

Experimental investigation of flame propagation in H₂ - air mixtures in tube with moving on tube walls water film

Yu. N. Shebeko, A. Ya. Korolchenko, R.R. Ionaitis,
S.G. Tsarichenko, V. Yu. Navzenya, A. V. Trunev,
A. A. Zaitzev, S.N. Papkov

All Russian Scientific Research Institute
for Fire Protection
143900, Balashikha - 3, Moscow Region, Russia

A B S T R A C T

Experimental investigations of a flame propagation in H₂-air mixtures in a tube with the moving on tube walls water film are executed. Sufficient differences in flame propagation with and without the moving water film are revealed. By means of the numerical modelling of a flame propagation in a smooth tube with the account of heat losses into tube walls and the comparison of numerical and experimental pressure-time histories it was found that the values of an effective flame turbulization factor are in the range 10 to 30 for the mixtures with the hydrogen concentrations from 15 to 30 % (vol.), and the higher is the laminar burning velocity of the mixture the lower is the effective turbulization factor. The significant intensification of the hydrogen-air mixtures combustion in the tube with the moving water film is shown. For the mixtures with relatively high burning velocities (hydrogen concentrations from 20 to 30 % (vol.)) the maximum explosion pressure in the case of an availability of the moving water film is higher, and for the mixtures with the relatively low burning velocities (H₂ concentration 15 % (vol.)) - is lower than for the case with an absence of the moving water film. This effect is due to the competition between the heat losses increase by means of the water evaporation in the combustion products region and the heat losses decrease by means of the combustion intensification. The multi-peak structure of the pressure-time curve during the gaseous mixture explosion in the tube with the moving water film is revealed. A probable reason of this effect is a water film superheating at its contact with the hot combustion products till the temperature, which exceeds the limiting homogenic nucleation temperature and the following explosive water film evaporation. The possibility of a

hydroshock occurrence in a liquid which is adjacent to a cavity with the combustible hydrogen-air mixture during its combustion is found. The maximum value of the pressure in a pressure wave in the liquid is 2-3 times higher than the maximum explosion pressure.

I N T R O D U C T I O N

In the chemical and another branches of an industry a water film cooling is widely used. Simultaneously with the availability of the moving water film the combustible gaseous mixtures can be circulated or produced during technological equipment operation. The ignition and combustion of such mixtures can give rise the equipment destruction, because the moving water film can produce significant flame turbulization with the sufficient explosive loading increase. The another hazard connected with the gaseous mixtures combustion in apparatus with the moving water film is the possibility of a hydroshock occurrence at an abrupt change of an liquid flow due to the gaseous explosion. At the same time the data about such processes, which were published in literature, are rather incomplete for the reliable prediction of the possible explosion loadings.

The combustion of gaseous mixtures in tubes is considered in [1-10]. As a rule these investigations are executed in smooth tubes without obstacles for various values of L/D ratio (L and D are the length and diameter of the tube respectively), or in tubes with obstacles in the form of spirals or rings [1-8]. It was found that in smooth tubes the significant combustion intensification (including transition of deflagration to detonation) takes place mainly for the mixtures with high burning velocities which contain hydrogen or acetylene, or in which pure oxygen is the oxidizer. The combustion intensification is more strong in the presence of obstacles, but in this case high explosion loadings are possible for the mixtures with high burning velocities. In [9,10] the preliminary results of investigations of the combustion intensification by means of the moving water films are presented for hydrogen-air mixtures.

This investigation is aimed on the further determination of explosion loadings characteristics (in gas and liquid phase) at combustion of hydrogen-air mixtures in tubes with the moving on tubes walls water film.

EXPERIMENTAL

Experiments were performed on the set-ups "Fragment" and "Channel".

The set-up "Fragment" has the reaction vessel in the form of the vertical tube made from stainless steel with internal diameter 80 mm and height 2,5 m. In the upper part of the reaction tube the film-maker is placed which produces the moving on the internal wall surface water film. Its mean velocity is near 0.1 m/s, and its mean thickness is 1,5-2 mm. The set-up has the vacuum pumping system, the mixer for gaseous combustible mixture preparing, static and dynamic pressure detectors, the ignition source and the detectors registration system. Experiments were executed by a following manner.

The mixer was evacuated to residual pressure which is not greater than 0,5 kPa, and then the combustible hydrogen-air mixture was created in it by partial pressures. The mixing was made by means of convective flows produced by a local heating in the lower part of the mixer. The mixing duration was not less than 1 hour. The reaction vessel was evacuated to a residual pressure which was not greater than 0.5 kPa, and then the combustible mixture was supplied into reaction vessel to a pressure 0.1 MPa. The permissible pressure ($\cong 2.0$ MPa) and the mixer volume (5 dm^3) were great enough in order to execute an each experimental series with the combustible mixtures of an identical composition. The required water flow through a film-maker was set (if experiments are executed with the moving water film), and after 2 minutes the combustion was initiated by means of a fused nichrome wire with energy near 10 J. Some experiments were performed with the mixture ignition by means of a special chamber section filled by a high energetic stoichiometric hydrogen - oxygen ($2\text{H}_2 + \text{O}_2$) mixture (preignition chamber). The combustion initiation in this section was made by a mentioned above fused nichrome wire. Till the ignition moment the ignition section was separated from the part of tube with H_2 - air mixture by a thin film which is destroyed shortly after $2\text{H}_2 + \text{O}_2$ mixture initiation. The pressure in the reaction vessel during gaseous mixture combustion was measured by a pressure transducer with a time constant 1 ms. Relative errors of measurements of all parameters don't exceed 10 %.

The main part of the large-scale set-up "Channel" is a reaction vessel in the form of vertical tube made from stainless steel with an internal diameter 86,5 mm and height 21.85 m. In the upper part of the tube a long pivot is attached by means of a flexible cable,

and at the lower part of the pivot a water film maker is placed. Water is supplied to the upper part of the reaction vessel. At a distance of 6 m from the lower part of the tube three arrangements are placed: a pressure detector, an ignition source and a valve for combustible mixture supplying. The creation of a gaseous cavity below the film - maker was made by introducing the hydrogen - air mixture from the mixer described above into the tube through the mentioned above valve placed on the height 6 m from the lower part of the tube. As an ignition source the fused nichrome wire with the energy deposited near 10 J was used. The mixture ignition was made after 60 s after the gaseous cavity formation. A height of gaseous cavity was measured by a special liquid level detector. Three detectors were used for the measuring pressure in the lower and upper liquid column and in the gaseous cavity during the hydrogen-air mixture combustion. A time constant of these pressure detectors is equal 0.1 ms. The water flow was measured by a standard diaphragm and a pressure detector. Experiments were executed with the hydrogen-air mixtures with H₂ concentrations 18 and 36 % (vol.).

R E S U L T S

a. Experiments on the set-up "Fragment"

Experiments on the set-up "Fragment" were executed with and without the moving water film with the hydrogen contained mixtures of compositions pointed in the Table 1. The results of the experimental determination of the maximum explosion pressure ΔP and the mean pressure rise rate dp/dt are presented in this table too.

Table 1

Mixture components concentrations, % (vol.)			Ignition source and its position	Maximum explosion pressure ΔP , kPa		Mean explosion pressure rise rate, MPa/s
hydrogen	air	excess nitrogen		experimental	adiabatic	
15	85	0	fused wire placed below	260	470	1.53
20	80	0	fused wire placed below	290	550	2.22
30	70	0	fused wire placed below	400	680	13.33
30	32	38	fused wire placed below	160	400	0.39
30	70	0	fused wire placed in the middle	510	680	25.50
30	70	0	preignition chamber placed below	350	680	24.00

Table 2

Components concentrations, % (vol.)		Maximum explosion pressure ΔP , kPa		Mean explosion pressure rise rate, MPa/s
hydrogen	air	experimental	adiabatic	
15	85	120	470	10.0
20	80	520	550	65.0
25	75	850	640	212.5
30	70	900	680	300.0

The typical pressure-time curve for a combustion of hydrogen-air mixtures without a moving water film is presented in Fig.1. These curve is characterised by a sharp maximum with a following relatively slow pressure reduction due to a cooling of combustion products by means of their heat exchange with cold tube walls. The maximum explosion pressure is due to this effect sufficiently lower than adiabatic value.

In Fig.2 typical pressure-time curves for a flame propagation in the hydrogen-air mixtures in the tube with moving water film are shown. The values of maximum explosion pressures ΔP and mean explosion pressure rise rates dp/dt are presented in Table 2. As we can see the combustion process in the case of presence of the moving water film intensifies sufficiently. For hydrogen concentrations 25 and 30 % (vol.) the maximum explosion pressure is greater than adiabatic values. Qualitatively the same results were obtained in [1]. The values of dp/dt are much greater than in the case of absence of moving water film. The structure of the pressure-time curve for the hydrogen concentration 30 % (vol.) is rather complex and characterised by a availability of two maxima.

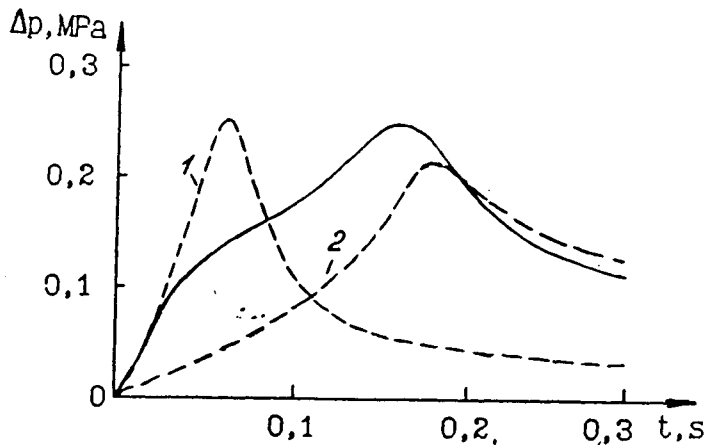


Fig. 1. Typical pressure ΔP - time t curve for the combustion of hydrogen-air mixtures in the reaction vessel of the set-up "Fragment" in the absence of a moving water film. Solid line - experiment, dashed line - theory.

$[H_2] = 15\%$ (vol.), ignition in the lower part of the tube,
 $\chi = 30(1)$ and $10(2)$.

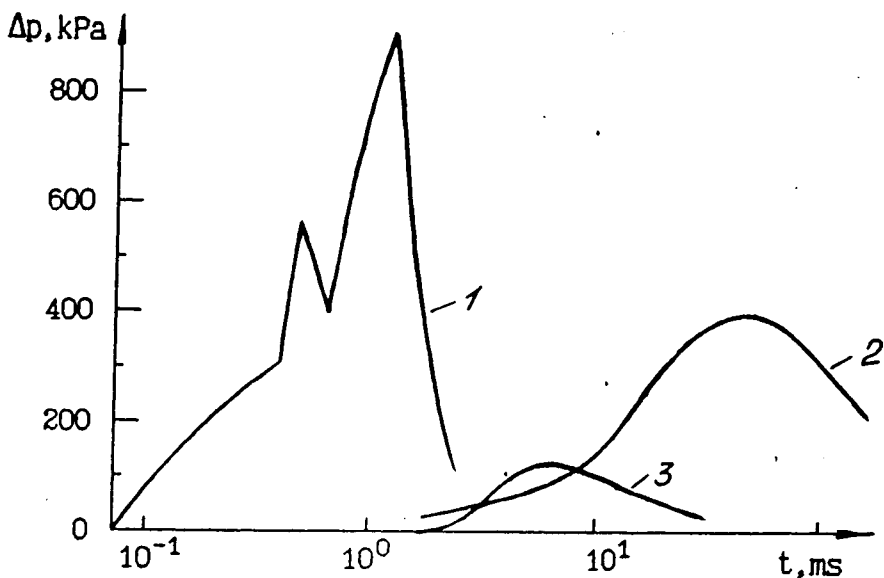


Fig. 2. Typical pressure ΔP - time t curves for the combustion of hydrogen - air mixtures in the reaction vessel of the set-up "Fragment" in the presence (1,3) and in the absence (2) of the moving water film. Hydrogen concentration 30 (1,2) and 15 (3) % (vol.).

It must be mentioned that increase of the maximum explosion pressure to the values exceeding adiabatic one is observed only for hydrogen concentrations 25 and 30 % (vol.). In the case of the hydrogen concentration 15 % (vol.) the reverse effect takes place: at the availability of the moving water film the maximum explosion pressure is lower than without one. But the value of dp/dt is much greater than in the case without moving water film.

b. Experiments on the set-up "Channel"

Large-scale experimental results of investigations of hydrogen-air mixtures combustion in a tube are presented in Fig. 3 as pressure-time curves for various pressure detectors positions. For the mixture with the hydrogen concentration 36 % (vol.) five experiments were executed with the water flows in the range from 2.0 to 3.2 $m^3/hour$. At the water film thickness 1.5 mm these flows correspond to a mean water film velocity from 0.14 to 0.22 m/s. For the mixture with the hydrogen concentration 18 % (vol.)

four experiments were executed. Conditions of these experiments and main parameters of pressure waves are presented in Table 3.

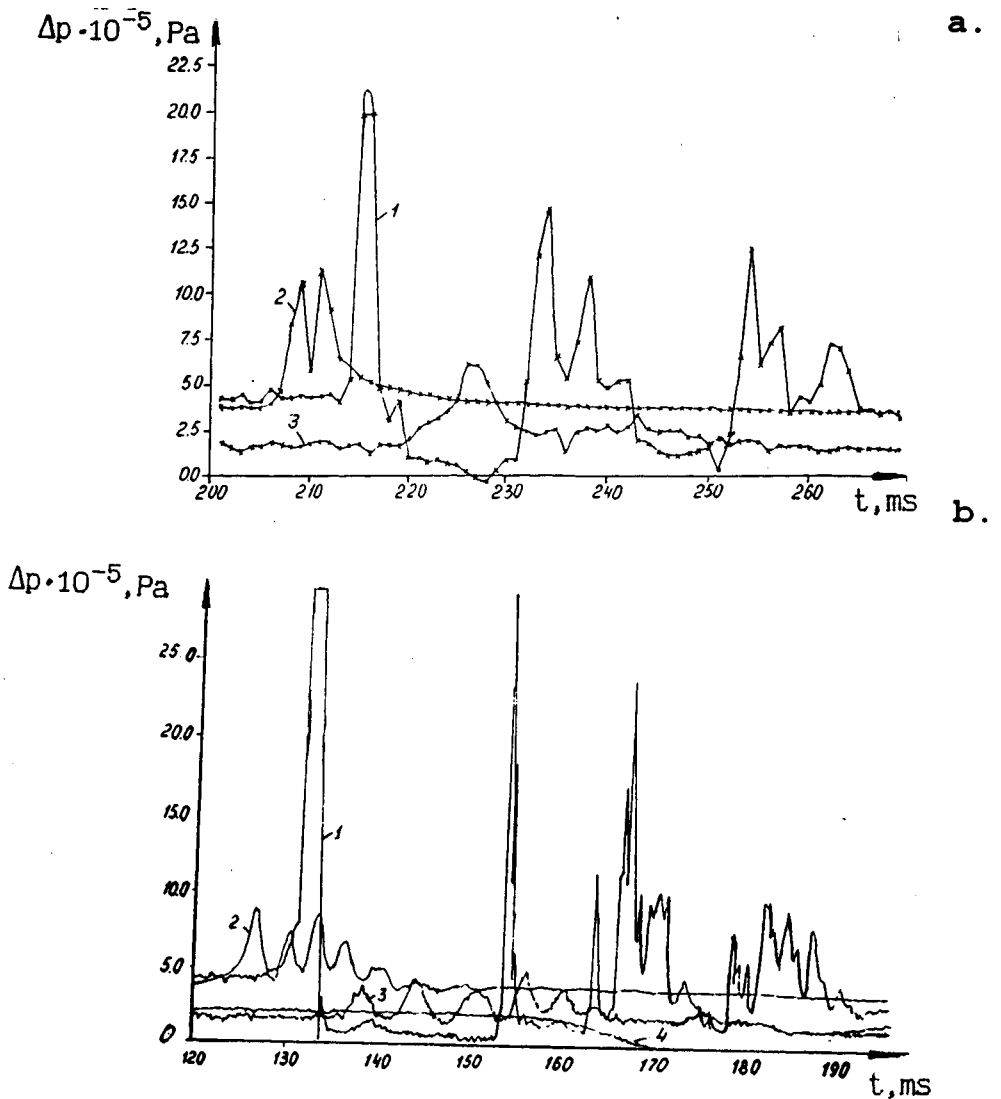


Fig. 3. Pressure ΔP -time t curves for the combustion of hydrogen - air mixtures in the reaction vessel of the set-up "Channel" in the presence of the moving water film. Hydrogen concentration 36 % (vol.) (a) and 18% (vol.).

1, 2, 3 - pressure-time curves for detectors placed in the lower, middle and upper part of the tube respectively. Combustion regimes (according to Table 3) 1(a) and 6(b).

Table 3

NN	Hydrogen concentration, % (vol.)	Water flow, m ³ /hour	Mean water film velocity, m/s	Initial pressure in a gaseous cavity, MPa	Height of gaseous cavity, m	Maximum pressure in a pressure wave, MPa		
						in gaseous cavity	in the lower part of the tube	in the upper part of the tube
1	36	2.0	0.14	0.38	1.15	1.13	> 2.0	0.60
2	36	2.0	0.14	0.38	1.15	1.15	>2.0	0.45
3	36	3.2	0.22	0.31	1.57	1.31	0.78	0.96
4	36	3.0	0.20	0.31	1.91	1.00	2.73	0.30
5	36	2.9	0.20	0.32	1.73	0.76	0.67	0.33
6	18	2.1	0.14	0.38	1.63	0.90	>3.0	0.50
7	18	2.0	0.14	0.39	1.68	0.90	3.00	0.70
8	18	3.2	0.22	0.37	1.91	0.68	>3.0	no data
9	18	0	0	0.39	1.64	1.18	2.94	no data

The analysis of presented above data shows that the combustion of the hydrogen-air mixtures in a tube causes a pressure wave in the liquid in the lower part of the tube with an amplitude exceeding sufficiently the pressure in a gaseous cavity. In experiments with mixtures containing 36 % (vol.) hydrogen the maximum pressure in the gaseous cavity is in the range from 0.76 to 1.31 MPa, and at the same time the maximum pressure in the liquid in the lower part of the tube exceeds in some cases the value 2.0 MPa. On pressure-time curves for the lower pressure detector the horizontal line in the peak shows the exceeding of the upper limiting pressure for the pressure detector, which is equal in some experiments 2.0, and in some experiments 3.0 MPa. As in the experiments on the set-up "Fragment" the complex structure of a pressure wave is revealed. There are two or more peaks in the pressure-time curve.

DISCUSSION

It was mentioned above that at the combustion of hydrogen-air mixtures in the reaction vessel of the set-up "Fragment" without the moving water film (Fig.1) the maximum explosion pressure is sufficiently lower due to heat losses into tube walls than the adiabatic value. As in [2], at the initial explosion stage the fast pressure increase is observed, and later the rate of a pressure increase becomes lower. This effect was qualitatively explained in [2] by a following mechanism. After the initial flame acceleration due to the flame front elongation a contact of the flame front with tube walls takes place. As a result the cooling of combustion products and the appropriate increase of heat losses from the flame front occur, and the flame velocity

decreases. But in the case of a large-scale apparatus [5] (tube diameter 1.45 m, length 100m) this effect was not observed. This fact demonstrates an important role of a scale factor in a mechanism of a flame acceleration in tubes.

For the determination of an effective turbulization factor for a flame propagation in tube without water film a numerical modelling of this process was executed. A flame turbulization and a heat exchange between combustion products were taken into account. A simple theoretical model [4] was used.

Typical calculated pressure - time curves are presented in Fig.1 for various values of turbulization factor χ . It can be seen that the initial explosion stage (till the time moment when the explosion pressure rise rate begins decrease) can be satisfactorily described at $\chi=20$ (the hydrogen concentration $C_{H_2}=15\%$ (vol.)), $\chi=15$ ($C_{H_2}=20\%$ (vol.)) and $\chi=10$ ($C_{H_2}=30\%$ (vol.)). That is the lower is a laminar burning velocity the higher is the flame turbulization. Qualitatively close results were obtained in [12] at the investigation of influence of a flame turbulization by means of fans on a flame propagation velocity.

As it can be seen from a comparison of pressure-time curves presented in Fig.1 and 2, the combustion character changes significantly if the moving water film is available on tube walls. The sufficient combustion intensification takes place because the explosion pressure rise rate dP/dt increase significantly. The nature of an intensification mechanism is a flame turbulization by a moving film.

The complex structure of pressure-time curves (Fig. 3), which is characterized by an availability of two or more peaks, is caused, for our opinion, by a following mechanism. At a combustion of a hydrogen-air mixture the hot combustion products are produced, which begin to transfer a heat to external bodies. In the absence of a moving water film these bodies are metal tube walls, and the structure of a pressure-time curve is characterized in this case by a presence of only one peak (Fig. 3). If a moving water film is present, the heat from hot combustion products is transferred to a water film which (completely or partly) is superheated to a temperature higher than normal boiling temperature, and because it the rapid evaporation occurs. According to [13-15], if a superheated liquid temperature exceeds the definite limit (the temperature limit of a homogeneous nucleation), the liquid boiling occurs in a explosive regime (this limit is approximately equal to 90%

of a critical temperature). In this case the first peak in the pressure-time curve is caused by a combustion of a hydrogen-air mixture. During the combustion products cooling by a heat transfer to a water film the pressure in the reaction vessel drops, and then at the explosive superheated liquid boiling the second pressure peak occurs. If not all liquid evaporates during this explosive boiling (for example, if a water film is thick enough), this liquid explosion repeats, and the following pressure peaks occur.

The maximum pressure in the lower liquid column registrated by a lower pressure detector is much higher than the maximum pressure in a gaseous cavity (Table 3). This effect couldn't take place in the case of the quasi-static loading (at a slow pressure elevation in a gaseous cavity), and is caused by a hydroshock. At the hydrogen-air mixture explosion the water flux through the tube becomes to be equal zero during the time interval of the explosion (20-25) ms. This fact is registrated by a flux detector placed in the lower part of the tube.

C O N C L U S I O N S

1. The experimental and theoretical investigations of the hydrogen-air flame propagation in a vertical tube with and without moving water film are executed. The sufficient difference of the mentioned above regims is revealed.

2. By means of the numerical modeling of a hydrogen-air mixture combustion in the tube without water film and the comparison of its results with experimental data it was found that the maximum value of a flame turbulization factor is in the range from 10 to 30 for mixtures with hydrogen concentrations from 15 to 30 % (vol.). The higher is the mixture laminar burning velocity the lower is a flame turbulization factor.

3. The sufficient intensification of combustion of hydrogen-air mixtures in tube with the moving water film is revealed. For mixtures with relatively high laminar burning velocities (the hydrogen concentration from 20 to 30 % (vol.)) the maximum explosion pressure increases, and for the mixture with the hydrogen concentration 15 % (vol.) decreases. This effect is due to the competition of heat loses decrease by means of a combustion time reduction and heat loses increase by means of a water evaporation in the combustion products region.

4. The multi-peak structure of pressure-time curves for explosion pressure waves in gaseous cavity with the moving water film is found. The probable reason of this effect is a water film superheating at its contact with hot

combustion products and a water evaporation in the explosive regime.

5. The possibility of a hydroshock formation in the liquid column placed lower the gaseous cavity, where the hydrogen-air mixture combustion takes place, is shown. The pressure wave amplitude in this case can be two-three times larger, than the maximum explosion pressure in a gaseous cavity.

R E F E R E N C E S

1. Lee, J.H.S., Knystautas, R., Freiman, A., *Combust. Flame* 56: 227-239 (1984).
2. Phylaktou, H.N., Andrews, G.E., Herath, P., *J. Loss Prevention Proc. Ind.* 3: 355-364 (1990).
3. Shelkin, K.I., *J. Thechnical Phisics* 17: 613-618 (1947).
4. Tennankore, K.N., Locfortune, J.F., in *Heat Transfer 1986. Proc. 8-th International Conference in San Francisco, 17-22 Aug. 1986, Washington, 1986*, pp. 843-848.
5. Abinov, A.G., Plotnikov, V.M., Shebeko, Yu.N., et. al., *Physics of Combustion and Explosion* 23: N1, 41-46 (1987).
6. Andrews, G.E., Herath, P., Philaktou, H.N., *J. Loss Prevention Proc. Ind.* 3: 291-302 (1990).
7. Lin, E.E., Funtikov, A.I., *Physics of Combustion and Explosion* 28: N2, 43-46 (1992).
8. Moen, I.O., Lee, J.H.S., Hjertager, B.H., Fuhre, K., Eckhoff, R.K., *Combust. Flame* 47: 31-52 (1992).
9. Tsarichenko, S.G., Shebeko, Yu.N., Trunev, A.V., Zaitzev A.A., Kaplin, A.Yu., *Physics of Combustion and Explosion* 29: N6, 14-19 (1993).
10. Shebeko, Yu.N., Tsarichenko, S.G., Korolchenko A.Ya., Ionaitis, R.R., in *Proceedings of the Second Asian-Pacific International Symposium on Combustion and Energy Utilization, World Publishing Corporarion, 1993*, pp.790-793.
11. Pinaev, A.V., Lyamin, G.A., *Physics of Combustion and Explosion* 25: N4, 75-80 (1989).
12. Al-Khishali, K.J., Bradley, D., Hall, S.F., *Combust. Flame* 54: 61-70 (1983).
13. Nikolaev, Yu.A., Topchyan, M.E., *Physics of Combustion and Explosion* 13: N3, 393-404 (1977).
14. Shepherd, J.E., Sturtevant, B., *J. Fluid Mechanics* 121: 379-402 (1982).
15. Reid, R.C., *Science* 203: 1263-1265 (1979).
16. Frost, D., Sturtevant, B., *J. Heat Transfer* 108: 418-424 (1986).