MICROWAVE RESONATOR METHOD TO MEASURE TRANSIENT MASS GASIFICATION RATE OF CONDENSED SYSTEMS

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Abstract. *The gasification rate of condensed systems is an important ballistic parameter which is widely used in designing the rocket motors and gas-generating devices. The paper presents information on the development of a new contactless method for measuring transient mass gasification rate of condensed systems based on dynamical recording the amount of tested material with a microwave sensor of the resonator type, whose signal is recorded by a network analyzer with high accuracy. The sensor design provides making time-resolved measurements of the gasification rate under vigorous blowing the reacting surface of a sample with a central channel. The sample length is chosen greater than the length of the measuring zone in the coaxial resonator sensor in order to eliminate the influence of the nonuniformity of the gasification process at the inlet and outlet of the channel. The time resolution of the sensor is of the order of 1 ms and apparent space sensitivity for the surface regression measurement is about few microns.*

INTRODUCTION

When designing various propulsion systems and gas-dynamic devices the burning rate of energetic material is an important ballistic parameter. It is known that in the case of steady-state combustion processes, it is necessary to measure the value of this parameter with an error of about 0.5-1.0%. In the present time, because of arising the new applications of energetic materials, the results of measurement of transient burning rate are increasingly in demand. They can also be effectively used as a source of information about the mechanism of combustion and serve as the basis for verification of existing combustion models. The proposed microwave method provides opportunities for obtaining such information. Actually, the problem of obtaining data on transient burning rate takes solving complex technical problems. It is estimated that to measure a 10% variation of the burning rate with a typical average value of 5–10 mm/s under periodic exposure with a frequency of 100–200 Hz to external power source, it is necessary to provide a spatial resolution of the method of few μm, and temporal resolution of no less than 1 ms. Numerous attempts have been made in the world to develop dynamic methods for measuring linear and mass burning rates using optical methods, X-rays, and microwave radiation [1–4]. Nevertheless, it can be argued that the currently available implementations of these methods do not provide the required accuracy and reliability in measuring the unsteady burning rate. Thus, there is a need for further development of novel high-performance methods of time resolved measurements.

Obviously, similar problems arise in determining the dynamic rate of pyrolysis of polymer and energetic materials used in hybrid and air-breathing jet engines. Therefore, in general, we have to speak about gasifying agents (GA) and their gasification rate.

EXPERIMENTAL TECHNIQUE

This paper presents information on the development of a new contactless method for measuring transient mass gasification rate based on dynamical recording of the amount of GA in a microwave sensor of the resonator type, whose signal is measured using a network analyzer with high accuracy and high temporal resolution. Note that the sensor design provides time-resolved measurements of the gasification rate with intense blowing of the surface of a sample having central channel opened for passage of gas flow. This type of information is in high demand by designers of hybrid engines, who currently have only very approximate values of the effective average rate of the fuel gasification.

The coaxial resonator sensor (CRS) (see Fig. 1) has an inner cavity which houses a protective plate and a quartz tube. A bored sample of the tested substance is firmly inserted into the central part of the tube. The measurement section is in the middle of the CRS. The sample length is greater than the length of the measuring zone of the CRS in order to eliminate the influence of the nonuniformity of the gasification process at the inlet and outlet of the channel.

After starting the sample blowing, gasification in its channel causes a change in the sample mass. This is accompanied by a change in the coupling evanescent waveguide attenuation, which is continuously recorded by a microwave network analyzer. The change in the signal is proportional to the change in the amount of the substance in the resonator.

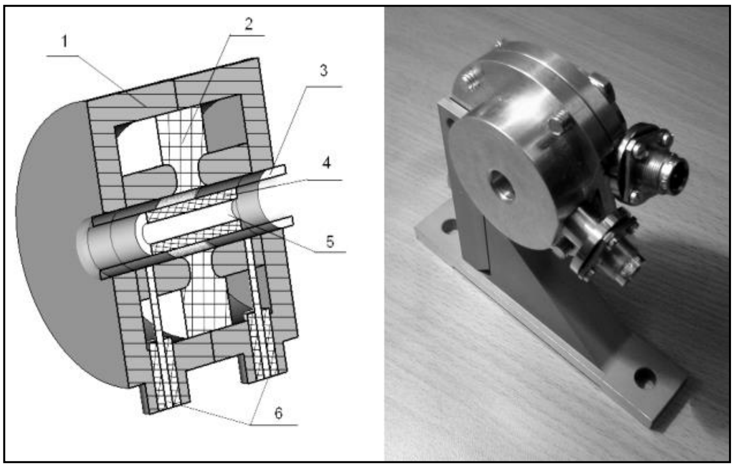

Fig. 1. Design and general appearance of the coaxial microwave resonator sensor: (1) sensor housing; (2) protective plate; (3) quartz tube; (4) GA sample; (5) channel in the GA sample; (6) microwave leads.

In the configuration considered, two symmetric coaxial resonators are coupled to each other through a capacitor gap which is partially filled with a GA sample. The ends of the sample are in the regions outside the gap. There the electric field is practically absent.

The performance of the microwave sensor in the form of a system of two quarter-wave coaxial resonators with a capacitive gap between them has the following important feature. Since the GA channel sample is placed in the region of a high electric microwave field, the change in the coupling between the coaxial resonators due to a change in the channel diameter during gasification of a GA sample leads to a significant change in the resonant frequency of the anti-phase oscillation mode.

According to electrodynamic calculations and sensor calibration data, with the maximum increase in the diameter of the channel in the GA sample (complete gasification of the substance), the change in the resonance frequency of the microwave-sensor is comparable

to the width of its resonance curve. The location of the working point on the slope of the resonance curve of the microwave-sensor is optimal and corresponds to the maximum gain slope. As an illustration, Fig. 2 shows a typical characteristic of the dynamic attenuation of the microwave signal as a function of the diameter of the channel.

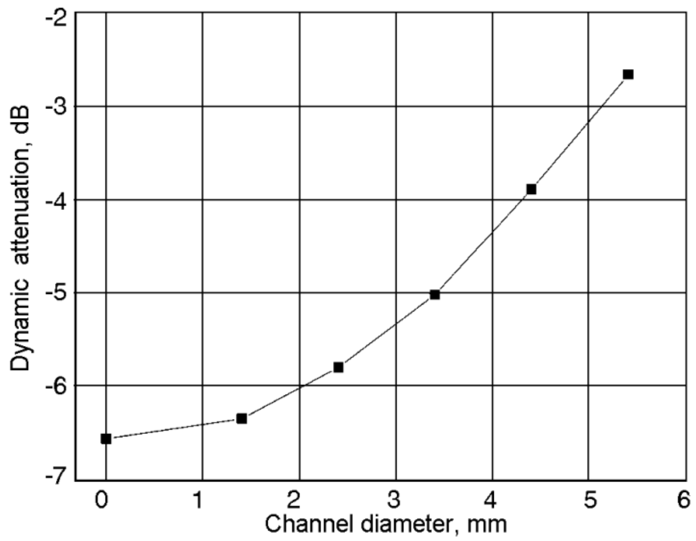

Fig. 2. Calibration of the coaxial resonator sensor. Dependency of the attenuation of the microwave signal vs channel diameter in a model sample.

The resolution of the resonant microwave sensor in determining the mass loss is high due to a significant change in the frequency of the anti-phase oscillation mode, characteristic of systems of coupled coaxial resonators. In operation on the slope of the resonance curve, the change in the dynamic attenuation reaches 4–10 dB for different designs microwave-sensor. In the modern high-sensitivity network analyzers produced by the Advantest or Rohde&Schwarz companies, the resolution in the radius of the channel may reach few micrometers.

The performance of the microwave sensor is affected by the composition of the combustion products in the central region of the channel and the heating of the sensor parts. This requires a detailed experimental study. In particular, it is planned to investigate the characteristics of the sensor when placing GA samples in insulating tubes made of various materials.

To calculate the gasification rate, we assume that for the same length and unchanged shape of the measuring section, the attenuation of the microwave radiation signal is proportional to the region occupied by the cross section of the sample, i. e., the difference between the total cross-sectional area of the sample (radius R equal to the inner radius of the quartz tube) and the area of channel opening (radius r). In this case, the derivative of the signal from the occupied section of the sample ΔS is proportional to the product of the current channel radius and gasification rate v:

$$\Delta S = S_0 - S(t) = \pi(R^2 - r^2) \qquad (1)$$

$$d\Delta S/dt = -2\pi r dr/dt \qquad (2)$$

Equations (1) and (2) imply the following expression for the gasification rate:

$$V = dr/dt = -(d\Delta S/dt)/2\pi(R^2 - \Delta S/\pi)^{0.5} \qquad (3)$$

From Eq.(3) it is seen that the accuracy of determining the gasification rate crucially depends on the accuracy of recording the microwave signal from the occupied section of the sensor, which, with the modern measurement tools, can reach 0.5%. The time resolution of the resonant sensor is of the order of 1 ms and is determined by the setting time of natural oscillations with a loaded Q factor of 230 at a frequency of 2300 MHz. The time resolution of the recording system can reach 10 μs, which certainly satisfies the requirements for the method of recording transient gasification rate.

CONCLUSION

The proposed method for measuring transient mass gasification rate can be used in various applications to obtain information on the gasification characteristics of polymer and energetic materials under vigorous blowing of the surface of bored samples. The time resolution of the microwave sensor is of the order of 1 ms and apparent space sensitivity for the surface regression measurement is several microns.

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R E FE R E N C E S

1. V. E. Zarko and K. K. Kuo, “Critical Review of Methods for Regression Rate Measurements of Condensed Phase Systems,” In: Non-intrusive Combustion

Diagnostics, Edit. by K. K. Kuo and T. Parr (Begell House, New York, 1994), pp. 600–623.
2. B. Evans, N. A. Favorito, and K. Kuo, “Study of Solid Fuel Burning-Rate Enhancement Behavior in an X-ray Translucent Hybrid Rocket Motor,” In: 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference&Exhibit, AIAA Paper 2005-3909; DOI: 10.2514/6.2005-3909.
3. V. E. Zarko, V. V. Perov, and V. N. Simonenko, “Critical Assessment of the Microwave Method for Measuring Steady-State and Transient Regression Rates of Solids,” In: Combustion of Energetic Materials, Edit. by K. K. Kuo and L. T. De Luca, Begell House, New York, (2002), pp. 725–732.
4. D. A. Yagodnikov, A. V. Sergeev, and V. V. Kozichev, “Experimental and Theoretical Basis for Improving the Accuracy of Measuring the Burning Rate of Energetic Condensed Systems by a Microwave Method,” Fiz. Goren. Vzryva 50 (2), 51–61 (2014) [Comb., Explo., Shock Waves 50 (2), 168–177 (2014)].