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Microwave resonator method for measuring transient mass gasification rate of condensed systems

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Abstract

The paper deals with developing a new contactless method for measuring transient mass gasification rate of condensed systems based on recording attenuation signal induced by the mass of tested material in a microwave sensor of resonator type. According estimations the temporal resolution of the sensor is better than 10^{-3} s and apparent space resolution is about few microns. The sensor design provides measurements of the gasification rate in conditions of intense gas blowing through a sample bore.

1. Introduction

When developing and designing different propulsion systems the burning (gasification) rate of energetic materials is one of the major ballistic parameters. It is known that in the case of steady-state combustion processes, it is necessary for practice to measure the value of this parameter with an error of about 0.5% or lower [1]. In addition, the results of unsteady burning rate measurements can be effectively used as a source of information about mechanism of combustion and provide background for verification of existing combustion models.

Actually, the problem of obtaining data on transient burning rate implies solution of complex technical problems. One can estimate that in order to measure 10% variation of the burning rate of average value 0.005÷0.01 m/s under periodic exposure to an external power source with a frequency of 100–200 Hz, it is necessary to provide spatial resolution of the method equal to few μm, and temporal resolution better than 10^{-3} s. Numerous attempts have been undertaken in the past to develop methods for dynamic 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 transient burning rate. Thus, there is a need for further development of novel high-performance methods for time resolved burning rate measurements.

Obviously, similar problems exist in determining the dynamic rate of pyrolysis (regression) of polymer and energetic materials used in hybrid and air-breathing jet engines. Therefore, in general, one may speak about gasifying substances (GS) and their gasification rate.

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

2. Description of the experimental procedure

To achieve the specified goal the microwave resonator method for dynamic measurement of mass of gasifying solid fuels has been developed based on the measurement of attenuation of a microwave signal passing through the resonator sensor [2] (Fig. 1) loaded with the investigated sample.

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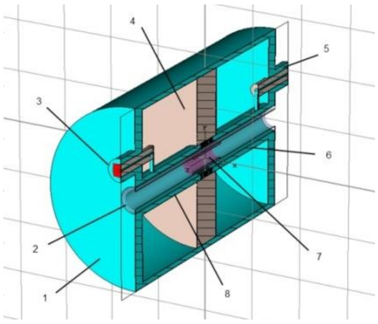

Figure 1: The sketch of microwave resonator sensor. 1 – case; 2 – protective tube; 3 – input port; 4 – centering disk; 5 – output port; 6 – output resonator; 7 – sample; 8 - input resonator.

The sensor is executed in the form of system of two coupled coaxial resonators excited on antiphase mode through one of two ports. Another port is intended for passing the microwave signal to the receiver of the network analyzer. The working area of the sensor is formed by a gap between coaxial resonators. For achievement of the highest uniformity of distribution of high-frequency electric field in the volume of studied sample the length of working area is chosen equal to its diameter. In the present design it is equal to 0.02 m.

When carrying out researches, the resonant characteristic of the sensor is preliminary determined and change of transitional attenuation S21 between sensor's ports on the chosen working frequency ***f*** is recorded. Insertion of a sample of solid fuel into working area of the sensor affects the resonant characteristic. The first change of the characteristic is connected with the shift of resonant frequency of an antiphase type of the fluctuations, which is caused by increase of radiofrequency couple between coaxial resonators at the expense of insertion of dielectric material. If the GS formulation includes the boron powder possessing considerable losses on high frequencies, the resonant characteristic S21 (***f***) in addition to shift also extends because of deterioration of the quality (Q-factor) of the system of coupled resonators on the antiphase mode.

Before firing experiments, the sensor is calibrated by using samples of studied material having different bore radius (Fig. 2). The sample length (0.04 m) is chosen longer than the length of the measuring zone (0.02 m) in the coaxial resonator sensor in order to eliminate the influence of the nonuniformity of gasification process at the channel inlet and outlet. The high linearity of the calibration characteristic S21 (*r*) in the bore radiuses range of $(4 \div 8) \times 10^{-3}$ m is the result of special design of the sensor and optimal selection of operation frequency. This allows minimizing the number of calibration samples up to one sample of studied material. In this case the second point in the calibration characteristic is determined in the absence of GS material in the working area of sensor.

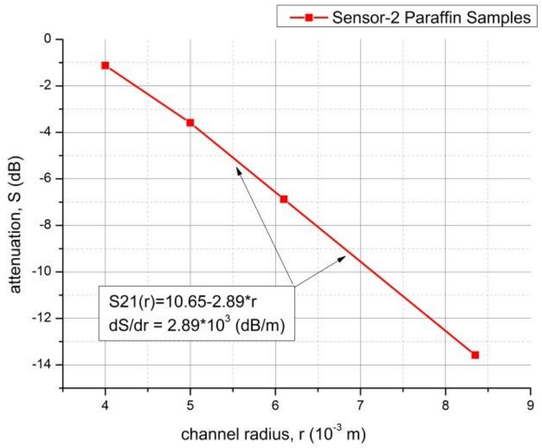

Figure 2: Example of calibration for paraffin samples.

To calculate the gasification rate, we assume that for the fixed length and invariable shape of the measuring section, the attenuation of microwave radiation signal is proportional to the region occupied by the cross section of the sample equal to the difference between the total cross-sectional area of the sample (radius R equal to the inner radius of the protective tube) and that of bore (radius r). In this case, the derivative of the signal from occupied section of the sample ΔS is proportional to the product of the current bore radius and regression rate V_{regr}:

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

$$d\Delta S/dt = -2\pi r\, dr/dt \tag{2}$$

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

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

From (3) it is seen that the accuracy of determining the gasification rate crucially depends on the accuracy of the microwave signal recording, and with the modern measurement tools it can reach 0.5%. The time resolution of the resonant sensor is of the order of parts of 10^{-3} s.

In the case of linear *dS*/*dr* dependency for fast evaluation of the burning (gasification) rate value one may employ a simple procedure via using experimental magnitude of *dS*/*dt*. Namely, the burning rate value can be determined as

$$V_{regr} = dr/dt = (dS/dt)/(dS/dr) \tag{4}$$

Such approach has been used in the present work for treating the preliminary experimental data on the gasification rate.

3. Experimental results and discussion

The experiments on determining the gasification rate of sold fuels under intense gas flow blowing were performed on the aerodynamic test facilities of the Institute of Theoretical and Applied Mechanics, Novosibirsk. The scheme of the test facility is shown in Figure 3. The air is compressed into Prechamber from the gas tanks and is subjected to Joule heating or to heating by firing in air of small amount of hydrogen. The hot air then is passing through the Nozzle to bored sample installed inside the microwave Gage. The pressure and temperature inside Prechamber are recorded by pressure transducer and thermocouple and collected by acquisition system. The temperature of air at the exit of Gas flow is measured by thermocouple.

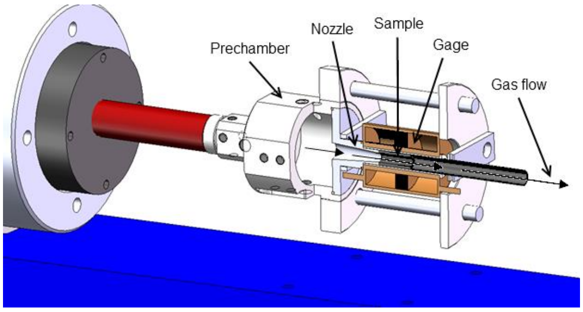
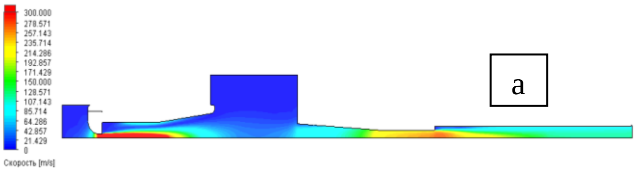


Figure 3: Sketch of experimental facility for tests on gas blowing through the specimen bore.

The properties of gas flow in the test facility are calculated via using ANSYS program. The examples of numerical calculation results corresponding to conditions P_{cham} = 0.4 MPa, P_{out} = 0.1 MPa, T_{chamb} = 500 K are shown in Fig. 4. At the sample front edge the pressure typically is reduced by 40% and air temperature by 150 ÷ 200 K.



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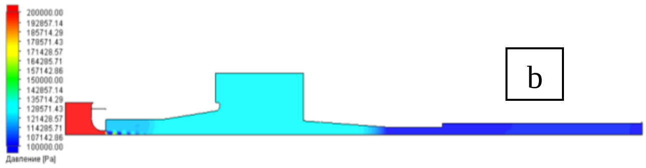

Figure 4: space distribution of gas velocity (a, in m/s) and pressure (b, in Pa) along the horizontal direction.

The examples of the records of pressure in Prechamber and temperature in Prechamber and in the outer part of gas flow are shown in Figure 5.

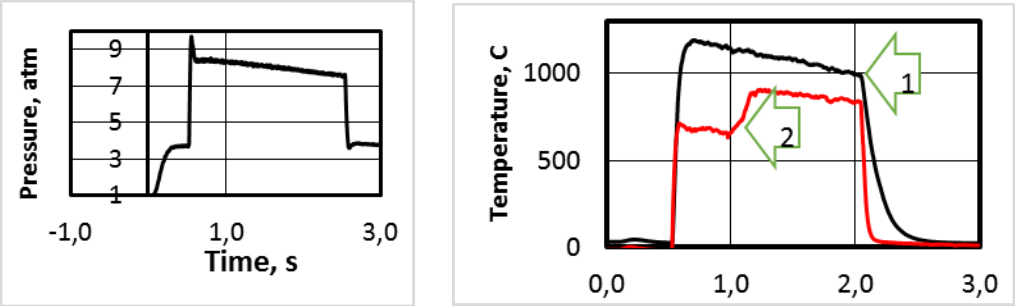

Figure 5: Illustrative records of the Prechamber pressure (left) and gas temperature (right) in Prechamber (1) and out of Gas flow (2).

The experiments were performed with pure paraffin P2, paraffin P2 with 20% of AlH_3 and Plexiglas samples upon blowing by hot air with the temperatures of 450 ÷ 1200 K and velocities of 150 ÷ 900 m/s. The bore diameter was 10 mm. Mass flow rate of air comprised 100 ÷ 800 kg/m^{2}s. Due to relatively high velocity of air blowing and short length of samples the flame was not recorded in the cases of pure P2 and Plexiglas samples. Only in the case of paraffin P2 with 20% of AlH_3 samples the flame was recorded at a moderate gas blowing velocity (Fig. 5, curve 2).
Below, some typical microwave transducer records for paraffin based and Plexiglas samples are presented.
1. Paraffin P2. The air mass flow rate equals 150 kg/m^{2}s. Prechamber pressure equals 0.4 MPa and temperature 570 K. $dS/dr = -2.89 \times 10^3$ dB/m, $Vregr = 1.9 \times 10^{-4}$ m/s. Sample was gasified totally by hot air.

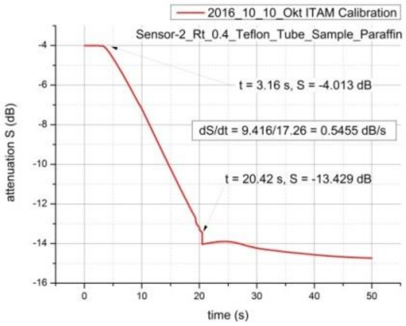

Figure 6: Pure P2 testing.

2. Paraffin P2+AlH_3 (20 %). The parameters of air flow are much stronger than in the previous case. The mass flow rate equals 540 kg/m^{2}s. Prechamber pressure equals 4 atm and temperature 1270 K. $dS/dr = -2.89 \times 10^3$ dB/m, $V_{regr} = 4.86 \times 10^{-3}$ m/s. Sample was gasified partially and its last portion was ejected by hot air flow.

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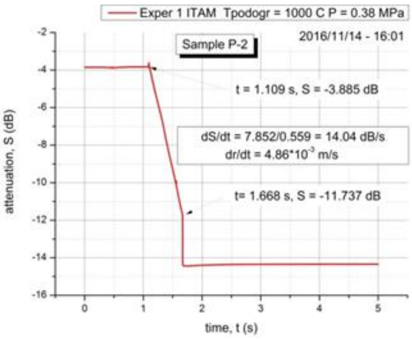

Figure 7: Pure P2+AlH3 testing.

3. Plexiglas. The air mass flow rate equals 530 kg/m^{2}s. The parameters of air flow are practically the same as in the previous case. Prechamber pressure equals 0.4 MPa and temperature 1270 K. dS/dr = -3.09 × 10^3 dB/m, V_{regr} = 2.2 × 10^{-4} m/s. The duration of gas blowing was 4s, the sample was gasified only partially.

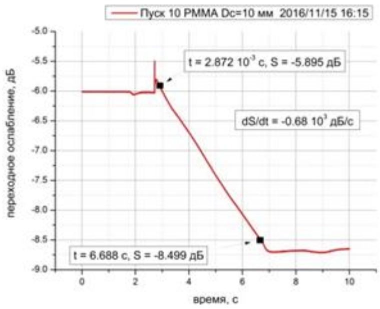

Figure 8: Plexiglas testing.

Actually, available experimental records demonstrate some specific features of regression behavior of paraffin based and Plexiglas samples. It is seen that the intense hot gas blowing of paraffin sample loaded with AlH_3 resulted in a high regression rate, 4.86 × 10^{-3} m/s and formation of the flame despite a relatively short sample length. The intense gas blowing has led to ejection of remaining portion of sample. In the case of Plexiglas sample, when using practically the same intensity parameters of air blowing (Prechamber pressure 0.4 MPa and temperature 1270 K), the gasification rate is much less and equal to 2.2 × 10^{-4} m/s.

Preliminary analysis of experimental data shows that the method proposed may allow measuring dynamics of the fuel regression with high technical parameters. Special tests with unloaded sensor revealed that the noise contribution into amplitude of measured signal equals 0.01 dB. Simple estimates with available data acquisition system give apparent magnitude of space resolution of the method equal to several micrometers and temporal resolution better than 10^{-3} s. Those parameters can be improved if one uses more sophisticated and powerful tools for recording microwave signals.

It is known from the literature that there is an optical method [5] invented by Italian researchers and intended for obtaining the time and space resolved data on gasification rate of solid fuels. Obviously, the method gives more detailed data as compared with the method of before and after run weighing a sample but there are some natural limitations owed to difficulties of precise measuring the diameter of bore and determination of the location of measuring point along the bore surface.

4. Conclusion

Experimental data presented testify the high potential abilities of microwave resonator method for measuring transient regression rate of solid fuels under intense gas blowing. The experience which was obtained during developing and preliminary testing the method and experimental facilities gives valuable background for further improvement of the method and elaboration of novel experimental approaches. It is planned in the nearest future to continue work with modified sensor, which may allow measuring regression parameters at enhanced pressure in the bore of the sample (1 ÷ 2 MPa) and in conditions of unsteady gas flow parameters.

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