Experimental Study of Heat Transfer to Thin Wall in Water-Cooled Cylindrical Rotating Detonation Engine

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1 Introduction

Detonation is a combustion phenomenon caused by shock waves propagating through a premixed fuel-air mixture [1]. It is characterized by the adiabatic compression of the premixed mixture initiated by the shock wave, and it is expected that compressors can be eliminated due to this phenomenon. In recent years, research has been focused on its application to rockets. Detonation-based engines can be classified into several types, with the Rotating Detonation Engine (RDE) being actively researched, as it can achieve steady thrust [2]. Typically, RDEs consist of an inner and outer cylinder, where the detonation wave propagates rotationally through the propellant supplied in the annular space between the cylinders to generate thrust. Interestingly, it has been discovered that detonation can also propagate rotationally in a cylindrical combustor without an inner cylinder, and such RDEs are referred to as Cylindrical RDEs, which have recently gained significant attention in research [3, 4]. One of the technical challenges for applying RDE in space propulsion systems is the high thermal load conditions inside the combustor. Experimental results from Rankin et al. [5], using a transparent combustor with visual access, have confirmed that the detonation wavefront and the subsequent reaction zone exhibit the most intense combustion. By using high-response heat flux gauges that can respond to the rotation period of the detonation wave, Theuerkauf et al. measured the periodic heat fluxes generated by the detonation wave, with peak values ranging from 1 MW/m² to 9 MW/m² [6]. On the other hand, for the initial thermal design of the combustor, it is important to predict the time-averaged heat flux to determine the materials and wall thickness of the combustion chamber. Regarding the axial distribution of the time-averaged heat flux inside the combustor, Bykovskii and Vedernikov [7, 8] reported, based on thermocouple-based heat load measurement experiments, that the axial position with the highest temperature coincided with the height of the detonation wave. Similar trends were reported by Braun et al. [9] through numerical simulations of heat flux, which also supported the finding that the heat load in

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the detonation combustion region is exceptionally high. This suggests that RDEs require a different approach to thermal load management and cooler design than traditional rocket engines, where the maximum thermal load is typically experienced at the nozzle throat [10].

This study focuses on experimental research to achieve thermal equilibrium through a regenerative cooling system in RDEs. To realize an effective cooling mechanism, it is essential to investigate the heat transfer coefficient and heat flux in RDEs and clarify the thermal environment. However, many aspects of the thermal environment in RDEs remain unresolved. This study employs a cylindrical RDE with a wall-cooled combustion chamber utilizing external cooling water, and experimental tests are conducted to determine the heat transfer coefficient and heat flux experimentally, using experimental data and a heat conduction model.

2 Experimental Setup

The schematic diagram of the cylindrical RDE combustor used in this study is shown in Fig. 1. A characteristic of the combustor used in this experiment is that it has a wall-cooled combustion chamber with a 16 mm thick wall from the bottom of the combustion chamber. The material of the inner wall of the water-cooled combustion chamber is C1020, with a thickness of 1 mm. The outer wall is made of SUS304. The inner diameter of the combustion chamber is d_c = 20 mm. Cooling water is supplied through a 4.5 mm diameter hole at the bottom of the combustor, flows through a channel of diameter d_w = 45 mm in the circumferential direction of the combustor, and is discharged through a 4.5 mm diameter hole at the top of the combustor [11].

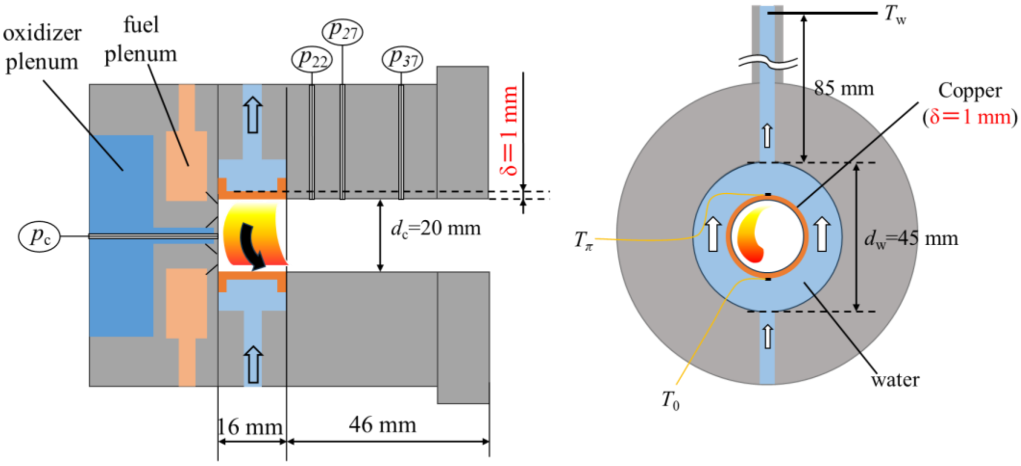

Fig.1 The RDE with water-cooled section
Left: A schematic of the RDE, Right: Cross-section view of water-cooled section

Details of the injector are outlined by Yokoo et al. [3, 4], and the reader is referred to those papers for further detail. For ignition, a pyrotechnic igniter (Kayaku Japan) containing an electric match is placed in the combustion chamber and detonated. Wall temperature measurements of the combustion chamber are performed at two locations on the circumferential position of the water-cooled combustion chamber at θ = 0 and θ = π, corresponding to the combustion chamber wall temperatures T_0 and T_π (Hereafter, the parameters on the cooling water inlet side are denoted by the subscript "0" and those on the outlet side by the subscript "π"). The thickness of the water-cooled combustion chamber wall is δ = 1 mm, so the temperature is measured 1 mm from the inner wall of the combustion chamber at all positions. The thermocouples are inserted into the cooling channel of the water-cooled combustion chamber through a feedthrough, and their tips adhere to the wall using Kapton tape to ensure tight contact. The thermocouples used for wall temperature measurement are ultra-thin thermocouples manufactured by ANBE SMT Co. (KST (Pi) -50-200-300 (YY)). The temperature of the cooling water is measured at a location 85 mm from the outlet. For pressure measurement inside the combustion chamber, the combustion chamber pressure P_c is measured at the pressure port located at the center of the combustion chamber bottom. Additionally, pressure ports are installed on the combustion chamber sidewalls at z = 22, 27, and 37 mm, allowing for the measurement of the static pressure distribution inside the combustion chamber. The spontaneous light emissions inside the combustor were observed using a high-speed camera (v2011, Phantom Co.). The high-speed camera was positioned outside the vacuum chamber and captured images through a quartz glass window, with a frame rate of 430,769 fps and an exposure time of 0.4 μs.

The experimental conditions of this study are as follows: propellant flow rate of 18.3 ± 0.3 g/s, equivalence ratio of 1.6 ± 0.1, backpressure of 20 kPa, and cooling water flow rate of 45 ± 1 g/s. The combustion test uses gas ethylene and gas oxygen as propellants, with a combustion duration of 1.6 s. In this study, the combustion test is conducted while cooling water is circulated in the circumferential direction of the combustor. The cooling water flow rate is calculated by measuring the weight of the cooling water discharge.

3 Results and Fitting

Fig. 2 shows a series of continuous images of the axial spontaneous light emission captured by the high-speed camera. The rotational propagation of the high-intensity region, which is considered to be the detonation wave, can be observed. The detonation propagation frequency was 28.9 kHz, and the propagation velocity was 1816 m/s.

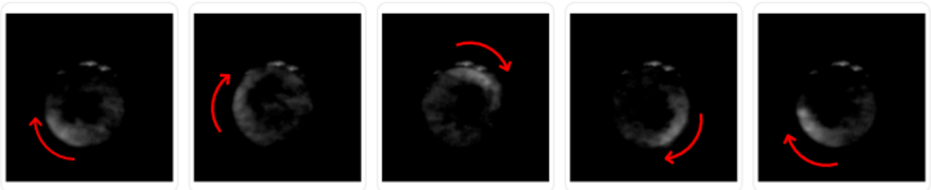

Fig. 2 Axial images of high-luminescence area in the Cylindrical RDE

The temperature and pressure histories are shown in Fig. 3. The cooling water temperature is denoted as T_w, and the pressure at a distance z from the combustion chamber bottom is denoted as P_z.

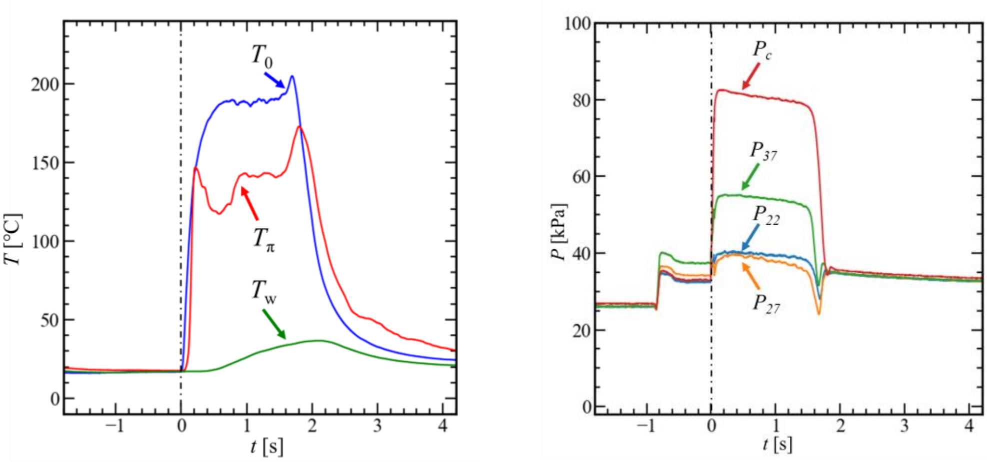

Fig. 3 Time variation of temperature and pressure

The wall temperature measurement results during the combustion tests are compared with the calculated results from the heat conduction model shown in Fig. 4, and the heat transfer coefficient is

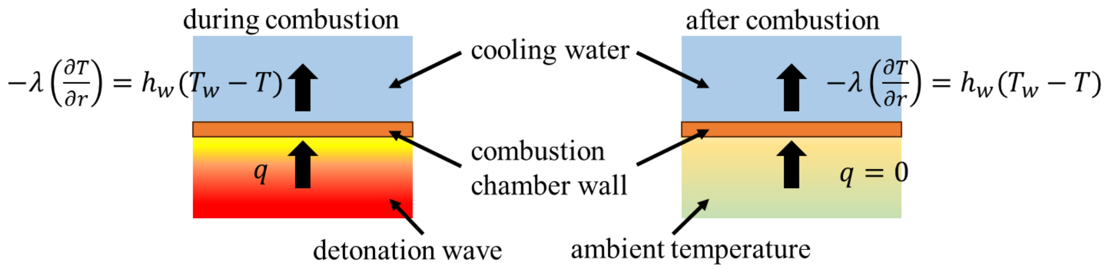

Fig. 4 Heat conduction model

determined through fitting. The fundamental heat conduction equation used in solving the heat conduction model in this study is the axisymmetric one-dimensional unsteady-state heat conduction equation. This equation is shown in the following (1) equation.

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho c}\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) \tag{1}$$

λ is the thermal conductivity, ρ is the density, and c is the specific heat. By applying the upwind difference method to solve equation (1) explicitly, equation (2) is obtained.

$$T_i^{j+1} = T_i^j + \frac{\alpha \cdot dt}{dr^2}\left[\left(1 - \frac{dr}{2r_i}\right)T_{i-1}^j - 2T_i^j + \left(1 + \frac{dr}{2r_i}\right)T_{i+1}^j\right] \tag{2}$$

To prevent the solution from diverging, the time step dt is set to 0.01 ms, and the spatial step in the radial direction of the combustor dr is set to 0.05 mm. The initial condition is the experimental data of the wall temperature at the fitting start time. The fitting start time for determining the heat transfer coefficient on the cooling water side is taken as the point in the experimental data when the temperature began to decrease from the thermal equilibrium state after the combustion test had concluded. The following two boundary conditions are applied:

I. Regarding the heat flux entering the inner wall of the combustion chamber (at r = 10 mm), since the fitting start time is after the combustion test has concluded, for convenience, it is assumed that no heat exchange occurs after the fitting start time, and q = 0 is assumed.

II. At the combustion chamber wall (at r = 11 mm), the combustor is continuously cooled by the cooling water. The heat flux during this process is expressed by Fourier's law and Newton's law of cooling, as shown in equation (3) [12].

$$q = -\lambda\left(\frac{\partial T}{\partial r}\right) = h(T_w - T) \tag{3}$$

T_w is the temperature of the cooling water, and the measured value just before the start of the combustion test was used. The heat transfer coefficient h is a fitting parameter. As shown in equation (4), h is determined by minimizing the sum of the squared differences between the wall temperature T_{exp} obtained experimentally and the corresponding temperature T_{cal} from the computational model at each time step, over a fitting interval of 2.0 seconds.

$$\Delta = \sum\left[T_{exp}(i) - T_{cal}(i)\right]^2 \tag{4}$$

Based on the cooling water heat transfer coefficient previously determined, the wall temperature measurement results are compared with the calculation results from the heat conduction model, and the heat flux is determined through fitting. The heat conduction equation is given by equation (1). The initial condition is the experimental data of the wall temperature just prior to combustion ignition. The following two boundary conditions are applied:

I. For the heat flux entering the inner wall of the combustion chamber (at r = 10 mm), it is assumed to be constant until the combustion ends, and this heat flux is denoted as q.

II. At the combustion chamber wall (at r = 11 mm), the combustor is constantly cooled by the cooling water. The heat transfer coefficient of the cooling water during combustion and after combustion remains constant, and the values of h_0 and h_π, previously determined by fitting.

The incoming heat flux q is a fitting parameter. As shown in equation (4), q is determined by minimizing the sum of the squared differences between the wall temperature T_{exp} , obtained experimentally, and the corresponding temperature T_{cal} from the computational model, over a fitting interval of 1.5 seconds. The heat transfer coefficient h and heat flux q obtained by fitting are shown in Table1. Fig. 5 shows the fitting results graphs between the wall temperature measurement data and the heat conduction model calculation results for each experimental condition

Table1. Fitting results of heat transfer coefficient and heat flux

Measurement Location	heat transfer coefficient h kW/(m^{2}K)	heat flux q MW/m^2
Inlet side (0)	8.5	1.80
Outlet side (π)	5.5	0.95

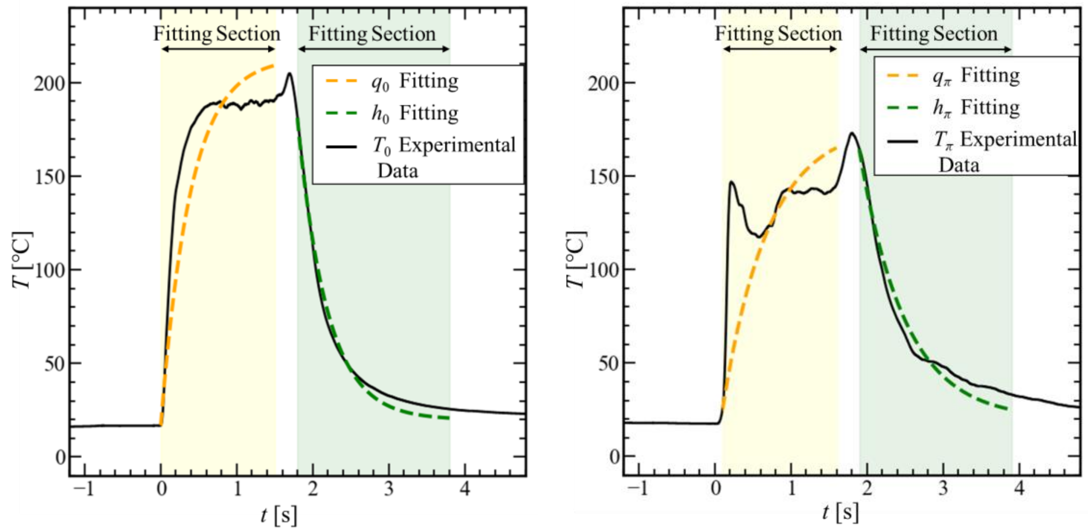

Fig. 5 Fitting wall temperature measurement results with heat transfer model calculations Left: Cooling water inlet side fitting, Right: Cooling water outlet side fitting

4 Conclusion

The wall temperature history of a 1.6-second combustion test in a Cylindrical RDE with a 1 mm copper wall and water cooling near the injector was used to predict the wall heat flux and cooling water heat transfer coefficient through fitting. The fitting results yielded q_0 = 1.80 MW/m^2, q_π = 0.95 MW/m^2, h_0 = 8.5 kW/(m^{2}K), and h_π = 5.5 kW/(m^{2}K). The obtained heat flux values are consistent in order of magnitude with other heat flux prediction studies for RDEs, and no significant discrepancies are expected. However, since the combustor used has injector holes arranged circumferentially, it is assumed that the incoming heat flux is uniform in the circumferential direction. In contrast, the obtained results show significant differences in the incoming heat flux between the cooling water inlet and outlet sides, which suggests that the wall temperature at the cooling water outlet may not have been accurately measured.

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