Practical applicability of the method for measuring pressure of controlled medium on the example of a pulsating combustion boiler

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Abstract. This paper proposes a new way to study the nature of vibration component of pressure change over time for an energy device. This method makes it possible to record and process measurement results, compare frequency characteristics at various points of the device working space, and evaluate the presence of defects in its work. The authors have identified the main problems of developing a measuring complex to study the nature of vibration component of the pressure change over time for an energy device, and numerical and field tests have been carried out.

1. Introduction

The urgency of the problem of increasing the efficiency of heat sources is an indisputable argument while developing new heat-generating devices and modernization of existing ones [1-7]. Traditional methods, such as increasing the power of burner, the use of fuel with increased heat release during combustion, an increase in the surface of heat transfer, etc. are not always feasible and are often costly. A simple mechanical transfer of accumulated experience in the design, construction and operation of gas consumption facilities is absolutely unacceptable in modern conditions. Therefore, it is necessary to develop heating equipment for new and more efficient ways of technical development and environmental safety [8-11]. In this direction, the implementation of pulsating combustion processes in heat and power plants seems very promising. This mode of combustion allows providing maximum completeness of heat generation of fuel, significantly intensifies heat and mass transfer processes and increases the thermal stress of the combustion chamber. Under such conditions, a decrease in the metal content of the structure, reducing the cost of installation and maintenance of thermal power plants is obvious. In addition, the products of combustion meet the most stringent environmental requirements.

Nowadays, in many countries intensive research is being conducted in the field of design and implementation of heat and power plants based on pulsating combustion in technological processes. The absence of a burner as such and significant flue gas pressure at the outlet that does not require a high chimney, maintaining performance even at an overpressure close to zero in the supply gas pipeline are additional advantages of the pulsating combustion boiler, ensuring its attractiveness in the heat and power sector of the market. However, the widespread introduction of pulsating combustion devices into technological processes is hampered by the absence of a reliable theory of the working
process for calculating design parameters during their design, as well as calibration calculations for determining the effectiveness of their work. In previous works [8, 12], the mathematical apparatus and the method for calculating energy devices based on a non-equilibrium method of burning fuel are described in detail. However, the main problem with the implementation of such a technique is determination of the actual dependence of the change in pressure of the medium over time, the accuracy of which strongly influences the results of the calibration calculation of the energy device. The method should be implemented through a measuring complex, which can be applied to configure the operating modes of the device under study.

Therefore, an urgent task is simulation of vibration processes and creation of a universal measuring complex for determining the nature of the vibration component of the pressure over time for an energy device.

2. A review on pressure measurement techniques

The developed method relates to the measuring technique and active non-destructive testing and can be used to measure the pressure of the controlled medium. The method includes measuring the nature of vibration component of the pressure change over time for the energy device, allows one to work out the start-stop mode, start-up mode, long-term operation and shutdown of the energy device, as well as transients at changing the main (resonance frequency, fuel and air composition and flow) and additional (fuel pressure, temperature of the operating medium) operating parameters of the energy device, makes it possible to record and process measurement results, to compare frequency characteristics in various points of the working device space, and to evaluate the presence of defects in their work.

The analysis of methods for measuring pressure showed the following. Nowadays, a method for measuring the pressure of the medium is known [8]. Atmospheric pressure $P_{atm}$ acts on one end of a U-shaped tube, partially filled with working fluid. The other end of the tube is connected to the area of the measured pressure $P_{chan}$ by means of various types of supply devices. At $P_{chan} > P_{atm}$, the liquid located in the part of the connected measured pressure will be forced out to the part connected to the atmosphere. As a result, a liquid column is formed between the levels of liquids located in different parts of the U-shaped tube, the height of which is the measured excess pressure. However, this method is acceptable for determining the amplitude of fluctuations of the medium; it is impossible to determine the nature of the change in pressure of the medium using it.

In addition, there is a method of pressure measuring, which consists in placing a pressure sensor in a test medium, placing a temperature sensor on a pressure sensor, recording the output signals of the pressure sensor and the temperature sensor. These signals determine the pressure of medium, form mechanical oscillations with a frequency greater than the possible frequency of oscillations of the working pressure of the medium in the medium under study, extract the variable signal from the output signal of the sensor with the frequency of specified mechanical oscillations. Diagnostic functions are determined from this signal and the output signals of the sensor and the temperature sensor, by the deviation of which from the nominal value, the error of pressure measurement is judged.

The disadvantages of the existing method are the difficulty of calibrating and assigning units of measurement by a sensor to units of pressure, while the sensor is not acoustically isolated from the environment, which makes the measurement dependent on any noise.

The closest to the proposed method is a method of measuring blood pressure, when the compressor pumps air into the cuff to achieve a pressure value that is obviously greater than the maximum pressure of the patient, after which the cuff pressure decreases through the decompression valve, during which the decision block enters cuff pressure fluctuation signals from a pressure sensor. The microprocessor receives these signals through an analog-to-digital converter. All of these signals, in addition, are recorded by a multi-channel recorder.

The disadvantage of such a system is low noise immunity of measurements, especially under conditions of uneven and intense fluctuations in the pressure of medium, that is, precisely when pressure measurements are of great practical interest. When starting the boiler, internal combustion
engine or their transient modes, the form of pressure measurement over time is distorted, which can lead to incorrect measurement and technical conclusion about the performance of the power facility. An additional disadvantage is also the functional failure of the method, consisting in a limited range of the studied objects.

Thus, the development is relevant and can find direct application in various sectors of energy and utilities.

3. Description of the proposed method

The purpose of the study was to improve the accuracy and informativeness of pressure measurement methods, to create the ability to measure and predict system operation in non-stationary conditions of vibration combustion, to assess the presence of defects in the operation of energy devices.

The advantages of the proposed solution in comparison with analogues are the following:

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

2. Acoustic isolation of the mechanical signal-to-analog conversion system, which improves the measurement accuracy at the lowest pressure amplitudes and reduces the measurement time.

3. When testing the energy device for analysis, not only the maximum, average and minimum pressure of the working medium are displayed, but also the dynamics of pressure change over a given period of time. This allows evaluating the accuracy of measurement in the presence of any errors and, in cases where interference caused erroneous measurement, do not take into account the values obtained; to reconfigure the amplitude of oscillations for the obtained curve of pressure change, without changing the overall picture of the process (in the case of adjusting the amplitude to the desired value); to assess the relationship of oscillations at various points of the working path of the energy device; to evaluate the influence of secondary parameters of the workflow on the pressure in the combustion chamber of the device (for example, the influence of the configuration of the working space).

This goal is achieved by the fact that the pressure of medium in at least one measuring point on the impulse tube is perceived by a mechanical-electrical converter placed in a heat-sound-insulated acoustic capacitance, in which the mechanical oscillation is converted into an electrical signal by an electronic circuit consisting of EMF source and resistance. The signal is transmitted to an analog-to-digital conversion device, where a digital signal is formed in dimensionless units, the conversion to the pressure dimension of which carried out using two U-shaped manometers, configured so that one of them measures the maximum pressure, and the second – the minimum one, while the non-return valve in the case of measuring the maximum pressure passes a drop in fluid levels towards the atmosphere and blocks towards the measured medium. In case of measuring the minimum pressure it passes a drop in fluid levels in the direction of the measured liquid and blocks in the direction of the atmosphere. Using the software of the computing unit, the digital signal of the sound change is converted into pressure in dimensionless units, and the pressure is converted from dimensionless units to pressure dimensions in order to measure and predict the operation of the energy system under non-stationary conditions of vibration burning, to evaluate the presence of defects in the energy devices.

For clarity, figure 1 shows the scheme of pressure measurement, and figure 2 shows the results of the study using the proposed method and a comparison with the known method of measuring pressure.

Figure 1 schematically shows a measuring device consisting of a heat and sound insulated body 1 in which acoustic the following parts are placed: acoustic capacitance 2, a pulse tube 3 connected to acoustic capacity at one end, and heat and sound insulation 4, which fills the free space of enclosure 1. In acoustic capacitance an electric transducer, in particular, a carbon microphone 5, included in an electrical circuit consisting of an EMF source 6 and resistance 7. The signal output is connected by an analog-to-digital conversion and registration device 8.
The scheme for measuring the nature of the pressure oscillation consists of an impulse tube 3 attached to the object under measurement 9, a contact tube 10 installed in the sleeve 11 and fixed in it by means of heat and sound insulating material 12.

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

The device for implementing the proposed method works as follows. Depending on the test task, at least one measurement point is selected at which the pressure of medium will be measured. In the measurement object 9, a sleeve 11 is preliminarily arranged, in which the contact tube 10 is fixed. To avoid thermal and noise effects, a heat and sound insulating material 12 is used on the measurement system. The contact tube 10 is connected to the pulse tube 3 from one side, and from another one is placed into the object under test 9 in such a way to interact with the environment. The system for measuring the amplitude of pressure fluctuations is calibrated using standard methods and instrumentation (conventionally not shown).

When the object under study 9 is operating, the medium pressure on the pulse tube 3 is perceived by the mechanical-electrical converter 5, while the external environmental noise is extinguished by heat and sound insulation 4. In the converter 5, the received sound signal is converted by an electrical circuit consisting of an EMF source 6 and resistance 7 to an analog signal transmitted to the analog-to-digital conversion device 8, in particular, the PC sound card, where a digital signal is formed, which is, in particular, a periodic process of sound change in dimensionless units in time.

Measurement of the amplitude of pressure fluctuations using two U-shaped pressure gauges 13, configured so that one of them is set to measure the maximum pressure, and the second one to measure the minimum pressure. Through the impulse tube 3, the pressure of the medium is transferred to the working fluid of the manometer 13, which is exerted by the atmospheric pressure on the open side of the pressure gauge, causing the fluid level to change depending on whether the measured pressure is higher or the atmospheric one. The valve 14 in case of measuring the maximum pressure passes the differential levels of fluid in the direction of the atmosphere and blocks in the direction of the measured medium; in the case of measuring the minimum pressure – on the contrary: it passes in the direction of the measured liquid and blocks in the direction of the atmosphere.

Using the software of the computing unit (conventionally not shown), the digital signal of the sound change is converted into pressure in dimensionless units, and also converted from dimensionless units into pressure dimension.

By processing the data of the analog-digital conversion device 8 and pressure gauges 13 on a computer, it is possible to obtain the frequency-pulse nature of the propagation of thermo-acoustic oscillations in the coordinates $P$-$\tau$. 

Figure 1. Principal scheme of the measuring device.
4. Description of mathematical methods
An example of the implementation of the proposed method is given for study of frequency-pulse nature of the propagation of thermo-acoustic oscillations in the operating boiler of pulsating combustion of the PV type based on the Helmholtz resonator under the following conditions:
- Pressure in gas pipe is 102 kPa;
- Pressure in air pipe is 100 kPa (atmospheric pressure);
- Fuel consumption is 36 m3/h;
- Water temperature at the boiler inlet is 44 ºC;
- Water temperature at the boiler outlet is 50 ºC;
- Excess air ratio is 1.25;
- Resonance frequency is 33 Hz;
- Adiabat index of flue gas \( \gamma=1.4 \).
- The studies were conducted in three stages: obtaining an analog signal with its conversion to digital using an audio computer editor; mathematical processing of the audio signal in a periodic process and determining the values of the amplitudes of oscillations.
- At first stage, a sound signal was received from a 5-angle microphone signal converter. Mathematical processing of the sound file was carried out using the MathCAD program and the additional Signal Processing package designed to process audio signals. The signal was read from the sound file, obtaining complete information about it and building the original signal graph. Next, to go from the voltage dimensions to the pressure dimensions, the signal was calibrated using a U-shaped manometer.

5. Experimental results
For comparison, the data on the pressure amplitude are correlated with the results of similar experiments by Korean researchers [13] for the Helmholtz chamber with an aerodynamic valve – PCS (Pulsating Combustion System). Figure 2 presents the obtained frequency characteristics using the method [13] and the proposed method for a period of time in ms.

Based on the results of an experimental study using this method, it became possible to present the process of pressure change in the path of pulsating combustion boiler in the form of a diagram describing the processes occurring in this process. Here: A-B is pressure increase in the process of combustion of the fuel-air mixture; B-A' is the flue gas cooling process; C-F is the process of natural

![Figure 2. Comparison of the cycle of pulse-frequency diagrams: B.1 - PCS [13]; B.2 - PV-400.](image-url)
gas intake through the gas-pulsating valve; D-E is the process of air flow through the air-pulsating valve; A-A’ is time of one cycle (determined by the acoustic properties of the resonator), \( P_g \) is pressure in the gas fuel pipe, \( P_a \) is atmospheric pressure (pressure in the air pipe).

6. Conclusions

A new method for studying the nature of vibration component of pressure change over time for an energy device is proposed. It allows one to work out the start-stop mode, start mode, long-term operation and stop of the energy device, transient modes when the main (resonance frequency, consumption and flow of fuel and air) and additional (fuel pressure, temperature of the working environment) parameters of the energy device change. Also, it allows one to record and process measurement results, compare frequency characteristics in various points of the working space devices to evaluate the presence of defects in their work. Literary and patent review has shown that this method is not currently used, and devices that implement this method are not available in the market for measuring instruments. The use of measuring complex based on the proposed method will allow testing the engineering methodology of design and calibration calculations of devices based on vibratory, pulsating or detonation fuel combustion, and apply energy-efficient devices of the energy complex to the further development of the industry. The authors have identified the main problems of developing a measuring complex to study the nature of vibration component of the pressure change over time for an energy device, conducted numerical and field tests. A prototype of a measuring complex has been developed that implements all the possibilities of such a method. Tests were carried out on the operating boiler of pulsating combustion PV-400 installed in a water-heating boiler house of one of the educational buildings of Vologda State Technical University. Based on the simulation results, recommendations have been developed for improving the design of pulsating combustion boilers. The results are implemented at the enterprise producing such boilers.

References

[1] Anikina I D, Sergeyev V V, Amosov N T and Luchko M G 2017 Use of heat pumps in turbogenerator hydrogen cooling systems at thermal power plant Int. J. of Hydrogen Energy 42(1) pp 636–42
[2] Akhmetova I G and Chichirova N D 2017 Estimation of the effective heating systems radius as a method of the reliability improving and energy efficiency J. of Physics: Conference Series 891(1) p 012169
[3] Sebelev A, Kirillov A, Porshnev G, Lapshin K and Laskin A 2018 Thermodynamic analysis of design and part-load operation of a novel waste heat recovery unit MATEC Web of Conferences 245 p 04010
[4] Saari J, Sermynagina E, Kaikko J, Vakkilainen E and Sergeev V 2016 Integration of hydrothermal carbonization and a CHP plant: Part 2 –operational and economic analysis Energy 113 pp 574–85
[5] Paramonov A P, Kadyrov M R and Trinchenko A A 2017 Research on Influence of the Furnace Chamber Aerodynamics on Ecological Indicators of Boiler Plants (Part 1: Model of a Low-temperature Swirl Furnace) Procedia Engineering 206 pp 546–51
[6] Trinchenko A A and Paramonov A P 2017 Introduction of low-temperature swirl technology of burning as a way of increase in ecological of low power boilers IOP Conference Series: Earth and Environmental Science 90(1) p 012094
[7] Kharlamova T and Osipova K 2018 The state of modern heat power engineering and increasing the economic efficiency of heat supply MATEC Web of Conferences 245 p 05002
[8] Sinitsyn 2012 Science, Technology and Higher Education Westwood, Canada
[9] Ovchinikov P, Borodičecs A and Millers R 2017 Utilization potential of low temperature hydronic space heating systems in Russia J. of Building Engineering 13 pp 1–10
[10] Anikina I and Suslov V 2018 Influence of heat pumps inclusion in deaeration scheme of heating network make-up water on the operating modes of the TPP MATEC Web of Conferences 245
[11] Akhmetova I and Akhmetov T 2018 Analysis of additional factors for determining heat network pipelines failure rates *E3S Web of Conferences* **58** p 01011
[12] Shepherd J 2005 *Technical Report FM2005.002 GALCIT* California
[13] Keel S and Shin H D 1991 *Institute of Energy* **64**