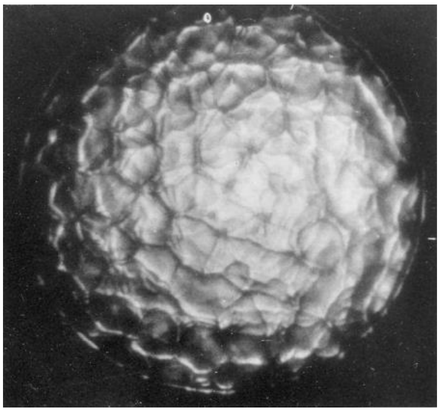

Figure 7. Cell structure of detonation wave's front at point explosion

L.I. Sedov has formulated a two-dimensional model, by using which the structure of two-fronted spin detonation has been calculated (Sedov, Korobeinikov & Markov, 1986).

The study of wave process during detonation propagation in plane complexly-shaped channels filled with air-hydrogen mixture at standard conditions with real kinetics of chemical interaction taken into account, has been carried out (Levin et al., 1998).

The influence of obstacle in channel on cell detonation wave propagation process has been studied. The obstacle is indestructible, transversal, and has parallel walls, length of which is shorter that channel width (Fig. 8) and positioned across the channel (Teodorczyk, Lee & Knystautas, 1991).

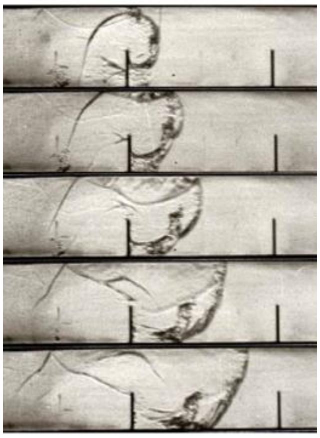

Figure 8. The study of obstacle's influence on detonation wave in channel

It has been established, that obstacle has a critical height (it depends on channel width), upon exceeding which the combustion detonation mode fails.

If detonative combustion is preserved, after wave passes the obstacle, the detonation wave cell structure reforms after a while. In case of detonation fail, after passing the obstacle, the possibility of its reformation via additional obstacle if same properties has been established.

In case when obstacle higher than critical height is destroyed, the influence of its existence time on detonation propagation process has been studied. In order to preserve combustion detonation mode, the obstacle existence time must not exceed some critical value. The conditions to preserve cell detonation wave in channel blocked by destructible transversal obstacle has been established.

The transition of formed cell detonation wave from channel with constant cross-section to suddenly expanding channel was investigated. In case when detonation enters suddenly expanding part from channel, width of which is lower than a half of critical width for detonation wave to enter the open space, the detonation mode is preserved, if expansions width doesn't exceed some critical value.

The problem of detonation stability in supersonic flow inside channels and pipe was investigated. It was shown in two-dimensional setup, that non-stationary pulsating detonation wave that propagates upwards by flow, can be localized by applying energy via low intensity electric discharge, at certain moments in time. In setting of quasi one-dimensional approach, the regularities in wave behavior have been established and shown the possibility of wave stabilization via channel special shape. Quasi-stationary and two-dimensional non-stationary models designed the work cycle of pulsating detonation engine, have been formulated in the work V.V. Mitrofanov & S.A. Zhdan (2004). The formula for specific impulse has been derived and engine thrust properties have been calculated

Research of detonation initiation

In order for detonation to form, the existence of powerful shock wave, capable of igniting the combustible mixture, is necessary. One of creating such wave is concentrated supply of energy – energy emission according to any law in some volume during short enough time period. In case of such initiation the gas combustion can occur in detonation wave and flame front. For instance, as time flows, the detonation wave can split into conventional shock wave and slow combustion front following it.

The most complete numerical research of detonation's initiation taking into account mechanism of occurring chemical processes, has only been carried out for mixtures hydrogen-chlorine and hydrogen-oxygen mixtures. The initiation of spherical and cylindrical detonation through energy application via electrical discharge in hydrogen-chlorine mixture, has been researched by V.A. Levin (Levin, Markov & Osinkin, 1981; Levin, Markov & Osinkin, 1984).

The nature of flow development and realization of combustion mode is conjugated with mutual influence of gas-dynamic and chemical processes and is dependent on initial composition (Bokhon & Shulepin, 1979; Lee, 1977) and state of the medium (Mitrofanov, 1982), initiation method and amount of applied energy (Knystautas & Lee, 1969) and conditions, at which initiation occurs (inert gas interlayer, solid casing).

Regardless of concentrated supply method, it is impossible to achieve detonation if the amount of energy is low. At the initial stage of flow development, when energy emitted from chemical reactions, compared to explosion, is low because of intense rarefaction wave that is present behind explosive wave, the ignition delay time drastically increases and combustion region promptly lags behind the frontal wave. As a result, the formed over compressed detonation wave splits into conventional compression shock and slow combustion front, velocity of which is defined by transfer processes.

With increase of explosion energy the shock wave fades more slowly, spread of gas-dynamic parameters, behind of it at sufficient distance from appearance site, becomes smoother at shock wave intensity sufficient enough to ignite the mixture. This leads to slow down of ignition region deviation from shock wave. The heat emission caused by mixture burnout outside of ignition front stimulates leveling and increase of mono-dynamic parameters in induction period, leading to decrease of ignition delay Heat supply can cause instability of flow behind shock wave and appearance of powerful transversal waves that intensify process of heat emission (Soloukhin, 1963). This results in either preservation of detonative combustion or its regeneration after over compressed detonation split.

In case of point explosion in resting gas mixture, cause by piston motion or concentrated energy supply, via laser for instance, the detonation wave, which is over compressed at the moment of appearance, propagates throughout the gas. As time flows, the detonation wave weakens (Fig. 9) and switches to Chapmen-Jouguet mode at finite distance from source of ignition (Markov, 1974).

With the increase of initial gas density at constant temperature and with decrease of detonation initiation energy, the distance at which this transition occurs reduces. The plane wave remains over compressed when distancing from initiation site, and its velocity asymptotically reaches the velocity of Chapmen-Jouguet wave.

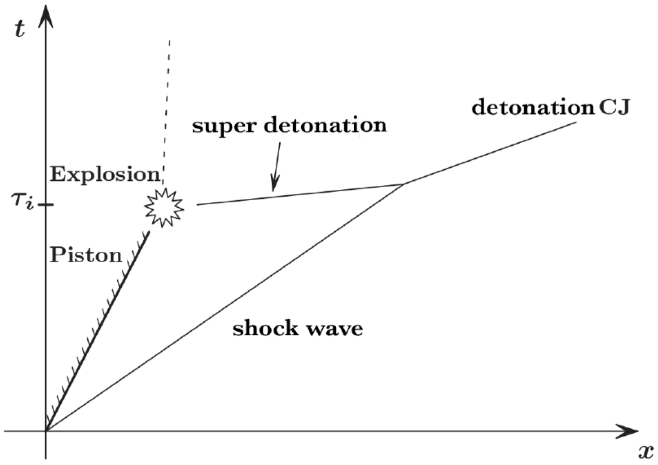

Figure 9. Transition of spherical detonation to Chapmen-Jouguet mode. τi - the moment of explosion

There is a critical value of initiation energy E*, the detonation starts to form only if this value is exceeded. In over critical cases, when detonative combustion starts at the moment of energy supply, a decent model for describing occurring flow is a model of infinitely thin detonation wave.

For a set of combustible gases the existence of critical initiation energy has been established and studied. When initiating spherical detonation with an electric spark, the critical energy is proportional to cube of detonation wave thickness or ignition delay. Carrying out of experiments on establishing critical energy is opposed by significant difficulties, which leads to the need of assessing the critical energy values (Troshin, 1979). At the initial stage of flow development, it is essential to take into account the kinetics of occurring chemical reactions, because the mutual influence of gas-dynamic and physical-chemical processes define the value of critical initiation energy.

In aforementioned work by V.A. Levin, V.V. Markov & S.F. Osinkin (1995) the values of critical energy when detonation is initiated with piston, electric discharge, exploding wire, TNT charge, was found and defined its dependency on combustible mixture parameters and space-time characteristics of energy sources, explained the, known from experiments, anomalous dependency of critical energy from duration of applied electrical charge. According to calculations, its conjugated with existence of specific energy application time, during which almost all gas mass, involved in formation of powerful shock wave that propagates through combustible mixture, flows out of charge's region, resulting in a strong density drop in said region. As a result, most of the input energy is then used to heat the remaining mass of the gas.

V.A. Levin, V.V. Markov & S.F. Osinkin (1995) have established dependency of critical energy on parameters of mixture, that forms as a result hydrogen diffusion into air from a point or a finite spherical volume. The detonation fades, is spherical charge is surrounded by an air layer, outer radius of which exceeds some critical value that is proportional to charge's radius.

For the case where a shielding air layer is located inside of combustible mixture and doesn't contact with a charge, the dependency of its minimal critical thickness on inner radius and energy of explosion has been derived. The critical energy is reduced by an order, if the spherical charge is surrounded by a hard shell of certain radius that is destroyed after some time after interacting with frontal shock wave.

The study of detonation original excitement mechanism was carried out. The possibility of initiating detonation in hydrogen-air mixture with collapse of spherical low pressure region with no additional energy supply from outside, has been established. The calculations conducted with various initial radiuses of collapsing sphere and pressure inside showed that even at normal conditions in external space, after the reflection of converging shock wave from flow symmetry center the self-sustaining detonation wave appears (Korobeinikov & Levin, 1969).

The detonation initiation in supersonic flow of hydrogen-air mixture with electric discharge with homogenous and non-homogeneous energy emission into space was studied (Westbrook & Dryer, 1984). The influence of discharge time and velocity of supersonic flow on detonation's formation was investigated. Established critical energies at detonation initiation with electrical discharge in a form of plane layer, and studied detonation dependency on charge layer thickness. The monotonous decrease of initiation energy with the decrease of the layer takes place in all reviewed cases. At relatively large values of layer thickness, the initiation occurs with only part of charges total energy, which ensures propagation of sufficiently intense frontal shock wave for a period of time close to formation of stable chemical reactions region with intense heat emission.

In case of instant electric discharge with non-uniform energy spread across the channel according to sinusoidal law, it is possible to decrease critical initiation energy via reflected from channel walls, powerful transversal wave, that forms when energy is supplied. The influence of energy supply duration and supersonic flow velocity on detonation formation, at non-uniform energy spread through the space of the discharge, has been studied. In addition, the effect of initiation energy growth with increase of discharge duration and flow velocity was studied.

The fundamental difference of laser initiation from other methods (explosion, electric discharge, surface heating, and spark) is a possibility of remote and almost instant excitement of process in large volumes of combustible mixture. The laser beam configuration (a ring or a stretched rectangle, for instance), can form not only divergent, but also plane or convergent combustion wave front, or a shock wave front in cans of plasma formation.

Discussion and Conclusion

Because of the attempts to use detonative combustion in engine setups, the fundamental problems of detonation in multi-dimensional statement of the problem and at non-stationary conditions are being widely researched. The initiation detonation and its stabilization in combustion chamber of limited volume, also has value for practical purposes.

The classic ZND model is the most basic one. It assumes that fuel mixture combusts instantly behind compression shock and detonation wave is a surface of strong discontinuity of gas-dynamic parameters (Fig. 2), which releases chemical energy (Grib, 1944). This model can be applied, if reaction region is compared to characteristic size of flow region.

In setting of classic model of infinitely thin detonation wave the properties of detonation wave have been studied thoroughly and many of problems of non-stationary one-dimensional and stationary two-dimensional gas-dynamics have been solved. Among those problems are: problem of gas motion behind detonation waves that propagate from infinitely low intensity ignition source in medium with constant or variable by radius starting density (Zeldovich, 1942); problem of detonating gas flow over cone (Kvashnina & Cherny, 1959); problem of arbitrary discontinuity breakdown in combustible mixture (Bam-Zelikovich, 1949), problem of detonation wave stability (Pukhachov, 1963).

By using analytical method, the laws of one-dimensional slightly over compressed infinitely thin detonation wave fading for all flow symmetry types, have been derived (Levin & Cherny, 1967; Cherny, 1967). The discovered laws have been proven later by numerical computations of flows that appear at point explosion in combustible gas (Markov, 1981). Specifically, it has been established that plane detonation wave changes to Chapmen-Jouguet mode at infinitely remote point, while cylindrical and spherical do so at the end destination from point they formed at.

After the shock wave structure of detonation has been established in experiments, the need of more adequate gas-dynamic and mathematical model arose. As the scientific view of detonation broadens the gas-dynamic models become more complex as well. The model proposed by V.P. Korobeinikov and V.A. Levin (1969) differs from ZND model, by describing non-stationary processes behind the front of detonation wave (the Euler equations, complimented by two model equations of chemic kinetics, one of which describes delay of ignition, and second – heat emission, are used). The model is successfully used to describe detonation's wave structure.

In setting of two-stage model, by using method of small parameter, the starting stage of flow development at point explosion was studied, which lead to the discovery of detonation wave disintegration phenomenon leading shock wave (monotonous increase of distance between intense heat emission region and frontal shock wave) (Korobeinikov et al., 1972).

Implications and Recommendations

We reviewed the history of research on problems, conjugated with detonative combustion. With changing concept of detonation the more complex its model became. First, the detonation wave was described as infinitely thin surface of parameters discontinuity (the ZND model), later the two-stage V.P. Korobeinikov and V.A. Levin (1969) model that takes into account influence of chemical transformations, occurring in combustion region, on parameters of leading wave, was used for the description. The next step was the concept of complex non-stationary tri-dimensional structure of detonation front. It was shown that over compressed plane wave asymptotically aspires towards stationary Chapmen-Jouguet detonation, but never reaches it. In case of cylindrical or spherical detonation its changes to Chapmen-Jouguet mode for a finite period time. This detonation is self-sustained. For detonation wave to appear, the fuel mixture must be supply with energy that exceeds some critical value, which is called critical initiation energy. If supplied energy is lower than critical than detonation occurs in standard mode. The various detonation initiation methods, such as spark, electrical discharge, ignition device, point explosion in enclosed volume, laser beam, has been studied. It was showed that laser beam can initiate over com-pressed detonation, including detonations with plane and converging front. Detonation wave propagation in channels with various configurations was reviewed. Detonation high combustion speed makes it attractive for application in jet and rocket engine. The thermodynamic efficiency of detonative combustion cycle is at least 25% more efficient that Brayton's cycle even at least efficient Chapmen-Jouguet mode. Switch to over compressed detonation drastically boosts detonation cycle efficiency.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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