

# Design of a Premixed Rotating Detonation Engine with a Porous Injector

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## 1 Introduction

Detonation waves propagating in an explosive premixture cause adiabatic compression of the premixture by the shock wave, and combustion is instantaneously completed behind the shock wave. The rotating detonation engine (RDE), which generates thrust by rotationally propagating the detonation wave, can achieve higher theoretical thermal efficiency than the constant volume, constant pressure combustion cycle [1]. Numerical calculations of RDE have shown that pressure gain combustion (PGC), in which the total pressure at the combustor outlet is higher than the total pressure at the combustor inlet, can be achieved [2]. PGC is also being achieved in experiments [3], but there is a large discrepancy between the numerical results and the experimental results [4]. The main reason for this discrepancy is currently unknown, and one factor that cannot be clarified is the complexity of the internal flow. In conventional RDEs, the fuel and oxidizer are mixed inside the combustor. Therefore, the internal flow is greatly influenced by the shape of the injector and combustor, and the mixing process also varies greatly depending on them. This study aims to simplify the internal flow and clarify the causes of pressure loss inside the RDE by pre-mixing the fuel and oxidizer before the test and flowing them into the combustor.

When operating an RDE with premixed gas, it is necessary to prevent flashback, a phenomenon in which the flame in the combustor propagates back to the upstream of the injector. Yang et al.[5] used a Tesla valve in the injector, and Ayers et al. [6] prevented this phenomenon by using sintered metal and successfully operated an RDE. However, all these reports were of the “premixing type,” in which the fuel and oxidizer are mixed upstream of the combustor and then flowed to the combustor. With

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premixing types, It is difficult to assess whether perfect mixing is achieved in the combustor. Therefore, we are currently working toward the operation of a “premixed type” RDE, in which a high-pressure premixed gas is prepared before flowing into the combustor.

Premixing equipment is currently available at the California Institute of Technology [7] and Nagoya University [8] and can be filled with 9.6 L and 1 L of premixed gas up to 300 kPa, respectively. In addition, an injector using sintered metal is used to prevent flashback.

## 2 Prediction of Porous Injector Characteristics that Prevent Flashback

This chapter discusses the characteristic values of porous materials that can prevent flashback. Here, based on previous studies, we consider two types of flame quenching conditions that must be satisfied by porous materials: one for detonation and the other for laminar flame speed. According to Radulescu et al.[9] detonation waves cannot maintain their structure when passing through voids less than the cell size. The cell size can be expressed by Shepherd et al.[10] as a function of the combustor pressure  $p_c$ , so the following quenching condition can be considered, taking the porous hydraulic diameter as  $d_h$ .

$$d_h = 83.829p_c^{-1.1515}, \quad (1)$$

For laminar flames, the Peclet number is often used as a quenching condition, defined in terms of laminar flame speed  $S_L$ , thermal diffusivity  $\alpha$ , and  $d_h$ . It was shown by Spalding et al.[11] to be theoretically 60.5 when using a hydrocarbon premixture. The  $d_h$  is summarized by the following equation,

$$d_h = \frac{60.5\alpha}{S_L}, \quad (2)$$

$\alpha$  and  $S_L$  can be obtained using Cantera's GRI-mech 3.0 model[12] with initial pressure, initial temperature, and equivalent ratio as variables. Fig. 1 shows a graph of the critical hydraulic diameter obtained from the quenching conditions when the initial temperature is 300 K and the equivalent ratio is 1, and the initial pressure is varied as the  $p_c$ . The premixed gas can be filled up to 300 kPa, so the porous material should have a hydraulic diameter of 84  $\mu\text{m}$  or less.

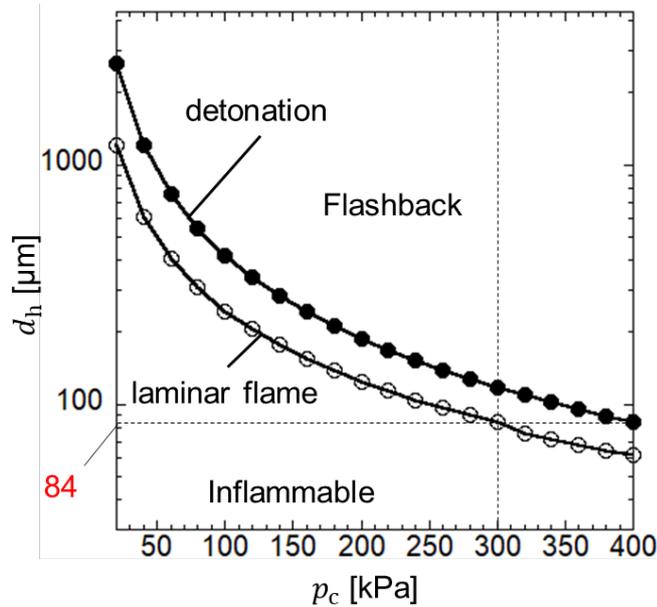


Figure 1: Critical hydraulic diameters for detonation and laminar flames obtained from quenching conditions. (initial temperature = 300 K)

### 3 Confirmation of the existence of RDE operation available duration

It is shown in the previous section that the smaller the hydraulic diameter of the porous material, the better the flame-quenching ability. However, the smaller the hydraulic diameter of the porous material, the greater the pressure drop and thus the lower the performance of the porous material as an injector. A common method for evaluating the possibility of RDE operation is to use the mixture layer height  $H$  of unburned premixed gas at the time of detonation wave passage. The required layer height  $H_{cr}$  can be expressed by Bykovskii et al.[13] using the detonation cell size  $\lambda$  in the following equation,

$$\frac{H_{cr}}{\lambda} = 12 \pm 5, \quad (3)$$

$\lambda$  is uniquely determined when  $p_c$  is constant. However, as noted in Chapter 1, the tank volume and pressure are not large enough to allow steady-state operation of the RDE. In this chapter, we model the RDE from the tank to the combustion chamber outlet and perform unsteady calculations to verify that the duration to satisfy  $H_{cr}$  is sufficient for the experiment.

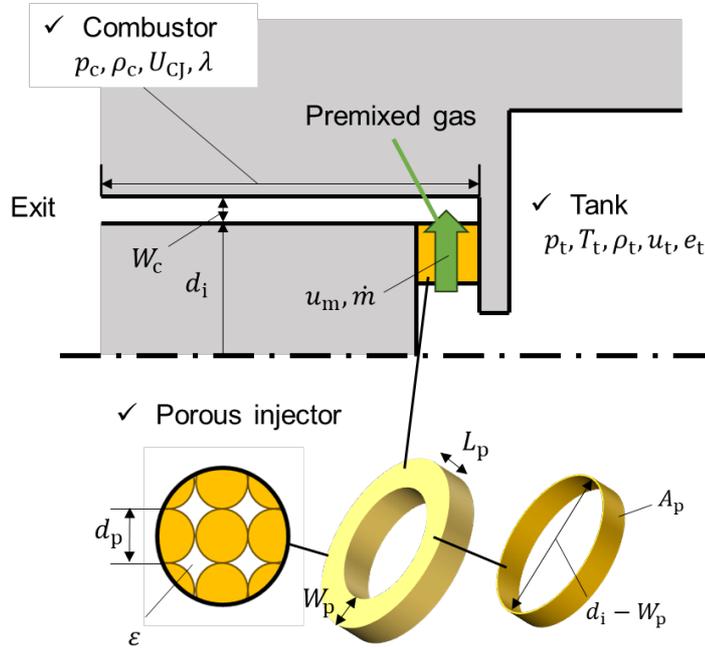


Figure 2: Premixed RDE model from tank to combustion chamber outlet

Figure 2 shows the sections of the RDE model and the variables. It is important to note that all state quantities are non-stationary, since the tank decreases pressure as soon as the experiment begins. For the quantity of state in the tank, using the tank density  $\rho_t$ , tank volume  $V_t$ , and mass flow rate  $\dot{m}$ , the unsteady mass conservation equation is

$$\frac{\partial}{\partial t}(\rho_t V_t) = -\dot{m}, \quad (4)$$

Using the tank internal energy  $e_t$ , the tank pressure  $p_t$ , and the flow velocity  $u_t$  in the tank, the energy conservation equation is

$$\frac{\partial}{\partial t}(\rho_t V_t e_t) = -\dot{m} \left( e_t + \frac{p_t}{\rho_t} + \frac{1}{2} u_t^2 \right), \quad (5)$$

Using the specific heat ratio  $\gamma$  and assuming calorically perfect gas and a slow flow velocity in the tank, we obtain

$$\frac{d\rho_t}{dt} = -\frac{\dot{m}}{V_t}, \quad (6)$$

$$\frac{dp_t}{dt} = -\frac{\gamma\dot{m}p_t}{V_t\rho_t}, \quad (7)$$

Next, we consider the quantities of state before and after the porous material. In the steady state, the porous material is subjected to viscous and inertial forces from the passing fluid.[14] The force balance equation is given by the following relationship using the pressure drop  $dp/dx$ , viscosity coefficient  $\mu$ , and fluid mean velocity  $u_m$ ,

$$-\frac{dp}{dx} = \alpha\mu u_m + \beta\rho u_m^2, \quad (8)$$

$\alpha$  and  $\beta$  are constants, and using the grain size of the porous material  $d_p$ , and the porosity  $\varepsilon$  [15], [16], we have,

$$\alpha = \frac{180(1-\varepsilon)^2}{d_p^2\varepsilon^3}, \quad (9)$$

$$\beta = \frac{1.8(1-\varepsilon)}{d_p\varepsilon^3}, \quad (10)$$

Here, the following equation relating hydraulic diameter to particle diameter can be used to relate to the quenching condition.[17]

$$d_p = \frac{1-\varepsilon}{0.423\varepsilon^{1.25}} d_h, \quad (11)$$

Assuming that the fluid is at a constant temperature as it passes through the porous media, we obtain,

$$p_t^2 - p_c^2 = 2RT_t W_p \left\{ \alpha\mu \left( \frac{\dot{m}}{A_p} \right) + \beta \left( \frac{\dot{m}}{A_p} \right)^2 \right\}, \quad (12)$$

$R$  is the gas constant,  $T_t$  is the gas temperature in the tank,  $p_c$  is the combustor pressure, and  $W_p$  and  $A_p$  are the width of the porous material and the cross-sectional area perpendicular to the flow path, respectively. In the combustor, assuming 100% combustion efficiency and choke at the outlet, the equation defining characteristic exhaust velocity is adopted.  $c^*$  as characteristic velocity and  $A_{th}$  as throat cross section,

$$p_c = c^* \frac{\dot{m}}{A_{th}} = c^* \frac{A_p}{A_{th}} \frac{\dot{m}}{A_p}, \quad (13)$$

Figure 3 shows the calculation method. Here,  $i$  represents the calculation step. Calculation results assuming premixed C<sub>2</sub>H<sub>4</sub>-O<sub>2</sub> (equivalence ratio: 1) are shown in Figure 4, which gives time history of the state of the tank and combustor when the engine starts at 0 seconds. The various parameters used in the calculations are listed in Table 1. Figure 4 also expresses whether the filling height  $H$ , calculated from the obtained time history, satisfies  $H_{cr}$ .  $H$  can be calculated using the density of unburned premixed gas in the combustor  $\rho_c$  from the following equation.[18]

$$H = \frac{\dot{m}}{\rho_c W_c U_{CJ}}, \quad (14)$$

The current calculations indicate that the test duration is 21.4 ms. This calculation method can be applied not only to determine the characteristic values of the porous material, but also to calculate the optimization of the combustor geometry, since the parameters of the combustor can be changed.

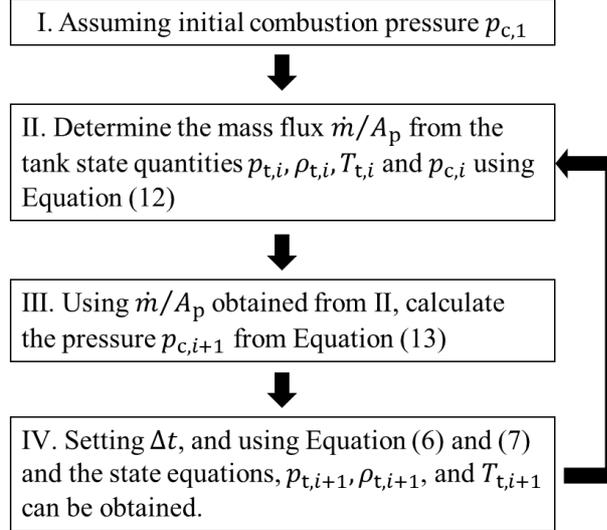


Figure 3: Calculation method of state quantity prediction model for premixed RDE

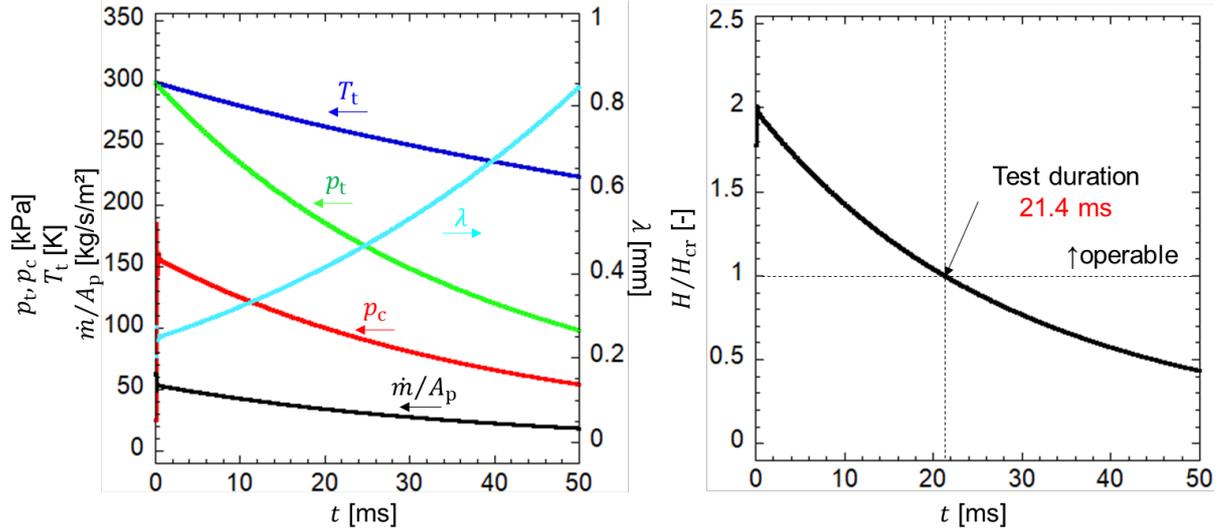


Figure 4: Prediction results of state quantities during RDE operation. Left: Time history of each state quantity. Right: Actual filling height against required filling height.

Table 1: Each characteristic value used in the calculation

$p_{t,1}$	initial tank pressure [kPa]	300
$T_{t,1}$	initial tank temperature [K]	300
$p_{c,1}$	initial combustor pressure [kPa]	25
$R$	gas constant [J/kg/K]	263
$\gamma$	specific heat ratio [-]	1.36
$\mu$	viscosity coefficient [ $\mu\text{Pa}\cdot\text{s}$ ]	17.6
$c^*$	characteristic velocity [m/s]	1691[19]
$W_c$	combustor width [mm]	2.5

$d_i$	combustor inner cylinder diameter [mm]	90
$d_h$	hydraulic diameter [ $\mu\text{m}$ ]	84
$L_p$	porous thickness [mm]	5
$W_p$	porous width [mm]	10
$\varepsilon$	Porosity [-]	0.38
$V_t$	tank volume [L]	0.98
$U_{CJ}$	CJ detonation velocity [m/s]	2340[19]

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