Method for the Controlled Environment Pressure Measuring

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Abstract: In this paper we propose a new method of studying the nature of the vibration component for the pressure change over time for the energy device that permits to work out the start-stop mode, run mode of the continuous operation and the shutdown of the energy device, the transient modes, when you change the basic (a resonance frequency, a flow and composition of fuel and air) and additional (a fuel pressure, a working medium temperature) operation parameters of the energy device, gives you the opportunity to register and process the measurement results to compare the frequency characteristics at various points of the devices working space, to evaluate the presence of defects in their work. The literary and the patent survey have showed that this method is not currently used, and the devices implementing such a method, are not available on the measuring devices market. The application of measuring complex based on the proposed method, will allow us to try out engineering technique of the design and verification calculations of the devices based on a vibrating, pulsating or detonation fuel combustion, and to apply the energy efficient devices of the energy complex for the further branch development. The author has identified the main problems of the pilot plant development for the measuring complex, the character of the vibration component for the pressure change over time for the energy device, and also the numerical and full-scale tests were carried out. The prototype of measuring complex that implements all the features of this method was developed. The tests on the operating boiler of intermittent burning PV-400, installed in the hot water boiler house in one of the academic buildings of the Vologda State Technical University were made. Based on the simulation results were developed the recommendations on improving the design technology of the pulsating combustion boilers. The results were transmitted and implemented at the enterprise, which produces such boiler units. This work was financially supported by the Ministry of Education and Science of the Russian Federation.
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Keywords: a vibration characteristic, an environmental pressure, an intermittent burning, a frequency diagram, energy efficiency.

1. Introduction

Actuality of the problem of improving the heat sources efficiency is the undisputed argument at the development of new thermal generating devices and the upgrading of existing. The traditional methods, such as the increasing capacity of combustion unit, the using of fuel with a high combustion heat generation, the increasing the heat transfer surface and etc., are not always achievable and often are quite costly. A simple mechanical transfer of accumulated experience in the design, construction and operation of gas consumption units is absolutely unacceptable in the modern world. Therefore it is necessary to develop the heat engineering according to the new and more effective ways of technological development and environmental safety [1]. In this direction, the implementation of pulsating combustion processes in heat-engineering plants is quite promising. Such combustion mode allows us to provide the maximum completeness of higher heating value, significantly to intensify the heat and mass transfer processes and to increase the calorific intensity of combustion chamber. Under such conditions, it becomes obviously a reduction of metal capacity in the structures, a reduction of expenses for the thermal power plants installation and maintenance. In addition, the combustion products meet the most rigorous environmental requirements.

Nowadays, many countries carry out the intensive research in the design and introduction of the thermal power plants on the basis of pulsating combustion into the technological processes. The additional advantages of the boiler pulsating combustion, which ensure its attractiveness in the heat and power market sector are: an absence of burner per se and the considerable pressure of flue gas outlet that does not require a high smokestack, a keeping of working capacity even at an excess pressure close to zero in the feeding gas pipeline. However, the widespread adoption of pulsating combustion devices into the technological processes is constrained by the lack of a reliable workflow theory for the design parameters calculating in their design, as well as the checking calculation to determine the effectiveness of their work. In previous papers [1, 5, 6] we described in detail the mathematical apparatus and a calculating technique of the energy devices based on the non-equilibrium fuel combustion method. However, the main problem of implementing such methods is to determine the actual dependency of environmental pressure changes over time, the accuracy of which greatly affects the results of calibration calculation for the energy device. The method shall be implemented through the measuring complex, which can be used to configure the operating modes of the tested device.

Therefore, the urgent task is the modeling of vibrating processes and the creation of a universal measuring complex to determine the vibration component nature for the pressure changes over time for the power device.

2. Main body.

Pulsating combustion is an unstable combustion mode with the time-varying dynamic characteristics of the process, which have a periodic component.

The possibility of pulsating combustion was theoretically substantiated by Ch. Strett (Lord Rayleigh) at the end of XIX century in England. The devices of vibration combustion of useful purpose with the main directions to solve a number of problems of industrial power system and in creating of aircraft engines [5] have been developed.

The Pulsating combustion issue is closely connected with research in the field of gas detonation. Its usage can be substantiated with a desire to convert the chemical energy of fuel into the kinetic energy most efficiently. The gas parameters at detonation combustion are many times greater than at the normal combustion. The fullest overview of the gas detonation is given in the work of T.E. Bazhenov. The researches of this phenomenon were performed in the foreign works of E. Wintenberger, M. Cooper, J.E. Shepherd [6-9].

Alongside with the theoretical calculations on methods of fuel combustion, a lot of experiments on plants with the similar processes have been carried out. The special interest is the study of thermoacoustic oscillations in different facilities. Such as a singing flame of Higgins, a Helmholtz resonator, a Zondhauss plant, the tubes of Rijke, Schmidt and Marcone. Such type combustion processes were modeled on various configurations furnace devices for the different types of fuel (solid, liquid and gas) by V.S. Severyanin, B.D. Katznelson, S.I.Keel, A.V. Potapkin and others. The attempts to construct a theory of fire modeling were undertaken over half a century ago. Many authors have made the general task definition for the jet fire modeling, the flame propagation in a tube of detonation combustion, the creation of these models and the empirical confirmation of their validity.

In this respect the works of D.A. Frank-Kamensky, N.N. Semenov are the most interesting. The study of flame and gas explosion in the tubes is given in the work of S. Jackson. The author gives the basic concepts of the turbulent stream theory the model of a flame front in a turbulent stream according to the theory of Damkohler. On the basis of experiments, made by Nikuradze, for the flame in the stream with the tube turbulence, this model has been written down through the turbulent combustion rate.

By reference to all foregoing, we can say that the vibration combustion represents the set of acoustic, gas-dynamic, thermal- diffusion, chemical-kinetics, and other physical processes. At the same time, when studying the mechanism of this complex phenomenon, the fundamental importance has the theory.

For studying we selected the heat generator of water heating type, the combustion chamber and the heating surface of which are aligned and represent a heat exchanger of tube in a tube type. The geometric characteristics of the heat exchanger are selected in such manner that they determine the resonant frequency of pulsation in the combustion zone and the convective-radiative heat exchange surface. The geometry is made on the basis of idea of the resonator created by G.L.F. Helmholtz.

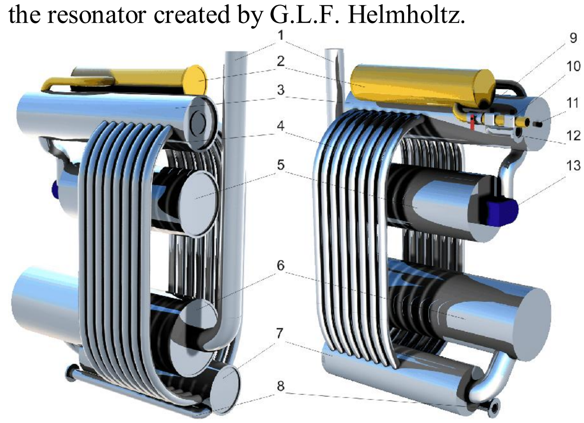

Fig.1 – Structure diagram of the boiler PV-400 [1]. 1 – smoke stack, 2 – gas receiver, 3 – combustion chamber, 4 – resonance tubes, 5 – air receiver, 6 – exhaust silencer, 7 – resonance receiver, 8 – water supply branch, 9 – valve to turn off the gas line, 10 – shut off solenoid valve, 11 – spark plug, 12 – water bleeding tap, 13 – forced-draught fan.

The artificial pulsations obtained in such way are imposed on the turbulent flow pulsations. The combustion is organized by the sequence of micro explosions series which energy is used to perform suction of air-fuel mixture components and the pushing of the combustion produced products into the environment. Under the conditions of formation of micro-explosions there is the selected harmonic transient heat transfer process with its amplitude and period. The more detailed description of the process is given in the works [5, 6].

The developed method relates to the measuring technique and the active and non-destructive control and can be used to measure the pressure of the controlled environment. The method includes measuring the nature of the vibration component of the pressure change in time for the power device, allows to complete start-stop mode, start mode, continuous operation and cutoff of the power device, transients modes while changing the fundamental (resonant frequency, flow and composition of the fuel and air) and additional (fuel pressure, operating medium temperature) operation parameters of the power device, makes it possible to register and process the measurement results, to compare the frequency characteristics at various points in the equipment workspace, to assess the presence of the defects in their work.

The conducted analysis of methods for measuring pressure has shown the following. Up to the present, the method of measuring medium pressure is known [2]. The atmospheric pressure P_{atm} affects one end of the U-shaped tube partially filled with a working fluid. The other end of the tube by means of various feeding devices is connected to the area of the measured pressure P_{meas}. If $P_{meas}>P_{atm}$, the liquid in the part of the supplied measured pressure will be displaced to the part connected with the atmosphere. As a result, between the levels of liquids, located in different parts of the U-shaped tube there will be the liquid column, the height of which is the measured excess pressure. However, this method is acceptable for determining the amplitude of the oscillations of the medium; the nature of the medium pressure changes using is impossible to determine.

In addition, the pressure measuring method is also known [3], involving placing a pressure sensor into the test medium, placing the temperature sensor on the pressure sensor, registering the outputs of the pressure sensor and temperature sensor. According to these signals it is possible to determine the pressure of the medium, form in the medium the mechanical oscillations with a frequency greater than the possible frequency of oscillation of the medium working pressure, emphasize in the output signal from the sensor the signal with the frequency of the predetermined mechanical oscillations. On the basis of this signal and the output signals of the sensor and temperature sensor one determines the diagnostic function according to the deviation of which from the nominal value the accuracy of the pressure measurement is judged.

The disadvantages of the existing method are the complexity of calibration and reference of the sensor units of measurement between the units of pressure, while the sensor is not acoustically isolated from the environment that leads to the dependence of the measurement on any noise.

The closest method to the proposed one is a method of measuring arterial tension [4] when the air in the compressor is inflated to the sleeve gasket in order to reach the pressure that is obviously higher than the maximum pressure of the patient, after which through the decompression there is the reduction of sleeve gasket pressure, and during this process the decision-making block receives the pressure oscillation signals in the sleeve gasket from the pressure sensor. The microprocessor receives these signals via an analog-digital converter. All these signals are also recorded by a multichannel recorder.

The disadvantage of this system is the low measurement noise immunity, especially in the conditions of non-uniform and intense medium pressure fluctuations, that is precisely when the pressure measurement is of the great practical interest. When starting the boiler, the combustion engine or their transient modes, the form of pressure measurement over time is distorted that can lead to incorrect measurement and technical conclusion on the working capacity of the power facility. The disadvantage is also a functional failure of the method consisting in the limited range of the studied objects.

The aim of the study was to improve the accuracy and information content of the pressure measurement methods, provision of the ability to measure and predict the system operation in the non-stationary conditions of vibration combustion, assessment of the presence of defects in the operation of power devices.

The advantages of the proposed solution comparing to the analogues are the following:

1. The ability to measure the parameters of the working process at high ambient temperatures in the heat-stressed area of the power device (over 700°C).

2. An acoustic isolation of the conversion system of the mechanical signal to an analog one that increases the measurement accuracy at the lowest pressure amplitudes and reduces the measurement time.

3. During the test of the power device for the analysis one displays not only the values of maximum, average and minimum pressure of the working environment, but also the dynamics of

pressure variations within a predetermined period of time allowing to evaluate the accuracy of measurement with the presence of any errors and, when the interference has caused the erroneous measurement, not to take into account the values obtained; to reconfigure the oscillation amplitude for the obtained curve of the pressure changes, without changing the overall picture of the process (in the case of amplitude setting to the desired value); to assess the relationship of oscillations at different points of the working path of the power device; to evaluate the effect of secondary workflow options on the pressure in the combustion chamber of the device (e.g., the impact of the workspace configuration).

The set object is achieved by the following way: the medium pressure in at least one measuring point in the impulse tube is perceived by the mechanic and electric transducer placed in the thermally and sound insulated acoustic container, wherein the mechanical oscillation is converted to an electrical signal by an electronic circuit comprising from the source of EMF and resistance, while the signal is transmitted to the device of the analog-digital conversion, where the digital signal is formed in dimensionless units, the transfer of pressure amount of which is made by means of two U-shaped gauges that are configured so that one measures the maximum pressure, and the second one measures the minimum pressure, wherein the check valve in the case of measuring the maximum pressure passes the liquid level difference to the atmosphere side and blocks the measured medium side; in the case of measuring the minimum pressure it passes to the side of the measured liquid and blocks the side to the atmosphere; using the software media of the computing unit one conducts the transformation of the changes digital signal of sound into the pressure in dimensionless units, as well as transformation of the dimensionless units into the dimension of pressure for the measurement and prediction of the energy system work in the non-stationary conditions of vibration combustion, assessment of the presence of defects in the operation of the power devices.

For descriptive reasons, Fig.2 shows a diagram of pressure measurement, Fig. 3 and 4 show the results of studies by the proposed method and the comparison with the well-known method of pressure measurement.

Fig.2 schematically shows a measuring device, consisting of the thermally and sound insulated housing 1 that accommodates an acoustic container 2, the pulse tube 3 having one end connected with an acoustic container, and thermally and sound insulation 4, filling the free space of the housing 1. The acoustic container 2 includes the mechanic and electric transduser, in particular, the carbon microphone 5 included in the electrical circuit state consisting of the source of EMF 6 and of resistance 7. The output of the signal is coupled by the device of analog-to-digital conversion and registration 8.

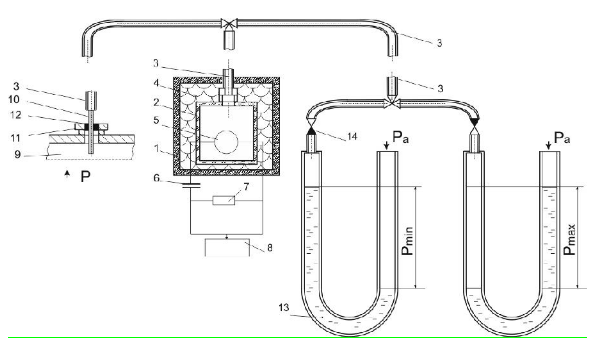

Fig.2 - Scheme for measuring the pressure oscillations character

The scheme for measuring the pressure oscillations character consists of the pulse tube 3 connected to the measuring object 9, contact tube 10, fitted into the case 11 and fixed therein by the thermally and sound insulating material 12.

The scheme for measuring oscillations amplitude is composed of two U-shaped pressure gauges 13 for measuring the medium pressure, connected by the pulse tube 3 with the check valve 14 installed so that the for the measurement of the minimum pressure P_{min} it is placed in the direction of the pressure gauge 13 and for the measurement of the maximum pressure P_{max} it is placed in the opposite direction. Here P is the measured medium pressure, P_a is the atmospheric pressure.

An apparatus for implementing the proposed method operates as follows. Depending on the objective of tests one selects at least one point of measurement in which the medium pressure will be measured. In the measuring object 9 the case 11 is pre-installed and the contact tube 10 is fixed in it. To avoid the heat and noise influence the thermally and sound insulation material 12 is applied on the measurement system. The contact tube 10 is connected on one side with the pulse tube 3 and on the other is placed in the measuring object 9 thus to interact with the medium. The calibration of the measurement system of pressure oscillations amplitude is made by using standard methods and measuring and test equipment (they are not shown).

During the operation of the measuring object 9 the medium pressure in the pulse tube 3 is perceived by the mechanic and electrical transducer 5 while the extraneous medium noises are suppressed due to thermal and acoustic insulation 4. In the transducer 5 the obtained electric signal is converted to by the electric scheme consisting of the source of EMF 6 and of resistance 7, to an analogue signal transmitted to the device of the analog-digital conversion 8, in particular a PC sound card, where a digital signal is formed presenting, in particular, the periodical process of the sound changes in dimensionless units over time.

The pressure oscillations amplitude measurement by means of two U-tube manometers 13 that are configured such that one of them is configured to measure the maximum pressure, and the second - to measure the minimum pressure. On the impulse tube 3 the environment pressure is transferred to the working fluid of manometer 13, on which from the side of its open part the atmospheric pressure effects, causing the fluid level to change, depending on what kind of pressure is higher - the measured or the atmospheric. The valve 14 in the case of measuring the maximum pressure let the differential of liquid level into the atmospheric side and blocks it toward the side of the measured environment; in case of measuring the minimum pressure - controversially: flows into the measured fluid side and blocks it toward the side of the atmosphere.

With the help of software environments of computing unit of computer (omitted for clarity) you shall map the digital signal of sound change into the pressure in dimensionless units, as well as the translation of the dimensionless units into dimensions of pressure.

By means of data processing of the device analog to digital conversion 8 and the manometers 13 on the computer you can receive the pulse frequency character of propagation of the thermoacoustic oscillations in the coordinates P-τ.

For example, the well-known formula [5] for a transfer function, this represents the relation of pressure oscillations inlet and outlet of the channel. It is a complex function, which depends on the phase velocity ω of spread pressure waves and the damping coefficient k.

$$p(x,\tau) = -c_z \rho \Delta P_\upsilon \cos\left(\omega\tau + \frac{\pi}{2}\right) e^{\omega kx} \quad . (1)$$

Here we have introduced the general trigonometric harmonic function for the wave periodic process characteristics, where ΔPυ - is the pressure changes in the process of thermoacoustic oscillations of the medium. To determine the pressure change ratio in the thermoacoustic processes of the environmental oscillations (due to the vibration combustion), you may use the following equations (2) – (5), where cz - a sound speed in the studied medium, ρ – an environmental density.

Sound velocity in the investigated medium (in m / s) can be determined from the equation (2):

$$c_z = \sqrt{\frac{\gamma \cdot R \cdot T}{M}} \quad , (2)$$

where, γ – is a specific heats ratio of the environment;

R – is an absolute gas constant;

T – is an environment temperature;

M – is a molar mass of the environment.

Pressure increase from the sonic wave (in Pa) can be determined from the equation (3):

$$\Delta P_z = 9800(\rho \cdot c_z \cdot \tau_g) \quad , (3)$$

where, τ_g – is a cycle time.

Medium motion speed in the sonic wave (in m / s) is defined as follows:

$$\upsilon = \frac{\Delta P_z}{\rho \cdot c_z} \quad . (4)$$

Increase of the medium pressure (in Pa) can be calculated from the equation (5):

$$\Delta P_\upsilon = 9800(\rho \cdot \upsilon \cdot \tau_g) \quad . (5)$$

An environment motion speed (in m / s) can be determined from the ratio of (6):

$$\upsilon(x,\tau) = \upsilon \ \sin(\omega\tau) e^{\omega kx} \quad . (6)$$

An example of the proposed method realization is shown for studying the character of pulse frequency distribution of thermoacoustic oscillations in the operating boiler of pulsating combustion of type PV based on the Helmholtz resonator at the following conditions:

- Pressure in the gas branch pipe – 102 kPa;
- Pressure in the air branch pipe – 100 kPa (atmospheric pressure);
- Fuel flow rate – 36 m^3/hr;
- Water temperature in the boiler inlet – 44 ºC;
- Water temperature in the water outlet – 50 ºC;
- Excess-air coefficient – 1,25;
- Resonance frequency – 33 Hz;
- Adiabatic exponent of fuel gas γ – 1,4.

The studies were conducted in three stages: Receiving of the analog signal with its transformation into a digital one, using the audio editor of the computer.

Mathematical processing of the audio signal into the periodic process.
Value determination of the vibration amplitudes.

At the first stage, using the built-in Windows program "SOUND RECORDER" was received an audio signal from the signal converter of 5 - carbon microphone and was recorded as a ***.wav** file. The preparation for the mathematical processing of audio file was performed by using the sound program Sound Forge. The mathematical processing of audio file was made by using the MathCAD software and an additional Signal Processing package, intended for the audio signals processing. We made the reading of signal from the audio file, getting of full information about it and the construction of initial signal chart. Next, the signal calibration test was conducted using the U-tube manometer to move from the stress dimension into the pressure dimension.

3. Findings.

For comparison, the pressure amplitude data were correlated with the results of similar experiments of the Korean researchers [10] for the Helmholtz chamber with an aerodynamic valve - PCS (Pulsating Combustion System). The results of two experiments are summarized in the table.

Table 1. Experimental results

Value	PCS	PV-400
Maximum amplitude, kPa	113,8	111,1
Minimum amplitude, kPa	93,1	91,5

In Fig.3 and 4, the results of studies on the frequency characteristics made with the method [10] and the proposed method for a period of time in msec are given.

Here, pos. A.1 and A.2 – are the fragments of the pressure oscillations in the boiler PCS and PV-400, respectively, B.1 and B.2 – one cycle of the vibrating boiler PCS and PV-400 combustion process, respectively. In view of the fact that the researches were conducted on two boilers of the same principle of operation in different ways of the pressure measurement, we can see that the data obtained by the first method, bear the big noise interference, which is reflected in each cycle processing of the periodic process of the pressure oscillations. This interference affects both the pressure oscillations amplitude value and the character of the pressure change over time, and the measurement error will affect the result of the boiler test and the futhure activities to make it more efficient.

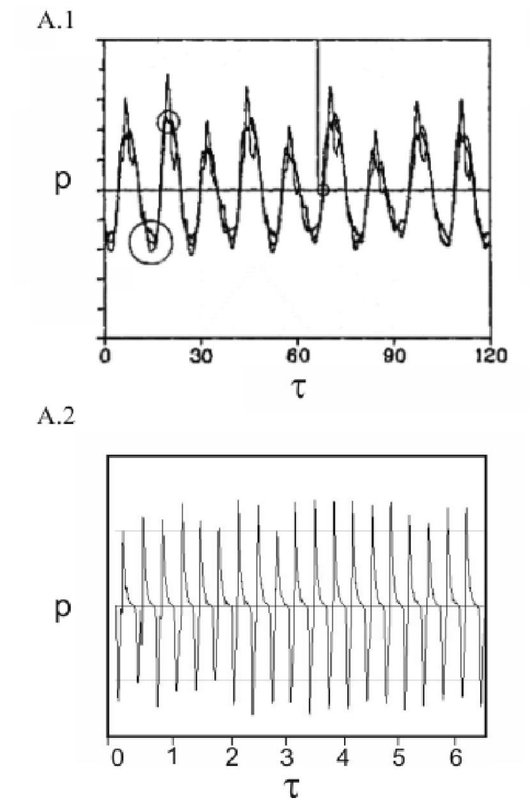

Fig.3 – Comparison of the pulse-frequency diagrams:
A.1 – PCS [10]; A.2 - PV-400

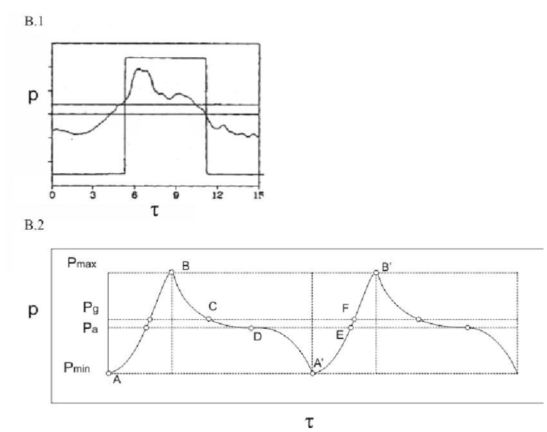

Fig.4 – Cycle comparison of the pulse-frequency diagrams:
B.1 – PCS [10]; B.2 - PV-400

Based on the results of experimental research using the above method, the process of pressure changes in the pulsating combustion boiler tract it became possible to represent it as a diagram with the description of processes occur in this case (Fig.4). Here: A-B – the pressure increase in the fuel-air mixture combustion process; B-A' – the cooling process of flue gases; C-F – the process of natural gas entering through the gas pulsing valve; D-E – the process of air entering through an air-pulsed valve; A-A' – 1st cycle time (is determined by the acoustic properties of the resonator), p_g – a pressure in the gas fuel branch pipe, p_a – an atmospheric pressure (the pressure in the air branch pipe).

4. Conclusion.

In conclusion we mention that the developed method relates to the measuring technique and an active non-destructive testing and can be used for measuring the pressure of the controlled environment, the detection of defects in the work of energy devices operating on the basis of vibrating (pulsating, detonation) fuel combustion used in the energy and transport.

The offered method ensures the opportunity to measure the working process parameters at high environmental temperatures in the heat-stressed area of the energy device (over 700 ◦C), and also creates an acoustic isolation of the conversion system for the mechanical signal to the analog signal, what increases the measurement accuracy at the lowest pressure amplitudes and reduces the measurement time.

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