Simulation of fire engineering processes in energy devices aimed at their optimization and improvement of reliability

Anton Alexandrovich Sinitsyn

Vologda State Technical University, ul. Razina, Bldg. 25, Apt. 2, Vologda 160029, Russia
Sinitsyn_a_a@inbox.ru

Abstract: The article determines applicability of investigation into simulation of fire engineering processes in energy devices (boilers, furnaces, internal combustion engines and others) aiming at their optimization and increase in reliability. Survey has demonstrated that the procedures of calculation of such devices are not widely available. Development of procedure of engineering design and verification is necessary for further advance of production of oscillating combustion apparatuses. The author has revealed main problems of development of calculation procedure of energy devices based on oscillating fuel combustion. In order to decrease probability of defects within operation and heterogeneous distribution of thermal loading for metal structure the author proposes mathematical model of hydrothermal parameters in dimensionless form, which makes it possible at the designing stage to determine reliability and efficiency of operation of such devices of various applications based on the principle of auto-oscillating fuel combustion. On the basis of simulation results recommendations are presented aimed at improvement of designing of pulse combustion boilers. The results have been delivered and implemented at a plant where such boiler units are produced. Practical value of the results is in development of procedure which facilitates analysis of hydrothermal processes in elements of commercial heat and power plants based on oscillating fuel combustion.

[Sinitsyn A.A. **Simulation of fire engineering processes in energy devices aimed at their optimization and improvement of reliability**. *Life Sci J* 2013;10(8s):442-447] (ISSN:1097-8135). http://www.lifesciencesite.com. 73

Keywords: hydrothermal processes, mathematical model, pulsating combustion, energy efficiency.

1. Introduction

Within development of new devices and examination of existing ones it is highly important to study their efficiency and reliability. In fire engineering apparatuses areas with overheating of critical components can exist. At heterogeneous distribution of temperature on metal surfaces of apparatuses local areas can occur where wall temperature is significantly higher than average value. This can lead to situation when metal starts to flow, is deformed, thus causing occurrence of emergency situations not only of the apparatus but of overall energy system.

Therefore, simulation of thermal and hydrothermal processes in apparatuses with high temperature of heat carrier is a very urgent problem both at designing stage and at estimation of technical state of operating apparatuses.

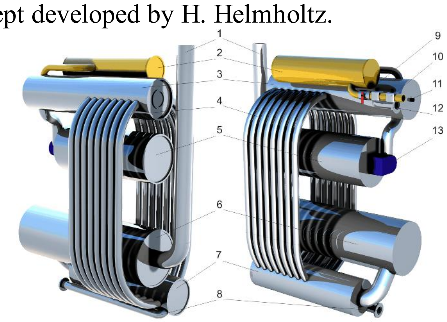
At present, in addition to boilers with conventional combustion, pulse combustion boilers (PCB) are applied (PCB). They include apparatuses where hydrothermal forms of energy are intensified by means of artificially created vibrations due to appropriately selected geometry of heat exchanger. Such mode makes it possible to provide maximum completeness of heat emission within fuel combustion, to intensify significantly heat and mass transfers and to increase thermal intensity of combustion chamber. Under such conditions it is obvious that the design dimensions are reduced, costs of mounting and maintenance of heat and power plants decrease [1].

However, the gained experience of operation of such energy devices showed that there exist such negative issues of operation as burning-out and breakdown of separating wall between working and cooling heat carrier, noise and increased vibrations of structures.

Within studies of shut-down of PV-400 400 kW boiler (INTEKO, Korolev) defects were detected; breakdown in combustion chamber due to overheating of metal wall was revealed. The flowchart of modernized PV-800 800 kW boiler, KREMZ, Kimovsk with the aim of increase in surface area of heat transfer includes tube with reversible water flow. During operation it was overheated and metal was broken.

Therefore, it is an urgent problem to simulate thermal and hydrothermal processes in such boilers with subsequent consideration for peculiar features in new apparatus designs.

2. Experimental. The simulation was performed for hot-water thermal generator with combined combustion chamber and heating surfaces, which form tube-in-tube heat exchanger. Geometrical properties of the heat exchanger are selected so that to determine resonant frequency of pulsations in combustion area and convective-emissive surface of heat exchange. The geometry is based on resonator concept developed by H. Helmholtz.



1 – stack, 2 – gas receiver, 3 – combustion chamber, 4 – resonant tubes, 5 – air receiver, 6 – exhaust silencer, 7 – resonant receiver, 8 – water inlet manifold, 9 – gas fitting shut-off cock, 10 – electromagnetic shut-off valve, 11 – ignition plug, 12 – water outlet manifold, 13 – blower fan.

Figure. 1. Schematic view of PV-400 boiler [2]

Thus obtained artificial pulsations are superimposed on pulsation of turbulent flow. Combustion is performed by a series of microexplosions, the energy of which is used for induction work of components of fuel mixture, as well as for propulsion of formed combustion products into environment. The conditions of microexplosions are based on selected harmonic non-stationary heat exchange with its amplitude and period. More detailed description can be found elsewhere [1--6].

Numerous works are devoted to studies of combustion, gas dynamics and heat transfer in similar units, development of mathematical models of considered processes, see, for instance, [7-9]. The work [10] is especially interesting, where similar system is studied, however, the study is limited to obtaining of pulse characteristic without further mathematical description of oscillating combustion. Common disadvantage of the aforementioned works is that they do not propose solution of problems of heat and mass exchange under conditions of non-stationary combustion using wave equation, which would make it possible to perform more complete calculation of pulsation properties of such flow, to determine actual parameters of working medium in combustion chamber, to obtain actual situation of heat transfer for similar devices with the aim of further development of their calculations.

Thermodynamic set of equations is written for duct of pulse combustion boiler:

$$F_{\text{г}} c_{p\text{г}} \rho_{\text{г}} \frac{\partial T_{\text{г}}}{\partial \tau} dx + F_{\text{г}} c_{p\text{г}} \rho_{\text{г}} \upsilon^{\text{г}}_{x\ \text{ср}} \frac{\partial T_{\text{г}}}{\partial x} dx + \alpha_{\text{г}}(\tau) U_{\text{г}} dx \left(T_{\text{г}}(\tau) - T_{w\,\text{г}} \right) + q_b(\tau) = 0,$$
$$\tau \geq 0;\ 0 \leq x \leq L \qquad (1)$$

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = \frac{1}{a} \frac{\partial T}{\partial \tau}, \qquad (2)$$
$$\tau \geq 0;\ 0 \leq x \leq L;\ 0 \leq y \leq (b + h + \delta)$$

$$T(0.x, y) = f(x, y), \quad T_{\text{г}} = f(\tau)\ \text{,при } x=0$$
$$T_{\text{в}} = f(\tau, 0), \qquad (3)$$

$$F_{\text{в}} c_{p\,\text{в}} \rho_{\text{в}} \frac{\partial T_{\text{в}}}{\partial \tau} dx + F_{\text{в}} c_{p\,\text{в}} \rho_{\text{в}} \upsilon^{\text{в}}_{x\ \text{ср}} \frac{\partial T_{\text{в}}}{\partial x} dx + \alpha_{\text{в}}(\tau) U_{\text{в}} dx \left(T_{w\,\text{в}} - T_{\text{в}}(\tau) \right) = 0,$$
$$\tau \geq 0;\ 0 \leq x \leq L \qquad (4)$$

$$\lambda_w \left. \frac{\partial T}{\partial n} \right|_{y=b} = \alpha_{\text{г}}(\tau) \left(T_{\text{г}} - T_{w\,\text{г}} \right), \qquad (5)$$

$$\lambda_w \left. \frac{\partial T}{\partial n} \right|_{y=b+\delta} = \alpha_{\text{в}}(\tau) \left(T_{w\,\text{в}} - T_{\text{в}} \right). \qquad (6)$$

$$\frac{\partial^2 \upsilon}{\partial x^2} = \frac{1}{c^2} \frac{\partial^2 \upsilon}{\partial \tau^2}, \quad \frac{\partial^2 p}{\partial x^2} = \frac{1}{c^2} \frac{\partial^2 p}{\partial \tau^2}, \qquad (7)$$

where $q_b(\tau)$ is the power source determined by equation of burning-out as a function of time; b and h are the widths of gas and water channels, respectively, δ is the wall thickness, L is the length (see Fig. 4), c is the speed of sound in the considered medium.

Hydrodynamic system of equations:

$$\frac{\partial \upsilon}{\partial \tau} + \upsilon \frac{\partial \upsilon}{\partial x} + \upsilon \frac{\partial \upsilon}{\partial y} = \frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{1}{\rho y} \frac{\partial}{\partial y} (y \zeta_{\Sigma}), \ (8)$$

$$\frac{\partial p}{\partial \tau} + \frac{\partial (\rho \upsilon)}{\partial x} + \frac{\partial (\rho \upsilon)}{\partial y} = 0, \qquad (9)$$

where ζ_{Σ} is the cumulative value of friction stress on channel wall.

Interrelation between oscillations of heat emission rate $q_b(\tau)$ and flow velocity υ can be determined as follows:

$$q_b(\tau) = i \omega \upsilon(\tau) \int_0^{\infty} \frac{\partial q_b(\tau)}{\partial \upsilon} e^{-i\omega\tau} d\tau, \ (10)$$

where τ is the time of travelling of flame front from one stationary position to another; *i* is the imaginary unit; ω is the cyclic frequency.

The function of heat emission is determined by flame propagation $\Delta q_b(\tau)$, related with burning-out function $\Psi_m(\tau)$ as follows:

$$\Delta q_b(\tau) = q_f \Delta m_f \Psi_m(\tau), \qquad (11)$$

where q_f is the heating capacity of fuel unit weight; m_f is the periodic component of mass flow; U_n is the velocity of flame propagation.

Then, at $U_n = var$ in dimensionless form at $\sigma = \tau / \tau_b$

$$\Psi(\sigma) = \begin{cases} 2 \cdot \sigma^2 - at\ 0 \le \sigma \le 0.5 \\ 1 - 2(\sigma - 1)^2 - at\ 0.5 \le \sigma \le 1 \\ 1 - at\ \sigma > 1 \end{cases}, \quad (12)$$

In order to implement the mathematical model (1)-(12) the system is transformed into dimensionless form and written as finite differences.

$$A_г \frac{\partial \Theta_г}{\partial Fo} + B_г Pe(Fo) \frac{\partial \Theta_г}{\partial \eta} + C_г Bi_г (Fo)(\Theta_г(Fo) - \Theta_{wг}) + D_г Kr(\Theta_г(Fo) - \Theta_{wг}) = 0, \quad (13)$$

$$\frac{\partial^2 \Theta}{\partial \eta^2} + \frac{\partial^2 \Theta}{\partial \xi^2} = \frac{\partial \Theta}{\partial F_0}, \quad (14)$$

$$\Theta(0, \eta, \xi) = f(\eta, \xi),$$

$$A_в \frac{\partial \Theta_в}{\partial Fo_0} + B_в Pe(Fo) \frac{\partial \Theta_в}{\partial \eta} + C_в Bi_в (Fo)(\Theta_{wв} - \Theta_в(Fo)) = 0, \quad (15)$$

$$\left. \frac{\partial \Theta}{\partial W} \right|_{\xi = \frac{b}{l}} = Bi_г (Fo)(\Theta_г(Fo) - \Theta_{wг}), \quad (16)$$

$$\left. \frac{\partial \Theta}{\partial W} \right|_{\xi = \frac{b+h}{l}} = Bi_в (Fo)(\Theta_{wв} - \Theta_в(Fo)), \quad (17)$$

$$\Theta_г = f(Fo); \Theta_в = f(Fo, 0) \text{ at } \eta = 0,$$

$$F\hat{\imath} > 0, \quad (18)$$

Here $\Theta = \frac{T}{T_{\max}}$ is the dimensionless parameter of temperature of medium; η and ξ are the dimensionless coordinates of space; the Biot number: $Bi = \frac{g_c \delta_c}{(T_c - T_г)\lambda_г}$, the Fourier number: $Fo = \frac{a_c t}{\delta_c^2}$, the Peclet number: $Pe = \frac{\upsilon l}{a'}$, and the Kirpichev number: $Kr = \frac{ql}{\lambda_f (T_c - T_г)}$; A, B, C, D are the dimensionless geometrical coefficients.

Set of equation (13)-(18) is the mathematical model of two-dimensional development of the process along dimensionless coordinates η and ξ, as well as in time. The method of equivalenting was applied to subdivide the non-stationary problem of oscillation combustion into stationary one-dimensional problem and harmonic one, which determines boundary conditions of the system.

$$B_г Pe(Fo) \frac{\partial \Theta_г}{\partial \eta} + C_г Bi_г (\eta)(\Theta_г(\eta) - \Theta_{wг}) = 0, \quad (19)$$

$$0 \le \Theta_г \le 1;\ 0 \le \eta \le 1;\ 0 \le \xi \le 1;$$

$$\frac{\partial^2 \Theta}{\partial \xi^2} = 0, \quad (20)$$

$$B_в Pe(Fo) \frac{\partial \Theta_в}{\partial \eta} + C_в Bi_в (\eta)(\Theta_{wв} - \Theta_в(\eta)) = 0, \quad (21)$$

$$\Omega = f(Eu, \Theta, \mathrm{Re}), \quad (22)$$

$$\frac{\partial Eu}{\partial \eta} + \frac{\mathrm{Re}}{8S^2} \xi_{mp} = 0, \quad (23)$$

Boundary conditions:

$$\eta = 0,\ \Omega_0 = 1 + \Omega_m f(Fo), \quad (24)$$

$$\eta = \eta_k,\ \Omega_k = 1. \quad (25)$$

where Ω is the parameter determining wave motion of the medium; S is the Stokes number; ξ_{mp} is the dimensionless coefficient of friction resistance; f is a certain harmonic function which describes variation of wave parameters in time [6].

This system was solved numerically. With this aim a numeric flowchart of finite difference solution of this system was developed.

Applying similar simplification, the process of heat conductivity in a wall is replaced with high amount of rods where stationary heat transfer occurs and which are isolated from each other:

$$\frac{\partial^2 \Theta}{\partial \eta^2} = 0, \quad (26)$$

Solution of stationary problem was performed by implementation of mathematical model for determination of averaged thermal and hydraulic properties of PCB operation along the considered duct. The simulation was aimed at determination of functional dependence of pressure variation along the hydrodynamic channel within heat exchange with cooling medium. This was obtained by determination of initial and boundary conditions characterizing limits of the process advances. They are as follows: geometrical dimensions of design object, parameters of state of heat carriers as a function of temperature, flow rate characteristics of gaseous and aqueous media, as well as operating input parameters.

As a result of the simulation, the thermohydrodynamic functions of distribution of heat carrier parameters along the considered PCB duct have been obtained.

Thermal function (TM):

$TM=f_T\,(L, S, T1, T2, T3, P_н, P_к)$, (27)

Hydraulic function (Pmax and Pmin)

$PM=f_P\,(L, S, T1, T2, T3, Pmax, Pmin)$, (28)

where L is the interval where pressure is determined; S is the step of sampling by length showing accuracy of calculations; $T1$ is the initial temperature of exhaust gases; $T2$ is the boundary temperature of cooling water; $T3$ is the initial wall temperature on internal side to gas; $P_н$ ist he initial pressure in combustion chamber; $P_к$ is the final pressure in combustion chamber [5].

As a consequence of the simulation the functions were obtained in MathCAD software which facilitate determination of pressure at preset length interval of duct of pulse combustion boiler with preset accuracy of calculations based on initial values of temperature of gaseous medium, wall temperature and final temperature of cooled gas carrier.

The tests were performed with various operating modes of the assembly (1 - 100 %, 2 - 90 %, 3 - 80 %, 4 - 70 %). With this aim variations of the oscillation amplitudes of medium pressure in the chamber were determined, as well as temperature distributions of gaseous and aqueous heat carrier along the boiler duct. The simulation results of PCB hydrothermal characteristics were analyzed and the following conclusions were obtained.

3. Results and discussion

1. Hydraulic characteristic

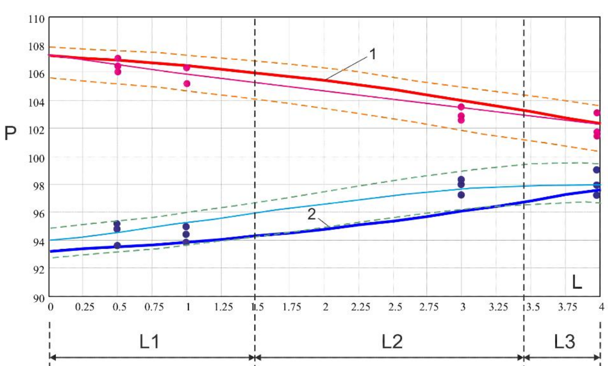


Figure 2. Pressure distribution in PCB along the channel length:

1 – maximum pressure; 2 – minimum pressure

● – *experimental data*; — – *calculations*

The main conditions influencing on pressure variations in gas channel is the pressure drop as a result of pulsing motion of the medium (see Fig. 2), where P is the medium pressure, kPa, L is the chamber length, m, consisting of L1 – combustion chamber, L2 – resonant tubes, and L3 – resonant receiver. Pressure loss for friction and local resistances are of minor importance. The calculated results correspond to experimental data.

2. Thermal characteristic

Distribution of temperatures T, C° in PCB along channel is determined by uniform decrease similarly to gaseous-aqueous heat exchanging recuperative apparatus with countercurrent flowchart of motion of heat carriers. The accuracy of the calculations was confirmed by experimental data.

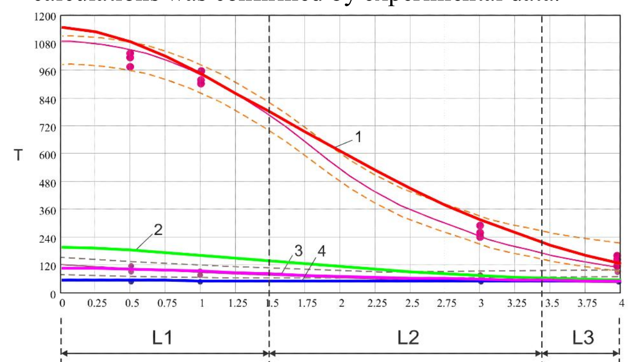


Figure 3. Temperature distribution in PCB along the channel: 1 – exhaust gases; 2 – gas side wall; 3 – water side wall; 4 – aqueous heat carrier

● – experimental data; — – calculations

3. Energy characteristic

Generalized energy characteristic was plotted for four operating modes, which reflects the dependence of heat intensity of channel cross-section q, kW/m^2 along its length L, m.

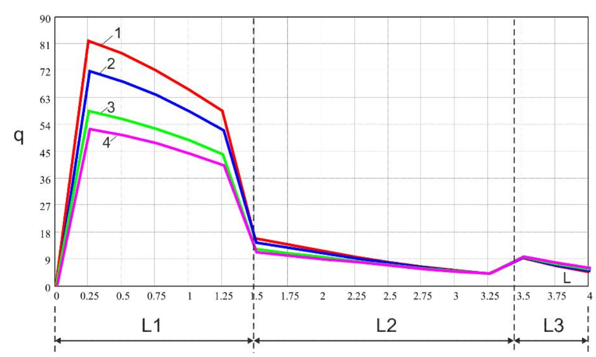


Figure 4. Heat intensity of PCB channel along its length

where **1** – mode No. 1; **2** – mode No. 2; **3** – mode No. 3; **4** – mode No. 4.

According to the distribution of heat flow in PCB along the duct more than 75 % of heat energy received by water is transferred in the combustion chamber, about 20 % in resonant tubes, and about 5 % in resonant receiver. The pattern of distribution of heat flow in PCB is also determined by design characteristics of resonant tubes (number, dimensions, ratio of cross-sections of gas and water). Their interrelation with characteristics of the combustion chamber varies its heat intensity in total fraction of boiler load.

4. Characteristic by means of generalized variables

In order to obtain more complete analysis of thermohydrodynamic properties of the apparatuses the numbers were determined which reflect parameters of the assembly within four operating modes. The number $Lx = \frac{l}{L}$ is the dimensionless distance where parameters vary; the Reynolds number $\mathrm{Re} = \frac{\upsilon \cdot l}{\nu}$; the Nusselt number $Nu = \frac{\alpha \cdot l}{\lambda}$; the Boltzmann number $Bo = \frac{\upsilon \cdot c_p \cdot \lambda}{C_0 \cdot T^3}$.

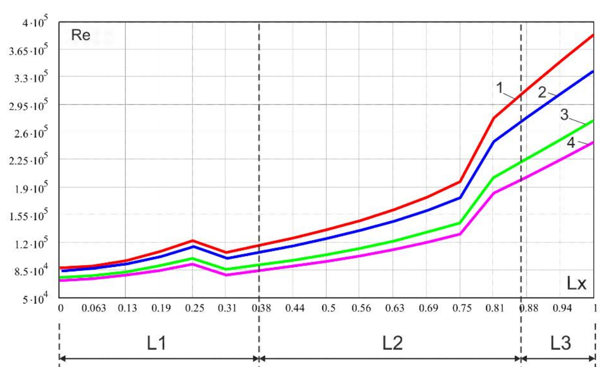


Figure *5*. Variation of Reynolds number as a function of geometric characteristics

Velocity distribution is illustrated in Fig. 5, where distinct influence of geometric characteristics of PCB can be observed (drops in resonant tubes), reflecting pressure drops for local resistances. In the combustion chamber with constant diameter the dependence was described by smooth increasing function.

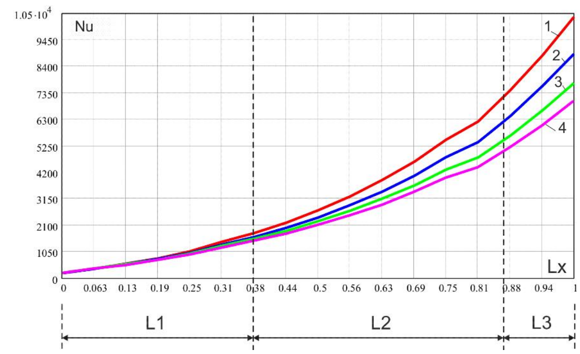


Figure 6. Variation of Nusselt number as a function of geometric characteristics

According to Fig. 6, the form of characteristic of convective component is determined by boundary conditions at the channel inlet and outlet, PCB operating mode, as well as wall thermal conditions. The function increase is determined by variation of properties of exhaust gases.

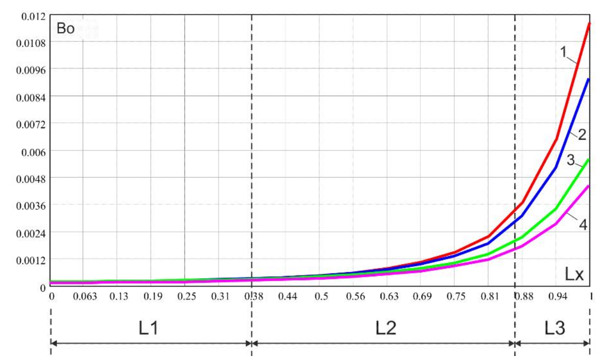


Figure. 7. Variation of Boltzmann number as a function of geometric characteristics

Similar situation for radiant component of complex heat exchange is depicted in Fig. 7. Decrease in heat exchange due to radiation is significant at outlet from resonant tubes (by 20 %) and receiver (by 80 %).

4. Conclusions

1. The developed mathematical model of hydrothermal processes in a pulse combustion unit makes it possible to visualize distribution of energy parameters across overall duct.
2. The proposed mathematical model facilitate simulation of the processes of mass transfer in pulse combustion boilers of preset configuration and various capacity; as well as visual representation of areas of intensive heat transfer and possible overheating of metal.

Corresponding Author:
Sinitsyn
Vologda State Technical University, ul. Razina,
Bldg. 25, Apt. 2, Vologda 160029, Russia
Sinitsyn_a_a@inbox.ru

References

1. Sinitsyn, A. A., Timoshenko P. O., Nikiforov O. Yu, 2012. Peculiar features of development of pilot installation for development of theory of physical processes accompanied with thermoacoustic oscillations during pulse-detonation fuel combustion. Moscow: Fundamental researches, 2012. No. 3-2. PP. 409-413.
2. Timoshenko, P. O., Sinitsyn A. A., 2012. Peculiar features of development of energy unit of pulse-detonation combustion of organic fuel. Izvestiya vysshikh uchebnykh zavedenii. Northern Caucasus Region. Series: Technical sciences. No. 3. PP. 22-27.
3. Sinitsyn, A. A., 2008. Study into vibration properties of boiler unit operation**.** Izv. VUZov. Priborostroenie. – Saint Petersburg: Publishing House of Saint Petersburg State University of Informational Technologies, Mechanics and Optics. Vol. 51, No. 7. PP. 68-71.
4. Sinitsyn, A. A., Igonin V. I., 2010. Study into peculiar features of pulse combustion boilers. Novosti teplosnabzheniya, No. 3 (115). PP. 24 – 27.
5. Sinitsyn, A.A. The working pulse diagram of the energy device for burning of gaseous fuels / A.A. Sinitsyn // Science, Technology and Higher Education [Text] : materials of the international research and practice conference, Vol. II, Westwood, December 11th–12th, 2012 / publishing office Accent Graphics communications – Westwood – Canada, 2012. – p.535-539.
6. Sinitsyn, A.A. Basics of thermoacoustic oscillations of a Helmholtz-type Pulsating Combustor: monograph. — Germany, Saarbrücken: LAP LAMBERT Academic Publishing GmbH & Co. KG, 2013. — 105 p.
7. Shepherd, J.E. Pulse detonation engines: Initiation, propagation and performance / J.E. Shepherd. – Technical Report FM2005.002, GALCIT. - California. – 2005. – p.52. (Final Report for Award ONR N00014-02-1-0589).
8. Chao, T.W. Gaseous Detonation-Driven Fracture of Tubes / T.W. Chao // PhD thesis: California Institute of Technology, Pasadena, - California. 2004. p. 22.
9. Cooper, M. Impulse Generation by Detonation Tubes / M. Cooper // PhD thesis: California Institute of Technology, Pasadena, - California. 2004. p. 238.
10. Keel, S.I. A Study of the Operating Characteristics of a Helmholtz-type Pulsating Combustor / S.I.Keel, Hyun Dong Shin // Institute of Energy. V. 64, 99. - 1991. – p.271-292.

7/30/2013