



## THEORETICAL AND PRACTICAL EVALUATION OF BURNING RATE OF DOUBLE BASE ROCKET PROPELLANTS

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### ABSTRACT:

Homogeneous propellants are still often used in small-to medium-sized rockets because of their smokeless qualities and the possibilities they offer of particular shapes and small burning thickness through rolling and extruding process. The study of burning rate characteristics is an important factor limiting the practical application of these propellants. In this work, the burning rate characteristics of a homogeneous double base propellant containing nitrocellulose, nitroglycerine, dinitrotoluene, centralite, dibutyl phthalate, calcium carbonate and vasiline as ingredients are determined experimentally and discussed. The nature of the burning rate is explained by the physical and chemical properties of the propellant. A simplified gas-phase model is used to evaluate the burning rate characteristics using a computer program. The obtained results were compared to those practically determined.

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### INTRODUCTION:

The behaviour of a propellant when it burns depends mainly on the properties of the components, on its microstructure and on the characteristics of the flow field. Since the physical structure of double-base propellants is homogeneous, the combustion flame structure appears to be homogeneous also and one-dimensional along the burning direction. The burning process is largely dependant on the combustion wave structure. This wave structure is a function of the propellant composition, pressure, and other various operating conditions. The combustion of double-base propellants is studied by many authors as Lengelle [1] and Kubota [2]. In this work a simplified model of combustion of homogeneous solid propellant is proposed and a computer program is elaborated. The input parameters are assigned and the obtained results were compared with the experimental results.

### EXPERIMENTAL PART:

#### 1. Materials:

The propellant used in this study is a double-base propellant with the following composition:

- Nitrocellulose (51.5%)
- Nitroglycerine (43%)
- Dinitrotoluene (0.8%)
- Centralite (1%)
- Dibutyl phthalate (3.25%)
- Calcium carbonate (1.25%)
- Vaseline (0.2%)

#### 2. Measurement of Rate of Burning:

The burning rate measurements are made in a strand burner. This consists of a closed isobaric bomb filled with nitrogen at a predetermined pressure and provided with electrical ignition and a means of measuring the time taken for the burning start to travel down the strand. The propellant should be conditioned to the required temperature (40 C and -30 C) before use.

### THEORETICAL MODEL, RESULTS AND DISCUSSION:

Fig.1 shows a schematic drawing of a simplified combustion temperature profile of a solid propellant. The temperature increases rapidly from initial temperature  $T_0$  to the burning surface temperature  $T_s$  just beneath the burning surface. At the burning surface either an endothermic decomposition reaction produces reactive gases. This reaction zone is called the solid phase reaction or condensed-phase reaction zone. The reactive gas are emitted from the burning surface and generate heat to form a luminous flame zone. Thus,

temperature increases in the gas-phase reaction zone and reaches a maximum in the luminous flame zone. In the luminous flame zone, the exothermic reaction is completed and the equilibrium combustion products are formed. The heat balance at the burning surface is in Fig.1 and is expressed as:

$$\lambda_p(dT/dx)_{s-} = \lambda_g(dT/dx)_{s+} + \rho_p r Q_s + I_f \quad (1)$$

The compressible conservation equations at steady state are:

$$\text{Mass: } \nabla \cdot (\rho v) = 0 \quad (2)$$

$$\text{Energy: } \nabla \cdot (\rho v c T - \lambda \nabla T) = - \sum_i w_i Q_i \quad (3)$$

assuming that the chemical reaction does not occur in the solid phase. The energy equation in the solid phase can be written by using equation (3), where  $wQ$  term is set equal to zero [3] as :

$$\lambda(d^2T/dx^2) - \rho u c (dT/dx) = 0 \quad (4)$$

Equation (2) gives the following mass balance relationship between gas and solid phases:

$$\rho_g u = \rho_p r \quad (5)$$

Thus the heat equation in the solid phase can be written as :

$$\lambda_p(d^2T/dx^2) - \rho_p r c (dT/dx) = 0 \quad (6)$$

Integrating equation (6) using the following boundary conditions :

$$T = T_o \quad \text{at } x = -$$

$$T = T_s \quad \text{at } x = 0$$

Neglecting the absorbed heat of vaporization and decomposition, the heat feed back from the burning surface to the solid phase at  $x=0$  is:

$$\lambda_p(dT/dx)_{s-} = \rho_p r c (T_s - T_o) \quad (7)$$

In the gas-phase zone, the reaction is very complicated. In general the exact solution of the conservation equations are difficult to obtain because of the lack of the kinetic parameters in the gas phase. For this reason, simplified reaction rate models in the gas phase are assumed. The energy equation, shown in equation (3) can be written in the following one-dimensional form:

$$\lambda_g(d^2T/dx^2) - \rho_g u_g c_{pg} (dT/dx) + w_g Q_g = 0 \quad (8)$$

Since  $w_g$  is a function of temperature, equation (8) is nonlinear and an analytical solution is not possible [4]. Assuming that  $w_g Q_g$  is constant initially and integrating equation (8), one obtains :

$$\lambda_g (dT/dx)_{s+} = Q_g \int_0^{\infty} \exp [- \rho_g u_g c_{pg} x / \lambda_g] w_g dx \tag{9}$$

If the reaction starts at the burning surface, equation (9) can be rewritten after integration as :

$$\lambda_g (dT/dx)_{s+} = (\lambda_g / \rho_g u_g c_{pg}) w_g Q_g [1 - \exp(- \rho_g u_g c_{pg} x_f / \lambda_g)] \tag{10}$$

It is known from the experimental results [5] that

$$\rho_g u_g c_{pg} x_f / \lambda_g \gg 1$$

For the propellant burning thus one can set

$$\exp(- \rho_g u_g c_{pg} x_f / \lambda_g) = 0$$

and equation (10) can be further simplified to :

$$\lambda_g (dT/dx)_{s+} = \lambda_g w_g Q_g / \rho_p r c_{pg} \tag{11}$$

In the gas phase, if one assumes a bimolecular one-step chemical reaction, the reaction rate is expressed as.

$$w_g = \rho_g Y_o Y_F Z_g \exp(-E_g/RT) \tag{12}$$

The burning rate of a propellant can be calculated by substituting equations (7) and (11) into the heat flux balance in equation (1), and assuming the radiation from the gas phase to the burning surface is negligible, that  $I_f = 0$ , one gets a simplified rate equation:

$$r = \left[ \frac{\lambda_g w_g Q_g}{\rho_p c_{pg} (T_s - T_o - Q_s/c)} \right]^{1/2} \tag{13}$$

Assuming second-order reaction in the gas phase as described in equation (12), and assuming the following equation of state in the gas phase:

$$\rho_g = P/R_g T_g \tag{14}$$

Equation (13) can be rewritten as:

$$r = P \left[ \frac{\lambda_g Q_g Y_o Y_F Z_g \exp(-E_g/RT_g)}{\rho_p c_{pg} (T_s - T_o - Q_s/c) R_g T_g} \right]^{1/2} \tag{15}$$

The regression rate of the propellant is dependent on  $T_s$ .

If one assumes that the decomposition reaction at the burning surface is expressed with an Arrhenius-type pyrolysis law, one gets:

$$r = Z_s \exp(-E_s/RT_s) \quad (16)$$

The burning rate of propellant can be calculated with equations (15) and (16). A computer program is elaborated at first to calculate the decomposition products of the propellant using the chemical composition, where the values of  $\lambda_g, C_{pg}, C, \rho_p,$  and  $R_g$  are determined. The values of  $Q_s$  is determined by the decomposition mechanism at the propellant surface. The kinetic parameters in the gas phase ( $Y_o, Y_F, Z_g, E_g, Q_g$ ) are determined by the reaction scheme in the gas phase. The  $T_g$  is determined by the following equation:

$$T_g = T_o + Q_s/C + Q_g/C_{pg} \quad (17)$$

The  $T_s$  is determined by a computer program using Newton-Raphson method to solve these equation numerically. Finally the burning rate of propellant can be calculated from equation (16).

A calculated example of the burning rate vs pressure is shown in Fig.2. The physical and chemical calculated and proposed parameters are shown in Table 1. As pressure increases, the burning rate increases. The increase is linear in a  $\ln r$  vs  $\ln P$  plot. From this plot the pressure exponent of burning rate, defined as  $n = (d \ln r / d \ln P)_T$  is calculated. With the increase in temperature the rate of burning increases.

The experimentally determined values of the rate of burning at  $T_o = 40$  C and  $-30$  C at various pressures are shown in Fig.2. The calculated results at the same temperatures and pressures are shown in the same figure. a slight increase in the calculated values of the burning rate is due to the errors in the determined physical and chemical parameters. This increase is still within the order of experimental measurements ( $\pm 0.2 \times 10^{-2}$  m/s). The calculated value of pressure exponent ( $n$ ) is confirmed by the experimentally observed value. the errors in experimental measurements are  $10^{-4}$  seconds in burning time and 0.1 bar in pressure. Five experiments are carried out at each pressure value.

### CONCLUSION:

The model used for the calculations is a very simple one and is applied only for homogeneous propellants having a one dimensional combustion wave. The obtained results show a good agreement with the experimental values, so the model can be used for prediction of the burning rate of homogeneous solid rocket propellants to optimize the formulations and minimize the experimental work. However, the model cannot be applied to propellants such as composite propellants which have a more complex combustion wave structure than that of double-base propellants.

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NOMENCLATURE:

- $c$  = specific heat of solids  
 $c_p$  = specific heat of gases at constant pressure  
 $E$  = Energy of activation.  
 $I_f$  = heat flux from gas phase to burning surface  
 $n$  = pressure exponent  
 $P$  = pressure  
 $r$  = burning rate  
 $R$  = universal gas constant  
 $R_g$  = gas constant  
 $Q$  = heat of reaction per unit mass.  
 $T$  = temperature  
 $u$  = gas flow velocity  
 $v$  = mass-averaged velocity vector  
 $w$  = reaction rate  
 $x$  = distance  
 $Y$  = molar concentration  
 $Z$  = pre-exponential factor.  
 $\lambda$  = thermal Conductivity.  
 $\rho$  = density

Subscripts

- $F$  = fuel  
 $g$  = gas phase  
 $i$  = ith chemical species  
 $o$  = reference state at 0  
 $O$  = oxidizer  
 $p$  = propellant

- s = burning surface of propellant
- s<sup>+</sup> = gas phase at burning surface of propellant
- s<sup>-</sup> = condensed phase at burning surface of propellant

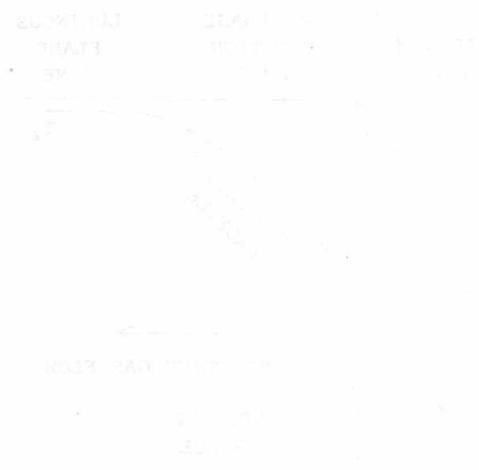


Table 1 Physical and Chemical Constants of the Propellant

|               |                                             |
|---------------|---------------------------------------------|
| $C_{pg}$      | 0.35 cal/g.K                                |
| $C_c$         | 0.35 cal/g.K                                |
| $\lambda_g$   | 0.0002 cal/cm.s.K                           |
| $\rho_p$      | 1.55 g/cm <sup>3</sup>                      |
| $E_g$         | 17 x 10 <sup>3</sup> cal/mole               |
| $Y_o Y_F Z_g$ | 2.3 x 10 <sup>15</sup> cm <sup>3</sup> /g.s |
| $Q_g$         | 330 cal/g                                   |
| $R_g$         | 3000 g.cm/g-K                               |
| $Q_s$         | 80 cal/g                                    |
| $Z_s$         | 5 x 10 <sup>5</sup> cm/s                    |
| $E_s$         | 17 x 10 <sup>3</sup> cal/mole               |

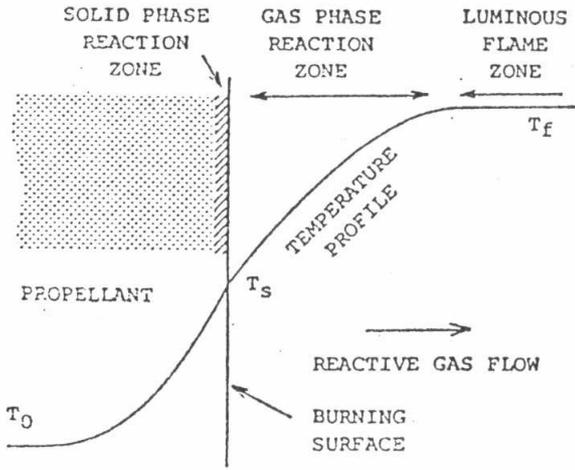


Fig.1 Simplified Temperature Profile of Combustion of a solid propellant After Kubota [2].

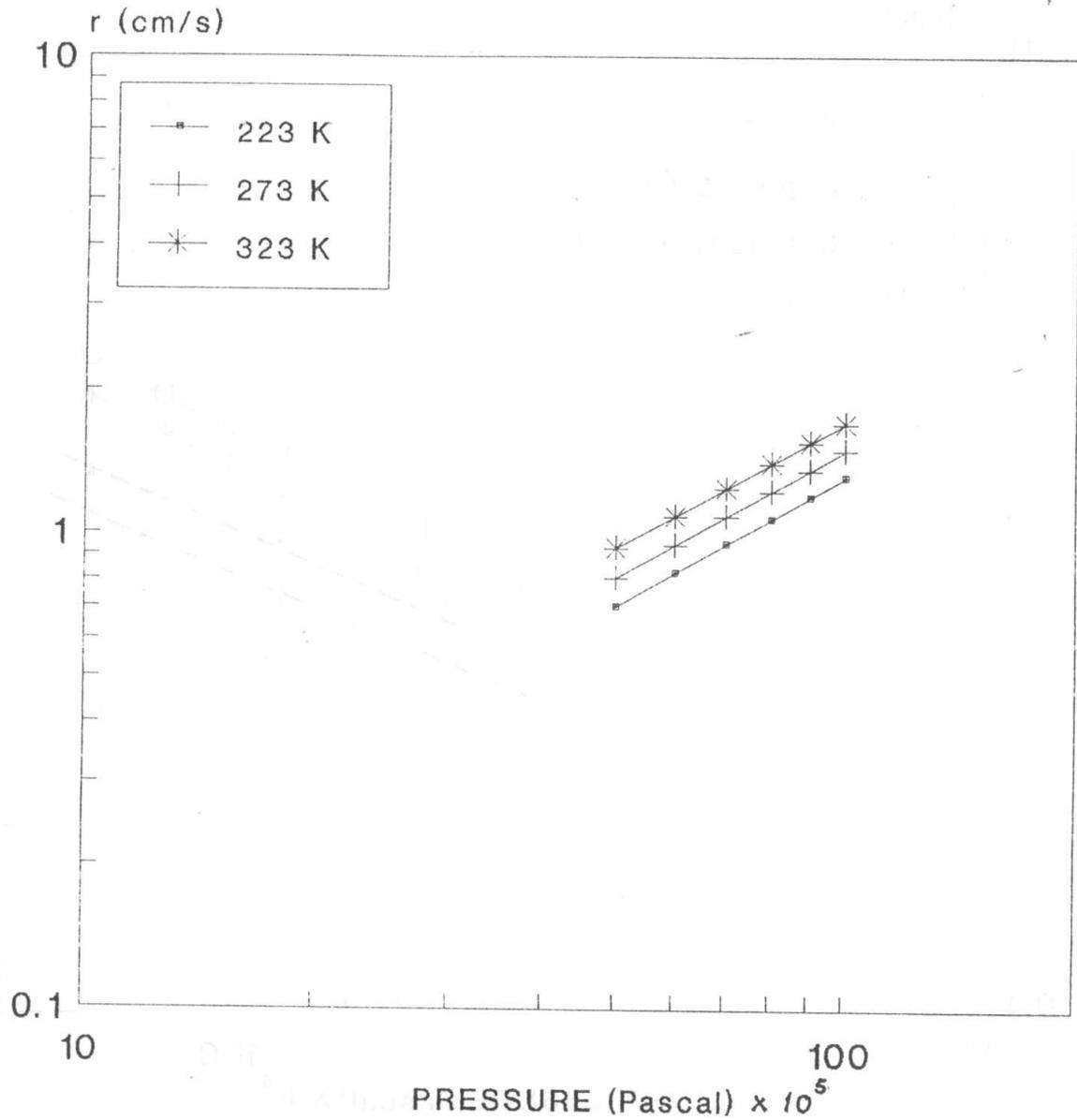


Fig.2 Calculated burning rate characteristics of a double-base propellant.

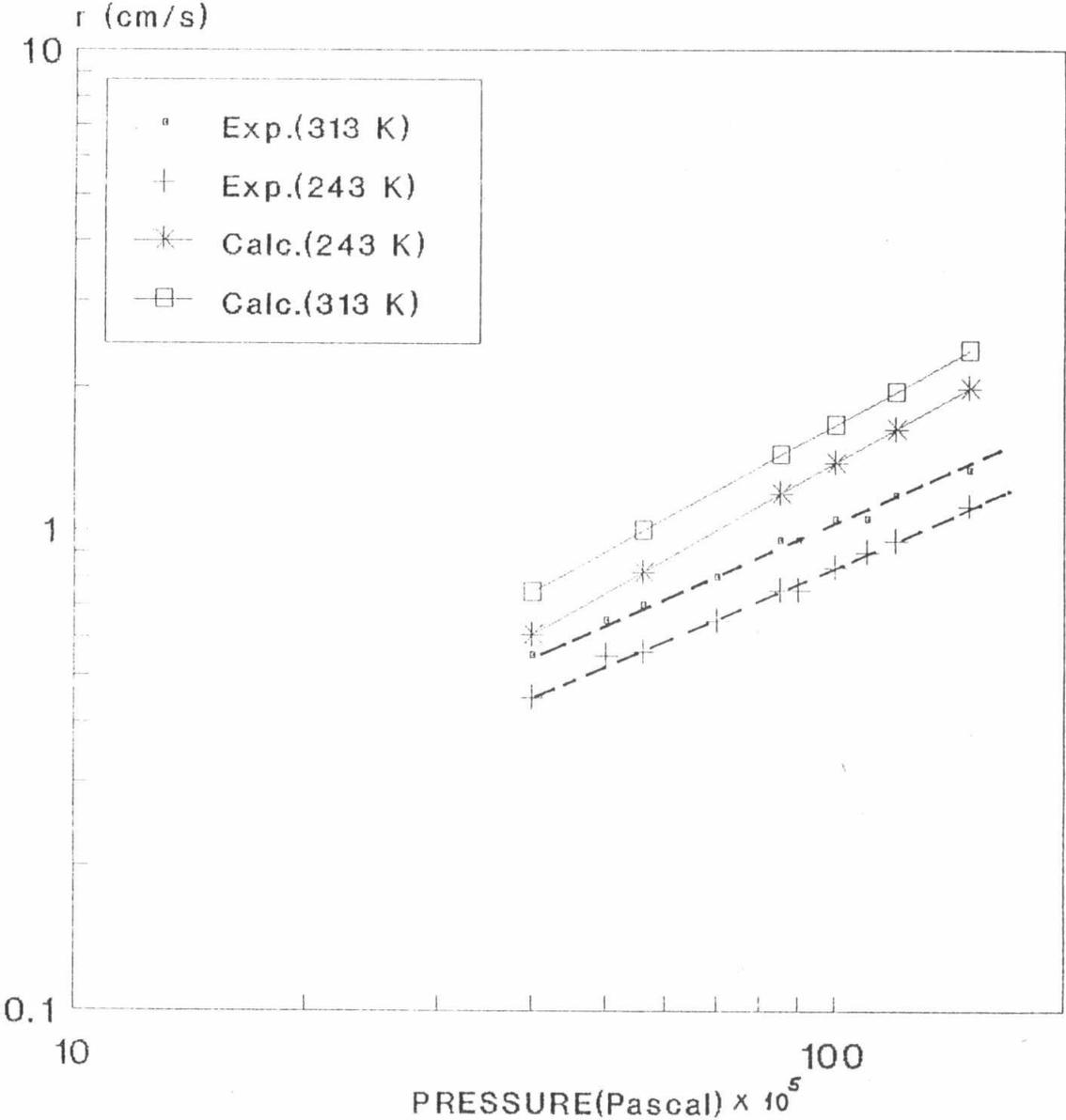


Fig.3 Experimental and calculated burning rate against pressure for double-base propellant.