

THEORETICAL AND EXPERIMENTAL INVESTIGATION OF A SHOCK WAVE
STRUCTURE IN MICROPOROUS LIQUIDS

E.A. Bushmanov, V.Yu. Velikodnyi, V.P. Vorotilin, A.V. Ereemeev, I.B. Timofeev*,
Yu.G. Yanovsky and D. M. Van Wie**

Institute of applied mechanics RAS Moscow, Russia,

*M.V.Lomonosov Moscow State University, Moscow, Russia, E-mail: igortim@orc.ru,

**Applied Physics Laboratory The Johns Hopkins University, USA

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

Introduction

Developing of new prospective samples of hypersonic air vehicles with Mach number of flight $M \geq 5$ requires a development of new engines since the efficiency of conventional jet-engines sharply decreases in this case. It is supposed to apply detonation and scram jets in this velocity range. One of the main requirement of such engines developing, testing and running consists in existence of cheap technological fuel. This fuel has to satisfy to ecological performance, it has to ensure a stable work of a scram jet at Mach numbers $M=3,5 \div 14$ and of a detonation engine at $M=0 \div 9$. Main direction of investigations is connected with such a fuel creation on basis of the aviation kerosene. In fact there is a problem of new fuel type creation with controlled physical and chemical properties depending on flight conditions.

It is well known [1,2] that preliminary bubbling of the liquid fuel (for example of the aviation kerosene) by an oxidizer (air, oxygen saturated air) or by flammable gases (CH_4 , H_2 , C_2H_2) essentially improves its spraying characteristics, mixing, range of a stream, and it decreases an ignition delay time. Generating of initial radicals, products of CO , H_2 , H_2O incomplete burning, products of $\Sigma \text{C}_x\text{H}_y$ conversion and cracking during this process can essentially decrease an induction time of chain reactions at lower initial temperature of the air-fuel mixture(see. [2,4]).

All these factors in aggregate favorably influence development of combustion and detonation processes. In the work are presented means and results of new device tests, which insure generating of "activated porous fuel" on liquid hydrocarbon basis and have indicated above advantages as a unit.

20050504 091

Analysis of physical processes and tests of devices for “activated porous fuel”

generating

Activated porous fuel generating process consists of the following consequently accomplishing stages:

1. Preliminary bubbling of initial fuel (for example of the aviation kerosene, straw oil, and mazut) under pressure of a disperser;
2. After transmission of it through a cavitator, where the following bubble splitting takes place;
3. Shock wave splitting of a gas-disperse mixture;
4. Dispersion of this mixture to the air stream.

A principle scheme of a device that insure a realization of all pointed out above processes is represented in Fig.1. All its main units are made of a transparent material-the organic glass. This allows to undertake visual observations of processes inside this device and with a help of these observations to select optimal modes of its work. A work of the device takes place in a following way. An initial liquid (a fuel) comes under pressure to an area in front of a disperser, through which a gas is forcing 8 (with a diameter of pores $40\div 100\ \mu\text{m}$) by a tube 10 (a diameter of a transmitting cross section is $5\div 7\ \text{mm}$). Created initial gas-disperse stream comes to a cavitator 4 (with the ratio of the transmitting cross section to the width $2,5:10\div 4:15$) through the basket 7 (with a size of a cell $0,5\div 1\ \text{mm}$). There the following splitting of bubbles takes place.

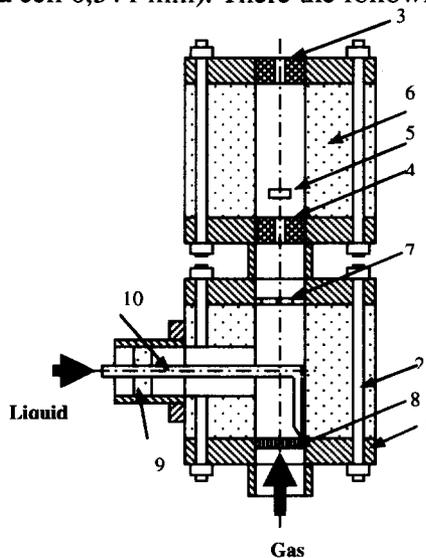


Fig.1. The scheme of the working part of the set up: 1 – the aluminum flange; 2 – the tightening pin; 3 – the sprayer; 4 – the cavitator; 5 – the shock wave generator; 6 – the body of the organic glass; 7 – the metallic basket; 8 – the disperser; 9 – the sealing device; 10 – the plastic tube, 11 – the transmitting working channel.

3 Workshop “Thermochemical processes in plasma aerodynamics”

After that the stream of the gas-disperse mixture having a velocity 40 – 80 m/s interacts with a shock wave generator 5 (a cylinder with the ratio of its diameter to its length 3:17÷5:17), which is located perpendicular to a flow. Then the gas-disperse stream comes to a sprayer 3 (with the ratio of its diameter to its width 2:10÷3.5:10). A diameter of transmitting working channel 11 is $D=18,5$ mm.

The key physical phenomenon, which is used in this device, is that a sound velocity in a gas-disperse medium can be two orders of magnitude smaller than in a pure liquid and by an order of magnitude smaller than in a gas. According to [5] the sound velocity value in the medium with the bubbles, which diameter is $d \sim 0,01$ mm, can be calculated on basis of the following equation:

$$a^2 = \frac{\partial p}{\partial \rho} = \frac{\kappa}{\rho_2 \varphi_1 (1 - \varphi_1)} p, \quad (1)$$

where a is the sound velocity, κ is the polytrope exponent, p is pressure, ρ is a liquid density, φ_1 is a volume gas content. The formulae (1) is valid at $0,1 < \varphi_1 < 0,9$. The sound velocity a at $\varphi \rightarrow 1$ works for the sound velocity a_g in the gas, but at $\varphi \rightarrow 0$ it works for the sound velocity in the liquid a_{liq} . The minimum of the sound velocity is reached at the volume gas content $\varphi = 0,5$. For example, its value is $a = 23$ m/s at $p = 1$ atm, and $a = 7$ m/s at $p = 0,1$ atm. It appears from this that the stream velocity equal to the sound velocity is easily reached at rather moderate pressures $p_{10} \geq 5$ atm, and at the volume gas contents at the inlet of the cavitator $\varphi_{10} \geq 0,2$.

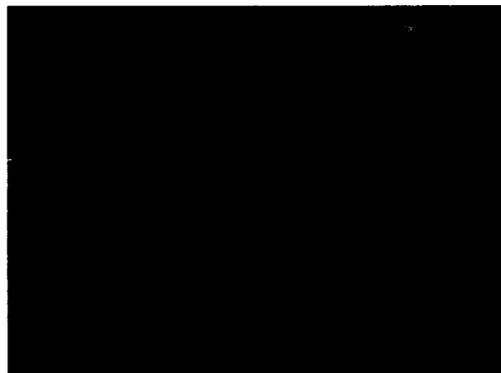


Fig.2. Shock wave in microporous liquid at $M=1,5$; $\varphi_1 = 0,7$; $C_1 = 40\text{m/c}$

In the photo 2 one can see a set up for “activated porous fuel” generating in working condition. The shock wave front, appearing during the gas-disperse stream flowing around the cylinder, is distinctly seen. In this case the water was used as a liquid and the air as a gas. The

3 Workshop “Thermochemical processes in plasma aerodynamics”

gas-disperse stream parameters are $M_I=1,5$, $\varphi_I \cong 0,7$, $C_I=40$ m/s (where C_I is a velocity of the gas-disperse stream скорость).

It is interesting to apply effects taking place at the shock wave impact on the microporous liquid (fuel) for its preliminary treatment by realization of the conversion and cracking processes, generation of radicals, partial oxidizing before spraying to a supersonic flow or a detonation chamber. Preliminary estimates and calculations of processes in some units of the device have been made (see Fig.1-2). A theory for a description of a shock wave structure in a gas-disperse flow with high volume gas content $\varphi_I \cong 0,3+0,95$ has been developed. An analytical solution of a problem has been obtained. A theory of the turbulent microporous stream mixing with a flow of the oxidizer has been developed as well.

A shock wave structure in a microporous liquid

The shock wave treatment of the “activated porous fuel” is the main technological process at its preparation. In the result there can be realized the isothermal shocks (temperatures of the liquid and the gas phases are equal), the adiabatic shocks (the gas phase temperature is considerably higher than the temperature of the liquid phase) and the intermediate variants at the gas-disperse stream interaction with the shock wave generator with respect to Mach number and the volume gas content. The model conceptions about the heterogeneous medium as the system of the interpenetrative components (phases) [6] were put to a basis of the theory of the shock wave structure in the microporous liquid. The cell model of the heterogeneous medium is used for the description of the dissipative mechanisms. It consists in the idea that the definite volume of the liquid “a cell” [6] corresponds to each bubble. Besides, the ideas and conceptions developed in [7,8] were used for the description of transport mechanisms and dissipative processes in the shock wave. Their essence consists in the following: separately each phase represents two groups that are characterized by their mean gasdynamic parameters. Each group in its turn consists of the cells (a bubble and the volume of the liquid connected to it). Interaction and the diffusion of the groups in the shock wave front is realized due to the turbulent transport of the cells. The dissipation and energy exchange between the cells takes place at the interface. The additional condition used by us at derivation of initial equations for the description of the shock wave structure in the microporous medium is the supposition that the enthalpy of the liquid does not change in the shock (see. [5]). With account of all said above we have:

$$\rho_I^g \varphi_s^g c_I + \rho_{II}^g \varphi_r^g c_{II} = A_{II}, \quad (1)$$

3 Workshop "Thermochemical processes in plasma aerodynamics"

$$\rho_l \varphi_s' c_l + \rho_l \varphi_\tau' c_{II} = A_{12}, \quad (2)$$

$$\varphi_s^g + \varphi_\tau^g + \varphi_s^l + \varphi_\tau^l = 1, \quad (3)$$

$$\rho_s c_l^2 + P_l(\varphi_s^g + \varphi_s^l) + \rho_\tau c_{II}^2 + P_{II}(\varphi_\tau^g + \varphi_\tau^l) = A_{13}, \quad (4)$$

$$\frac{\rho_s c_l^3}{2} + \frac{\gamma}{\gamma-1} P_l \varphi_s^g c_l + \frac{\rho_\tau c_{II}^3}{2} + \frac{\gamma}{\gamma-1} P_{II} \varphi_\tau^g c_{II} = A_{14}, \quad (5)$$

$$\begin{aligned} & \frac{d}{d(X/d_{bab})} \left\{ \frac{\gamma-3}{2(\gamma-1)} (P_l \varphi_s^g c_l + P_{II} \varphi_\tau^g c_{II}) \right\} = \\ & = -\frac{4}{\sqrt{\pi}} \sqrt{\frac{2}{3}} \frac{n M_l^2}{\varphi_l^{2/3} (1-\varphi_l)^{4/3}} \Gamma_{11} \left(1 - \frac{c_{II}}{c_l} \right)^3 \varphi_s^l \varphi_\tau^l, \end{aligned} \quad (6)$$

where $A_{11}, A_{12}, A_{13}, A_{14}$ -are known constants, ρ_l - is a density of the liquid phase, ρ_l^g, ρ_{II}^g -are densities of the gas phase in the incident flow and behind the shock, respectively, c_l, c_{II} - are the flow velocities before and behind the shock wave, P_l, P_{II} - pressure before and behind the front, $\varphi_s^g, \varphi_\tau^g$ - volume contents of the groups from the gas phase, $\varphi_s^l, \varphi_\tau^l$ - volume contents of the groups from the liquid phase- are the variables dependent on the current coordinate -X, n- is the polytrope exponent, M_l - is the Mach number in the incident flow, Γ_{11} - is know constant (see [8]), φ_l -is the volume gas content in the incident flow, $\rho_s = \rho_l^g \varphi_s^g + \rho_l \varphi_s^l$; $\rho_\tau = \rho_{II}^g \varphi_\tau^g + \rho_l \varphi_\tau^l$.

So c_l and P_l can be considered as constant equations (2)-(7) have an analytical solution. The values of $c_l, c_{II}, P_l, P_{II}, \varphi_l, \varphi_{II}$ are connected by the relation of Rankine and Hugoniot type for the disperse media in this case [5,6]:

$$\varphi_s^l = \frac{1 - \varphi_l}{1 + \exp\left(|B| (1 - \varphi_l) \frac{X}{d_{bab}} \right)}, \quad (8)$$

where X-is the current coordinate, d_{bab} -is the microbubble diameter,

$$|B| = \frac{4}{\sqrt{\pi}} \sqrt{\frac{2}{3}} \frac{n M_l^2 (1-\varphi_l)}{\varphi_l^{2/3} (1-\varphi_l)^{4/3}} \Gamma_{11} \frac{\left(1 - \frac{c_{II}}{c_l} \right)^3}{\frac{\gamma-3}{2(\gamma-1)} \left(\frac{\varphi_l P_{II} (1-\varphi_l)}{\varphi_l P_l (1-\varphi_l)} - 1 \right)}, \quad (9)$$

all the other variables $\varphi_\tau^l, \varphi_s^g, \varphi_\tau^g$ can be expressed through φ_s^l

Using (2)-(9) one can determine the pressure and the temperature distributions in the microbubbles, the density in the shock wave front and the shock wave width:

3 Workshop "Thermochemical processes in plasma aerodynamics"

$$\frac{d_{bab}}{\delta} = \frac{\left(\frac{d\rho}{d(X/d_{bab})} \right)_{\max}}{\rho_{II} - \rho_I}, \quad (10)$$

where δ - is the shock wave width. So we have

$$\frac{d_{bab}}{\delta} = \frac{|B|}{4}(1 - \varphi_I), \quad (11)$$

In Fig. 3 there is presented the variation of the ratio of the microbubble diameter in the incident flow, and the shock wave width with respect to the Mach number at different values of the volume gas content. One can make conclusions important for practical applications on a basis of data presented in the figure. The shock wave width is wide at the gas content decreasing $\varphi_I \leq 0,45$, and the isothermal shock is realized. The temperatures in the microbubbles and in the liquid phase are approximately equal in this case. So the fuel conversion and cracking in the shock wave does not have place even at considerable energy input to a flow $M_I \approx 5 + 10$.

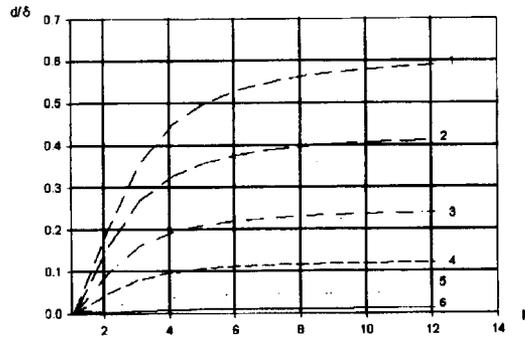


Fig.3. Dependences d/δ from Mach number at different gas content, polytropic exponent $n = 1,4$: 1 - $\varphi_I = 0,9$, 2 - $\varphi_I = 0,8$, 3 - $\varphi_I = 0,7$, 4 - $\varphi_I = 0,6$, 5 - $\varphi_I = 0,5$, 6 - $\varphi_I = 0,4$

The shock wave width is small at $\varphi_I \geq 0,7$, and the adiabatic mode of the SW formation is realized in this case. The gas temperature in the bubbles is considerably higher than the liquid phase temperature. Physical and chemical process are intensively realized in the bubbles already at the Mach numbers $M_I = 4-6$. The variation of the maximum achieved temperature in the microbubbles during the compression in the shock wave with respect to the Mach number is presented in Table at $\varphi_I = 0,8$.

3 Workshop “Thermochemical processes in plasma aerodynamics”

Table

M_1	2,8	3,5	4
T_{II} °K	962	1415	1758

Estimates of the mixing parameters of the turbulent porous stream in the drifting air flow

One the main important technological processes during the preparation of the “activated porous fuel” is its mixing with the oxidizer flow. Preliminary studies have shown that the stream spraying angle considerably increases (up to two times) at the increase of the volume gas content φ_1 , the range of the gas-disperse stream increases and the thinness of the dispersion improves also. In order to facilitate the search of the model optimal working modes simultaneously with the set up for generating of “the activated porous fuel” the theory of the turbulent porous liquid stream interaction with the transversal gas flow has been elaborated.

Formulation of a problem and derivation of equations describing the turbulent stream motion in the drifting flow

The mechanism of the capture and the derived from it the capture velocity value for the direct stream flow were substantiated earlier in [9]. It was made on a basis of the conception of the stream flow as the continuous chain of the large scale vortices. At the separating flow around them the capture of the liquid from the area of the external potential flow takes place. In the present paper we consider the generalization of the problem for the case of the turbulent stream flowing in the drifting flow of the external gas.

Let us consider the following formulation of the problem. The turbulent stream of the porous liquid flows out of the circular hole of r_0 radius at the initial velocity u_0 and the density ρ_0 into the space of some external gas. This gas moves in the direction of the axis x with the density ρ_∞ and the velocity u_∞ . The principle scheme of the flow is presented in Fig.4.

3 Workshop "Thermochemical processes in plasma aerodynamics"

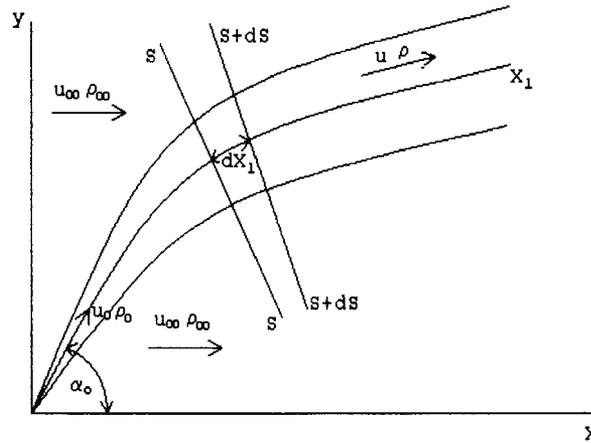


Fig.4. Conventional scheme of the turbulent porous stream propagation in the drifted gas flow: α_0 —the angel, at which the stream comes out, u_0 and ρ_0 —are the initial values of the stream velocity and density, u and ρ — are the current values of these parameters, u_∞ and ρ_∞ — are the velocity and density of the external gas.

The deviation of the stream trajectory takes place under the action of the external drifting flow from its initial direction at the angle α_0 to the axis x with the asymptotic coming to the direction along the axis x . Let us introduce the curvilinear coordinate x_1 , which is directed along the tangent in each point of the trajectory

$$x_1 = \int_0^x \sqrt{1+y'^2} dx,$$

where the stroke means the derivative over the variable x .

Earlier obtained in [9] equations of the external media capture, of the balance of the longitudinal momentum component balance, and the equation of the stream composition conserve the invariant form for the curvilinear stream also. For this purpose at the equations derivation is necessary to use the cross sections normal to the stream trajectory as it is shown in Fig. 4., with the distinction that instead of u_∞ it is necessary to use its projection u_{x_∞} on the stream direction in the given cross section x_1 .

$$u_{x_\infty} = u_\infty / \sqrt{1+y'^2}$$

The indicated equations can be written in the following form, if we take for the typical scales (by which the independent and sought variables take the dimensionless form) the radius of the initial stream cross section r_0 , its velocity u_0 and the density ρ_0 in this cross section:

3 Workshop "Thermochemical processes in plasma aerodynamics"

$$\frac{d(\rho u r^2)}{dx_1} = 2\gamma \rho_\infty |u - u_{x_\infty}| r$$

$$\frac{d}{dx_1} (\rho u^2 r^2) - u_{x_\infty} \frac{d}{dx_1} (\rho u r^2) = 0$$

$$\rho = \rho_\infty - \frac{(\rho_\infty - 1)}{u r^2}$$

In the obtained equation system we do not have an equation for the curvature of the stream trajectory. As it was mentioned above the curvature of the trajectory takes place under the dynamic head of the external gas flow around it. Considering the small part of the stream as the cylinder body, and making the natural supposition that its streaming has the separating character, we can write the equation for the resistance force acting a cylinder part of some small length dL in the form

$$F_f = \gamma \rho_\infty u_{x_\infty}^2 (rdL),$$

here $\gamma \approx 1$ is the resistance coefficient at sufficiently great Reynolds numbers. The trajectory curvature under the action of the resistance force leads to the centripetal force appearance that counterbalance it

$$F_c = \rho u^2 \pi (r^2 dL) / R,$$

where $R = -(1 + y'^2)^{3/2} / y''$ is the radius of curvature of the stream in the considered point of its trajectory.

Equating them F_f and F_c to each other one can obtain the missing equation that closes the system of equations, which describes the stream motion in the drifting flow of the external gas.

Some results of numerical calculations

Obtained system of equations can be solved in general case only numerically. The solution is dependent on three independent parameters – ratio of the velocity and density of the external flow and the stream in its initial cross section u_∞/u_0 , ρ_∞/ρ_0 and of the angle α_0 between the initial stream direction and the direction of the external gas flow. The dependence of the relative extension of the stream part (at which the stoichiometric relation of the fuel composition and the oxidizer is achieved) of the initial gas content φ_i represents the most interest. Since the initial gas content φ_i in the experiments can be varied in the range from 0,1 to 0,95, then for $\rho_0 = (\rho_K/\rho_B)(1 - \varphi_i) + \varphi_i$ we can find the estimate $\rho_0 \approx 700 \div 35$. At the same time the density of the mixture ρ differs from the unity by the small value about 10^{-2} at the stoichiometric mass relation.

3 Workshop "Thermochemical processes in plasma aerodynamics"

In the Fig.5 one can see the dependence of the dimensionless length $X_{st}(\varphi_l)/X(\varphi_l=0)$ (establishing of the stoichiometric mixture composition) of the volume gas content φ_l . The initial direction of the gas-disperse stream flowing out forms the right angle with the direction of the external gas flow.

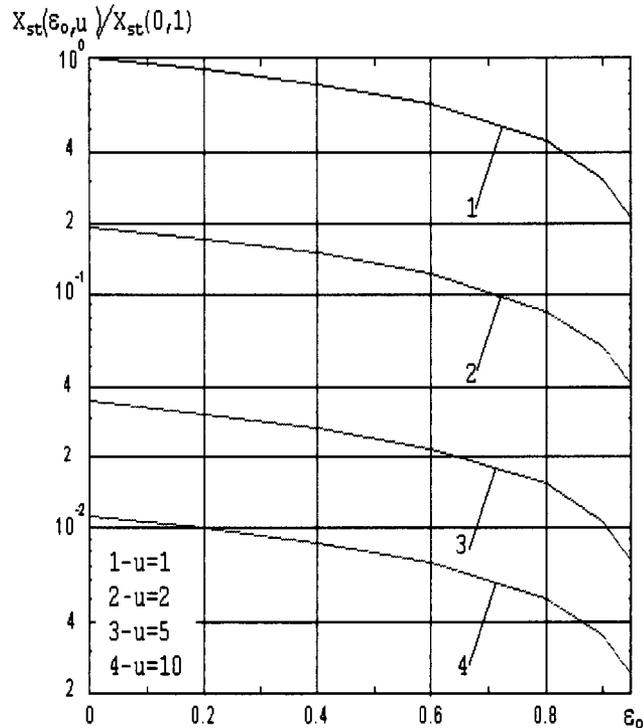


Fig.5 Curves of the dependence of stoichiometry relation establishing length via initial volume gas content of the stream ε_0 for a number of the drifting flow velocity values u_∞ , related to its value calculated at $\varepsilon_0=0$ and $u_\infty=1$.

As it is seen from the picture the relative extension of the stream part (at which the stoichiometric condition is achieved) monotonously decreases with the increase of the gas content parameter φ_l .

Conclusions

1. Means have been elaborated and devices have been manufactured for production of microporous liquids with the high gas content and the microbubble diameters $d \sim 10 - 50 \mu\text{m}$.
2. Shock waves visualizing methods in the microporous liquids have been elaborated; photos of the shock wave front at the flowing around a cylinder have been made.

3 Workshop “Thermochemical processes in plasma aerodynamics”

3. The realizing possibility of the partial conversion, cracking and oil products oxidizing in the presented in this paper devices on the fuel treatment has been theoretically validated.
4. The problem of the shock wave front in the microporous liquid has been analytically solved. Modes of the device work for the generating of the “activated porous fuel” were forecasted with the adiabatic regime of the compression in the shock were forecasted on its basis.
5. The theory of the turbulent porous liquid stream mixing with the transversal gas flow (oxidizer) has been elaborated. It was shown on its basis the possibility of the considerable decrease of the combustor sizes at the increase of the volume gas content in the fuel at the diffusional mechanism of the combustion.

References

1. *Avrashkov V., Baranovsky S., Levin V.* Gasdynamics Features of Supersonic Kerosene Combustion // AIAA-90-5268. P.8.
2. *Bushmanov E.A., Velikodnyi V.Yu., Timofeev I.B., Yanovsky Yu.G., David M. Van Wie* On the possibility of the activated porous fuel application in processes of supersonic and detonation burning. International Symposium Thermochemical and plasma processes in aerodynamics. Saint-Petersburg 15-19 July 2002, Holding Company Leninet P. 8
3. *Yanovsky Yu.G., Sapgir G.B., Sverdlov E.D., Baikov A.V.* Comparative study of combustion characteristics of the hydrocarbon fuel thermal chemical decomposition products in the submerged torch. Symposium Thermochemical processes in plasma aerodynamics. Saint-Petersburg May 30 – June 3 июня 2000. P.46-52.
4. *Velikodnyi V.Yu.* The Effect of translational nonequilibrium in a shock wave on initiation of the H_2+Cl_2 reaction// Chem. Phys. Reports. 2001. vol. 19(4). P. 787-792.
5. *Tsiklauri G.V., Danilin V.S., Seleznev L.I.* Adiabatic two-phase flows. Moscow. Atomizdat. 1973, 444 P.
6. *Nigmatulin R.I.* Basis of heterogeneous medium mechanics. Moscow. Nauka. 1978. 336 P.
7. *Struminskii V.V., Velikodnyi V.Yu.* A shock wave structure. Doklady AS USSR .1982. V.266. № 1. P. 28-31.
8. *Bashlykov A.M., Velikodnyi V.Yu.* A shock wave structure in a gas mixture. Zhurnal Technicheskoi Fiziki.1991.V. 61.№ 8. P. 33-42.
9. *Vorotilin V.P.* Properties of turbulent streams obtained on the concept basis about them as the continuous chain of the large scale vortices. In the collection of abstracts “Stability of homogeneous and heterogeneous liquid flows” Ed. V.V. Kozlov, Novosibirsk 2001, P.44.