A novel technique for the continuous evaluation of a burning rate of solid rocket propellant by using IR thermography

by Waldemar Swiderski* and Maciej Miszczak* and Andrzej Panas**

* Military Institute of Armament Technology, 05-220 Zielonka, Poland, waldemar.swiderski@wp.pl
** Military University of Technology, gen. S. Kaliskiego 2, Str., 00-908 Warsaw, Poland / Air Force Institute of Technology, Ksiecia Bolesława 6, Str., 01-494, Warsaw, Poland

Abstract

In this study, a novel technique for evaluating continuously burning rate of cylindrical cores made of a solid homogeneous propellant is presented. The propellant core was placed in the tube made of pyrolytic graphite (pyrographite). The burning rate of the rocket propellant has been determined by monitoring the burning front/zone movement on the external surface of the pyrographite tube by using an IR camera. A double-base propellant was applied in this particular validation experiment. The continuous thermal analysis of the burning front/zone has been possible due to the fact that pyrographite is characterized by a uniquely high anisotropy of thermal conductivity along its crystallographic perpendicular directions. The technique was verified by numerical modelling. The numerical results confirmed the proposed procedure performance when used for such investigations.

1. Introduction

The detection of the propagation of a burning front/zone in solid high-energetic materials, particularly, in solid rocket propellants, as well as the evaluation of the burning rate in such materials, acquired a large importance at the designing and tailoring stages of rocket/missile propelling systems (motors). This is especially true in the development of new compositions of solid rocket propellants, including the technological processes intended for manufacturing and designing novel rocket motor constructions. The corresponding test methods are necessary to determine internal ballistic properties/parameters of rockets and missiles, in particular, their propelling systems (motors).

To detect propagation of a burning front/zone, in order to measure a burning rate of solid rocket propellants, the test methods which use strand burners, often called Crawford bombs/burners, small-scale ballistic evaluation rocket motors and full-scale rocket motors, are often applied [1,2].

Strand burners – small pressure vessels usually equipped with window(s) [1-6] - contain propellant samples in the form of a strand or a bar of which surface is inhibited i.e. covered/screened by external coating to ensure the burning only on the propellant cross-sectional surface (not inhibited surface) directly exposed to ignition and burning. The propellant sample, being under pressure of an inert gas, is ignited at one end in order to obtain the so-called “end burning” configuration. Burning rate is usually measured by electric signals from embedded wires positioned in the sample at strictly determined distances (non-continuous measurement). The burning rate is calculated on the basis of time intervals which are measured between successive time points determined by melting/disruption of embedded wires. Through a strand burner window it is optionally possible to evaluate continuously the propagation of a burning front/zone by optical (VIS) registration systems [5,6]. The continuous measurement of burning front/zone propagation is also possible by means of ultrasonic (mechanical) waves emitted by transducers operating as generators and receivers of these waves. An ultrasonic wave generated by the transducer travels through the tested propellant, then it experiences reflection on the moving, burning surface (head of burning front) and goes back to the transducer. The measured values of return propagation times of the mechanical waves are directly dependent on burnt propellant thickness and wave velocities. In most cases, a coupling material is inserted between the transducer and the propellant thus producing the delay line which allows to measure burning propagation/regression rate up to total burning of the propellant sample. The coupling material also isolates the transducer from severe ambient conditions (high temperature, pressure and chemically aggressive combustion products). It is relatively difficult to choose a suitable coupling material which must be acoustically and chemically matched to the tested propellant material. Moreover, such coupling material should have also relatively high mechanical strength and good bonding properties. The stress-strain fields created by the internal pressure in material systems, mainly in the propellant sample during its combustion process, affect considerably the precision of ultrasound measurements.

Unfortunately, burning rate estimates measured by strand burners distinctly differ from those obtained by means of rocket motors. Usually, they are lower by 4-12 % [1]. These differences are caused by unrealistic conditions of the burning process in strand burners in comparison to rocket motor combustion chambers. However, in spite of this serious
disadvantage, strand burner test methods are still well-accepted at initial (reconnaissance) steps of investigations of rocket propelling systems.

Apart from the above-mentioned techniques, there is another test method which involves the determination of regression rate via course (curve) of pressure/thrust of combustion products in a rocket motor chamber, obtained during burning process of propellant charge [7,8]. In this method, the basic inaccuracy in burning rate determinations arrives from the uncertainty in the accurate setup of a start time and finish time points of the propellant burning based on the assumed pressure/thrust threshold on rising and descending part of pressure/thrust curve respectively. According to some studies of this issue [9], the differences between the estimates of start and finish times in the burning process, based on the use of course and shape of pressure curves, may result in the spread of determined values of burning duration up to 17 %.

Other solutions to analyze burning zone propagation parameters by using sub-scale and full-scale rocket motors, are based on the non-intrusive detection methods which involve Real-Time X-ray Radioscopy (RTR), microwave technique and plasma capacitance gauges [10].

The RTR technique requires the recording of X-ray image sequences of a moving burning zone in a propellant charge. This allows to evaluate burning zone movement during propellant combustion. Locating a burning surface is quite subjective because an operator or an RTR image digital processing software allow to select the position of a burning surface within the error range of 2 video pixels. Then, such error is dependent on the magnification of X-ray image. In addition, the unpleasant feature of the RTR technique is its complexity and high power requirements, as well as a high cost of X-ray equipment and high level of personnel hazard when dealing with X rays of high intensity.

The use of microwave technique is based on the analysis of a phase angle shift which occurs on the burning surface between incident and reflected microwaves transmitted by a microwave generator – usually horn antenna – which also acts as a wave receiver. This angle varies due to reduction in length of a burning propellant sample. The propellant burning rate is directly proportional to the rate of phase shift, and the coefficient of proportionality is the microwave phase constant in the propellant material. Such coefficient is a function of both a waveguide geometry and a dielectric constant of the propellant material. The microwave technique requires expensive hardware and advanced data acquisition devices, as well as digital data reduction instruments, which are necessary to improve interpretation of measurements results. The metallized solid propellants (e.g. commonly used propellants containing aluminum powder) make the microwave technique difficult to operate.

The plasma capacitance gauge method is based on the analysis of variations in electrical capacity of propellants – it includes an insulating material located between two electrodes: the first one is formed by the plasma generated by combustion gases, and second one is coated along the case of a rocket motor. The electrical capacitance of the propellant – insulating material structure increases with decrease in its thickness. So, this technique is mostly suitable for burning rate measurement of axially perforated rocket propellant grains in order to obtain information about changes of the propellant-insulating material thickness during combustion process, as well as about flame arrival time to the rocket motor case. In this technique, high electric conductivity of flames, along with pressure and temperature variations, influence greatly on the capacitance measurements.

For microwave and plasma capacitance methods, the variations in dielectric properties of materials in propellant-insulation systems, especially in their preheated material zone, should be taken into account. In the case of usage of ultrasonic and microwave methods, the common limitations, which are related to sources of measurement uncertainties, are caused by wave damping and reflection phenomena. These phenomena can change measurement accuracy and sometimes worsen the quality of input data.

In this work, a novel method for the continuous analysis of propagation parameters at the burning zone/surface in solid rocket propellant charge is presented. This method may operate during the combustion process being based on IR thermography. The movement of the burning surface/zone is instantaneously thermally monitored by recording the heat/temperature gradient profile on the internal surface of a high-conductive pyrolytic graphite (pyrographite) gauge. Then, the profile thermal signal is sending through graphite layers of the gauge parallel to the graphite hexagonal crystallographic grid, i.e. its (ab) crystallographic planes (Fig.1), towards the external wall of the gauge. The burning front/zone thermal signal movement on the external surface of the pyrographite gauge is registered by IR camera. So, the continuous registration of the burning front/zone is possible thanks to the usage of a pyrographite gauge, which is characterized by a high grade of thermal anisotropy. The anisotropy results in great differences in thermal and electric conductivity parallel and perpendicularly to the (ab) graphite pyrographite planes. The (ab) pyrographite planes should be properly positioned in regard to the propellant charge. Due to the above-mentioned configuration, the pyrographite gauge wall of high thermal conductivity, contacts with the external surface of propellant grains and the pyrographite crystallographic planes (ab). The latter ones are the planes of the deposition of hexagonal graphite crystallographic grid/layers which are situated perpendicularly to a predicted direction of burning surface movement in the propellant. Such system configuration which involves a propellant charge/ pyrographite gauge and an IR camera, makes possible to record thermal/temperature profiles of the moving burning zone and store the corresponding IR images produced by the external wall of the pyrographite gauge [11].

Similarly to other non-destructive optical test methods, such as VIS, RTR, the use of the IR thermographic technique requires a compromise between the spatial and time (frames per second) resolution.
2. Method and experimental set-up

The concept of the proposed test method [9] takes advantage of the unusually high anisotropy in thermal properties of pyrographite crystallographic structures. Pyrographite is characterized by extremely high anisotropy of thermal conductivity along its crystallographic perpendicular directions. The thermal conductivity along the crystallographic plane (ab) is comparable to the thermal conductivity of copper, and along the crystallographic axis (c), which is perpendicular to the (ab) plane, it is comparable to the thermal conductivity of ceramic materials (Fig. 1). Three identical highly-anisotropic pyrographite rings of the internal diameter 5.2 mm and external diameter 14.4 mm were connected with a heat-resistant glue to produce a single 16.7 mm-long graphite tube. Such tubes have very high thermal conductivity along their radius (about 350 W/m·K) but very small one along its generating line (about 1.77 W/m·K). The port of the tubes was filled by solid, homogeneous, double-base propellant. An experimental setup (Fig.2) provides possibilities to measure the burning speed by recording the moving burning front, as well as simultaneously evaluate stability of the burning process. The recording of propellant burning process characteristics was performed by using an IR camera AGEMA 900 LW of which the lens was placed perpendicularly to the longitudinal axis of tubes. The burning process of propellant was initiated from one of its ends (from the front) by using a CO₂ laser beam. Additionally, the burning process was recorded with a CCD camera.

![Figure 1. Pyrolytic graphite plates](image1)

![Figure 2. Experimental setup](image2)

3. Experimental Testing

In order to compare the usefulness of the copper, which is characterized by isotropic thermal conductivity, and the pyrographite in the analysis of the burning front of rocket propellants, some experimental investigations were conducted with...
both pyrographite and copper tubes (painted with black dull paint on the external side of the tube surface). In the corresponding thermograms (Fig 3 a-d), it is clearly seen that considerable differences in thermal conductivity of pyrographite along the tube axis and radius make possible to define the position of the burning front with a single pixel precision (Fig. 4). Thus, it is possible to note variations in the burning front position, i.e. to identify the burning speed along chosen propellant segments. As it follows from the thermograms (Fig.3 e-h), this is impossible in the case of copper tubes, because they are heated almost uniformly along their whole length (Fig.4). These observations confirm that temperature profiles on the surface of pyrographite tubes may change at different stages of rocket propellant burning (Fig.4); the same phenomena can be observed in the case of copper tubes (Fig.5).

4. Numerical modelling

Numerical modelling (Comsol package [12]) was used to verify the proposed technique, including the validation of the procedures intended for both qualitative and quantitative evaluation of burning phenomena. The obtained solution was related to a two-dimensional heat conduction problem in an axially-symmetric sample. The convective heat exchange, that occurs at the sample edges, was neglected. Thermal properties have been assumed independent on temperature. Therefore, the problem falls into the partial differential Fourier’s equation [13] with adequate initial and boundary conditions. It is believed that the accepted model reflects quite well a real cylindrical tube (Fig. 6). Both the front flat surface and the internal cylindrical surface are subject to convective/radiative losses at a constant temperature [14], see Table 1. On the external cylindrical surface, the heat exchange was modelled by using a linear burning rate which was determined in experiments. The burning front movement was modelled by varying spatial temperature distributions in time (Fig.7). The decrease of heat flux density at the distance of 0.35 mm behind the burning front was taken into consideration in extortion. The reduction of heat flux density, which propagated from combustion gases to the tube, was modelled by the 800°C drop in the combustion gas temperature within the time period from 0 to 9.1 s at the constant value of heat exchange coefficient
equal to 100 W/m²/K. It has been assumed that after 9.1 s the value of the heat exchange coefficient on the external section drops to zero, thus specifying the adiabatic status of the external surface after the burning process. The maximum temperature of combustion gases equal to 2250°C, along with the above-mentioned value of the heat exchange coefficient on the external surface, have been accepted to model the temperature increase at the coordinate point \((r,z) = (7.2 \text{ mm}, 8.35 \text{ mm})\). This assumption followed from the experiment. It is worth noting that the modelling of real heat exchange conditions at the burning front, including radiation, is very difficult. However, the accepted simple model of “moving” convection is believed to be sufficient to analyse dynamic phenomena at the burning front. The values of pyrographite anisotropic thermal properties have been accepted on the basis of our own experimental study. The specific heat value was determined by the DSC method, the density was measured directly by weighing the sample. The thermal conductivity was calculated by using the thermal diffusivity value which, in its turn, was determined by the forced oscillation method. The values accepted in calculations are presented in Table 2.

**Fig. 4.** Temperature profile on the surface of a pyrographite tube as a function of tube length (at different phases of the rocket propellant burning)

**Fig. 5.** Temperature profile on the surface of a copper tube as a function of tube length (at different phases of the rocket propellant burning)
Fig. 6. Geometry of the model and calculation results for two observation times
(burning front positions are adequately marked - red dotted line)

Table 1. Boundary and initial conditions accepted in calculations

<table>
<thead>
<tr>
<th>Initial condition</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform temperature distribution $T_0$</td>
<td>°C</td>
<td>22.3</td>
</tr>
<tr>
<td>Boundary condition – outer surfaces ($r=0$mm, $r=16.7$mm, $z=7.2$mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ambient temperature $T_{amb}$</td>
<td>°C</td>
<td>22.3</td>
</tr>
<tr>
<td>Heat transfer coefficient $h$</td>
<td>W·m⁻²·K⁻¹</td>
<td>4</td>
</tr>
<tr>
<td>Surface emissivity $\varepsilon$</td>
<td>n.a.</td>
<td>0.98</td>
</tr>
<tr>
<td>Ambient radiation temperature</td>
<td>°C</td>
<td>22.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Boundary condition – inner surface ($z=2.6$mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient temperature $T_{amb}$</td>
</tr>
<tr>
<td>Heat exchange coefficient $h$</td>
</tr>
<tr>
<td>Heat coefficient $h$</td>
</tr>
</tbody>
</table>

(*) Comsol software formula [10]: $T_{amb} = 2250*(z<(0.001835*t)) - 800*(z<(-0.0035+0.001835*t))$

Table 2. Material thermal properties used in modeling.

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Value</th>
</tr>
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<tr>
<td>Thermal conductivity – axial direction</td>
<td>W·m⁻¹·K⁻¹</td>
<td>2</td>
</tr>
<tr>
<td>Thermal conductivity – radial direction</td>
<td>W·m⁻¹·K⁻¹</td>
<td>250</td>
</tr>
<tr>
<td>Specific heat</td>
<td>J·kg⁻¹·K⁻¹</td>
<td>800</td>
</tr>
<tr>
<td>Density</td>
<td>kg·m⁻³</td>
<td>2200</td>
</tr>
</tbody>
</table>

In order to apply the final element numerical algorithm implemented in the Comsol software, the object was divided by 10 regular elements along the radius and 25 elements along the axis of the pyrographite tube. The calculation simulated 15 s of the burning process starting at $\tau = 0$ s with the step of 0.05 s. The results of simulation are shown in Fig. 6 and 8. The cross-sectional temperature distribution along the tube for two different time instants is presented in Fig.6. These times are long enough to let the burning front crossing the points with the axis coordinates $z = 8.35$ mm and $z = 11.70$ mm. These are the same points on the external surface of the tube for which variations in temperature profiles were identified during experimental tests. In Fig.8, temperature profiles obtained numerically are presented [15].

It is important to emphasize that the good match of calculated and experimental profiles at the observation point $z = 8.35$ mm is conditioned by a more general match between the model and the experiment based on the energy balance. However, the original result is that such match was observed also at the second observation point $z = 11.70$ mm independently on model tuning. The obtained results prove that it is possible to evaluate propagation characteristics of the propellant burning front by analyzing temperature distributions on the external surface of the tube with anisotropic properties. The necessary condition allowing successful evaluation method is to choose a test tube in such way that the direction of low thermal conductivity must fit the direction of the burning front, while the direction of high thermal conductivity must coincide...
with the direction where the ‘thermal information’ is collected. In fact, these directions are axial \( O_z \) and radial \( O_r \). The conclusions above are compatible with the results of earlier studies [16].

\[ \Delta \tau \]

**Fig. 7.** Illustration of burning front movement with speed 1.835 mm\( \cdot \)s\(^{-1} \) along the axis \( O_z \) inside the tube (Table 1)

\[ \Delta \tau \]

**Fig. 8.** Numerical temperature profiles at two selected points on the external surface

In order to estimate the possibility of the quantitative analysis, a burning front propagation rate was calculated. The calculation method was based on the determination of the time interval \( \Delta \tau \) between the isotherms which corresponded to selected points of observation. The speed of propagation was calculated by the following simple formula:

\[ v_{z,calc} = \frac{z_2 - z_1}{\Delta \tau} = \frac{11.7\, \text{mm} - 8.35\, \text{mm}}{\Delta \tau} \]  

(1)
The plot of the following ratio

\[
\frac{\Delta v_z}{v_z} = \frac{v_{z,calc} - v_z}{v_z} = \frac{v_{z,calc} - 1.835 \text{ mm} \cdot \text{s}^{-1}}{1.835 \text{ mm} \cdot \text{s}^{-1}}
\]

is presented in Fig.8 as a function of the limiting temperature. The maximum spread in data has not exceeded 2.8%. This result proves that the proposed test method can be effectively applied to the analysis of the burning front dynamics. The calculation of the burning rate applying the above-described technique resulted in the overestimation which ranged from 0.4% for the 7.7°C temperature threshold through 1.0% for 24°C up to 2.5% for the 35°C threshold.

5. Conclusions

The results of both experimental investigations and numerical simulations, which are presented in this study, confirm the correctness of the proposed test procedure intended for the determination of a burning rate of both solid rocket propellants and solid pyrotechnical mixtures. The essence of the modified test procedure is in taking advantage of anisotropic properties of pyrolytic graphite in such a way that the side temperature distribution in a test tube reflects the heat exchange in the internal opening. The averaged value of the burning rate in a tested mixture has been experimentally identified about 1.835 mm s⁻¹. The results obtained in two experimental tests matched each other quite well. The proposed test procedure has been confirmed by numerical modelling. The possibility to obtain satisfactory results in the identification of propellant burning front has been also confirmed. Our results prompt that the similar approach can be applied to measurements on propellants which are characterized by unstable burning. However, the practical implementation of a suitable experimental procedure in this case would require a more precise definition of metrological conditions. This can be done by applying numerical modelling.

REFERENCES