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Heat balance evaluation of double-base solid propellant combustion using thermography and laser heating on a burning surface

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A B S T R A C T

A new method is proposed using laser heating and thermography for estimating the heat transfer balance for burning solid propellant: heat production rate on burning surface $\dot{Q}_s$, heat flux from burning surface to solid phase Λ_p, and heat flux rate from flame to burning surface H_f. H_f is determined from the correlation between burning rate and power density of laser heating on burning surface; Λ_p is evaluated using the burning surface temperature measured with thermography. Double-base propellant is tested in a combustion chamber having a laser-introducing window, and is irradiated with an 808-nm laser at laser power densities ranging from 0.3 to 0.8 W/mm^2 with a back-pressure range from 0.02 to 0.60 MPa. The proposed method shows heat flux from burning surface to burning surface H_f of 1.7 W/mm^2, heat production rate on burning surface $\dot{Q}_s$ of 4.9 W/mm^2, and heat flux from burning surface to solid phase Λ_p of 6.6 W/mm^2 at a back pressure of 0.60 MPa. Laser power attenuation due to the flame is determined to evaluate the influence of laser power attenuation on the estimation of heat flux rate from flame to burning surface. The experiment shows that errors originating from laser power attenuation due to the flame are below 18%.

1. Introduction

We propose a new method using laser heating and thermography to estimate heat-flux balance for burning solid propellant: heat production rate on burning surface $\dot{q}_s$, heat flux from burning surface to solid phase Λ_p, and heat flux rate from flame to burning surface, H_f. In previous research, the temperature distribution in solid and gas phase was measured with thermocouples in burning solid propellant [1–3] to investigate H_f and Λ_p from the temperature profile. Nevertheless, the conventional method requires 10-µm-diam. thermocouples to reduce thermodynamic time constants. The fine thermocouples should be replaced after each temperature measurement because they would be damaged by high temperature combustion products. Calculating H_f requires thermal conductivity in the gas phase, which is evaluated from the chemical equilibrium calculation.

In this study, we propose a non-intrusive method using laser heating and thermography to clarify the thermal balance: H_f, Λ_p and $\dot{q}_s$ without measuring or theoretically estimating gas-phase thermal conductivity. A combustion chamber with a laser-introducing window was prototyped to evaluate the heat balance using the proposed method. Double-base propellant was tested in a combustion chamber having a laser introducing window at absolute pressures ranging from 0.02 to 0.6 MPa. Laser beam attenuation through the flame was measured because in the proposed method, errors in laser power density for heating burning surface possibly yields errors in H_f.

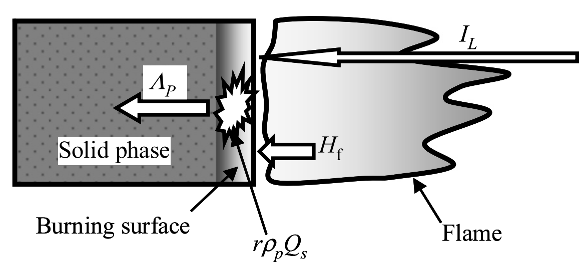

Fig. 1. Heat balance model with laser heating.

2. Principles

Fig. 1 illustrates a theoretical model of heat balance in a burning solid propellant under laser heating. A heat-balance equation for the burning surface has been proposed to analyze the burning solid propellant [4,5]. For a solid propellant with a burning

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Nomenclature

C_p	Specific heat of solid propellant . . . . . J/kg K	r	Burning rate . . . . . m/s
H_f	Heat flux from flame to burning surface . . . . . W/m^2	T	Temperature . . . . . K
I_L	Laser power density for heating burning surface . . . . . W/m^2	T_s	Burning surface temperature . . . . . K
P_b	Back pressure . . . . . MPa	T_0	Solid propellant temperature at $x = -\infty$
Q_s	Heat of reaction on burning surface . . . . . J/kg	λ_p	Thermal conductivity of solid propellant . . . . . W/m K
$\dot{q}_s$	Heat production rate on burning surface . . . . . W/m^2	Λ_p	Heat flux from burning surface to solid phase . W/m^2
		ρ_p	Propellant specific mass . . . . . kg/m^3

rate r, the solid phase has three heat fluxes: heat flux from burning surface to solid phase Λ_p, heat production on burning surface $\dot{q}_s$ and heat flux from flame to burning surface, H_f. In the proposed method, the burning surface is heated with a laser, and the resulting heat balance equation is expressed as

$$\Lambda_p = \rho_p r Q_s + H_f + I_L \tag{1}$$

where I_L is laser power density, ρ_p is solid propellant density, and Q_s is heat production on burning surface. For simplicity, $\dot{q}_s$ is replaced with $r\rho_p Q_s$. For the solid phase, the three-dimensional transient heat transfer equation is given as

$$\rho_p C_p \left(\frac{\partial T}{\partial t} + (r \cdot \nabla) T \right) = \lambda_p \Delta T \tag{2}$$

One-dimensional steady-state heat transfer equation is expressed as

$$\lambda_p \frac{d^2 T}{dx^2} - \rho_p C_p r \frac{dT}{dx} = 0 \tag{3}$$

with the boundary conditions:

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

$$T = T_0 \quad \text{at } x = -\infty$$

Integrating Eq. (2) with x, the heat flux from the burning surface to the solid phase Λ_p is expressed by

$$\Lambda_p = \lambda_p \left(\frac{dT}{dx} \right) = C_p \rho_p r (T_s - T_0) \tag{4}$$

Substituting Eq. (3) to Eq. (1) yields

$$r = a_L I_L + b_L \tag{5}$$

where

$$a_L = \frac{1}{C_p \rho_p (T_s - T_0) - \rho_p Q_s} \tag{6}$$

$$b_L = \frac{H_f}{C_p \rho_p (T_s - T_0) - \rho_p Q_s} \tag{7}$$

From Eqs. (5) and (6), H_f is expressed as

$$H_f = \frac{b_L}{a_L} \tag{8}$$

The value of H_f is determined by substituting the experimentally evaluated values of a_L and b_L into Eq. (8). Burning surface temperature is obtained with thermography. In general, double-base propellants have more complex flame structure than is shown in Fig. 1, and in the gas phase, present a step-like temperature structure and three zones: fizz zone, dark zone, and luminous flame zone. Hence, the heat flux from flame to burning surface H_f would consist of conductive heat transfer from fizz zone and radiative heat transfers from the three zones.

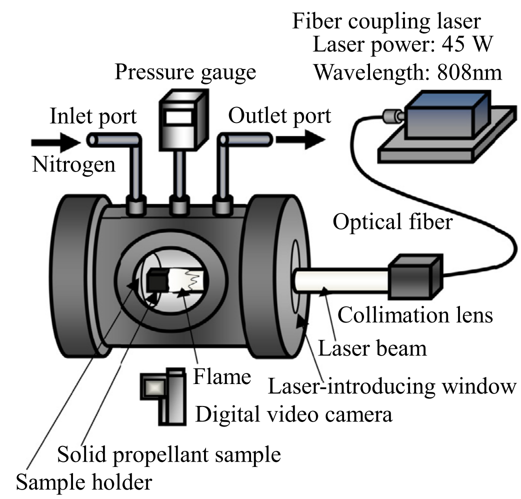

Fig. 2. Experimental apparatus.

3. Experimental apparatus

3.1. Combustion chamber with laser-introducing window

The cylindrical combustion chamber shown in Fig. 2 was utilized for heat-flux measurements. The combustion chamber had an outer diameter of 120 mm, an inner diameter of 54 mm, and a length of 320 mm. A solid propellant sample was adhered to a propellant holder, which was fixed at the left end. A BK-7 laser-introducing window of 50 mm in diameter was placed at the other end. The other BK-7 windows were positioned at the both sides to observe solid propellant combustion and measure the laser attenuation due to flame. In thermography, one of the BK-7 windows was replaced with a 50-mm-diam. Germanium window, which transmitted far infrared rays.

Nitrogen purge gas was introduced through inlet ports, and was expelled from outlet ports with combustion products. The nitrogen purge gas was provided from a high-pressure cylinder through the inlet ports, and was divided into two streams in the combustion chamber. One stream was supplied into the propellant holder, passing through holes in it. These holes align the nitrogen purge gas flow along the solid propellant.

The other nitrogen purge gas was injected into the laser-introducing window to prevent burned solid particles from attaching to the window and to remove combustion products along the laser beam path. Because the purge gas stream toward the burning surface possibly disturbed combustion, the gas flow rate for the laser-introducing window and that for the solid propellant holder were adjusted so that the combustion was not disturbed by the purge gas streams.

For target back pressures below 0.11 MPa, exhaust gas was evacuated using a rotary pump. At above 0.11 MPa, it was expelled by its own pressure. During measurements, back pressure was regulated by adjusting valves connected to both inlet and