# Heating and Acceleration of Particles by High-Frequency Pulsed Detonations

T. Endo[1], R. Obayashi[1], T. Tajiri[1], K. Kimura[1], Y. Morohashi[1], T. Johzaki[1], and K. Matsuoka[2]

[1] Department of Mechanical Systems Engineering, Hiroshima University
1-4-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8527, Japan

[2] Department of Aerospace Engineering, Nagoya University
Furo-cho, Chikusa, Nagoya, Aichi 464-8603, Japan

## 1 Introduction

It is important for the operation of a pulse-detonation combustor (PDC) that the residual hot burned gas is purged before refilling the PDC with fresh detonable gas. The authors developed a technology for the high-frequency operation of a PDC where all valves were kept open [1]. The principle of this technology is the following. The PDC is a tube, one end of which is closed and the other end open, and three gas-feeding pipes for fuel, oxygen, and inert gas are connected to the closed end. The supply pressures of the fuel and oxygen are set equally, but only the supply pressure of the inert gas is set higher. After the detonation initiation, the gas pressure inside the PDC becomes high and thereby the gas supply becomes stopped. After the detonation reaches the open end and the exhausting rarefaction wave reaches the closed end, the gas pressure around the closed end becomes lowered. Because the supply pressure of the inert gas is set higher than those of the fuel and oxygen, only the inert gas starts to be supplied first, and fuel and oxygen start to be supplied with some delay. By this delay, the residual hot burned gas is purged by the precedingly-supplied inert gas. We call this operation mode the GAP mode. Although the GAP-mode operation of a PDC is very stable and durable because it is moving-component free, pure fuel-oxygen combustion is impossible because the detonable gas is unavoidably diluted by the inert gas for the purge process in principle.

Recently, the authors developed another high-frequency operation mode of a PDC, which we call the liquid-purge (LIP) mode [2]. In the LIP-mode operation, the residual hot burned gas is purged by using the liquid-gas phase transition of liquid droplets. The principle of the LIP-mode operation is as follows. The PDC is a tube, one end of which is closed and the other end open, and two gas-feeding pipes for fuel and oxygen are connected to the closed end. Additionally, a liquid-droplet injector is installed at the closed end for injecting liquid droplets into the PDC for the purge process. The fuel and oxygen are supplied into the PDC in the valveless mode, similarly to the GAP mode. In the LIP-mode operation, in the final stage of the gas supply, namely just before the detonation initiation, liquid droplets are injected into the vicinity of the closed end. After the detonation initiation, the gas pressure inside the PDC becomes high and thereby the gas supply becomes stopped. Simultaneously, the liquid-gas phase transition of the injected liquid droplets starts in the hot burned gas in the vicinity of the closed end. The liquid-gas phase transition is endothermic and accompanied by roughly thousand-fold volume expansion, and thereby the hot burned gas is cooled and pushed toward the open end, namely purged. Although the liquid-droplet injector has to be actuated every cycle, almost pure fuel-oxygen combustion is possible in the LIP-mode operation because the liquid-gas phase transition of the injected liquid droplets is not so fast.

The authors intend to apply the developed technologies for the high-frequency operation of PDCs in the field of thermal spray [3,4]. In this paper, we describe the investigation results on the ability of the developed high-frequency PDCs to heat and accelerate particles of CoNiCrAlY, which is a material often used for thermal barrier coating.

## 2 Experiments

In the experiments, we used a PDC operated in the GAP mode shown in Fig. 1 and another PDC operated in the LIP mode shown in Fig. 2. A nozzle of 1.5 mm in inner diameter for powder supply was installed to each PDC. The powder was continuously supplied to the PDC by using a powder feeder together with carrier gas (argon) whose flow rate was 20 standard liter per minute (SLM), meaning the volume flow rate converted to the standard condition: 20 $^{o}$C and 1 atm, and supply pressure was 1.09 MPa. In the experiments, the time-averaged flow rates of gases were controlled by using mass flow controllers. In the GAP-mode operation, argon was used as the purging gas. In the LIP-mode operation, a liquid injector was installed at the closed end. By using the liquid injector, water droplets were injected at the supply pressure of 7.1 MPa into the PDC, where the Sauter mean diameter of the water droplets was 24.4 μm and the spray cone angle was 35$^{o}$ (half angle).

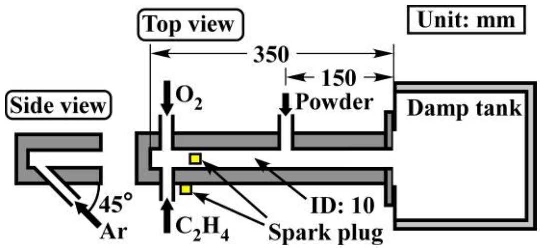

Fig. 1 PDC for the GAP-mode operation.

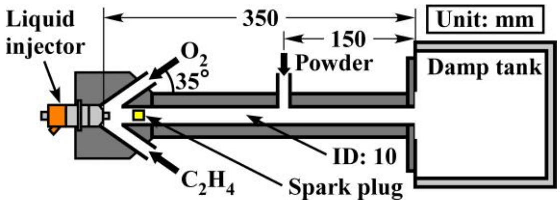

Fig. 2 PDC for the LIP-mode operation.

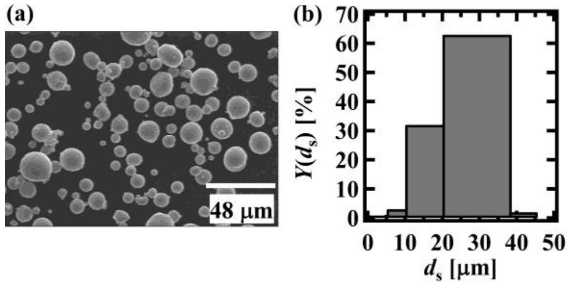

Fig. 3 CoNiCrAlY powder.
(a) Photograph. (b) Particle-size distribution.

The powder was CoNiCrAlY, whose mass ratio was Co:Ni:Cr:Al:Y=5:4:2.5:1:0.05 and melting point was about 1340 $^{o}$C. Figure 3 shows the CoNiCrAlY powder, where $d_s$ and $Y(d_s)$ are the particle diameter and mass fraction, respectively.

For the measurements of the temperature and speed of the in-flight particles, we used SprayWatch 2i (Oseir Ltd.), which was based on a single CCD camera where the viewfield was 21 mm horizontally and 28 mm vertically and its depth was 6 mm. The particle temperature was measured by two-color pyrometry at 700 and 850 nm, where the measurement duration was set to 0.2 ms. The particle speed was measured from the length of the particle trace during the known exposure time which was set to 0.5 μs.

The operation conditions of the PDCs are shown in Table 1. The CJ detonation parameters were calculated for the initial condition of 300 K and 1 atm. Both PDCs were operated at 150 Hz for 20 s. The supply rate of CoNiCrAlY powder was 20 g/min. We set the center of the viewfield of SprayWatch 2i to 0.1 m from the PDC exit on the elongation of the PDC axis, and varied the start timing of the measurement every 0.2 ms from the ignition timing, by which the time origin $t = 0$ was defined. The experiments were carried out without a substrate to be sprayed.

The measured temperature and speed of CoNiCrAlY powder are shown in Fig. 4, where $T_s$ and $u_s$ are the temperature and speed of the particles, respectively. As shown in Fig. 4(a), the highest particle temperature observed in the LIP-mode operation was higher than that in the GAP-mode operation by

Table 1 Operation conditions of PDCs.

| Operation mode | GAP | LIP |
|---|---|---|
| Supply pressure of $C_2H_4$ and $O_2$ [MPa] | 0.60 | 0.50 |
| Supply pressure of Ar [MPa] | 1.09 | – |
| Supply rate of $C_2H_4$ [SLM] | 88 | 106 |
| Supply rate of $O_2$ [SLM] | 240 | 300 |
| Supply rate of Ar [SLM] | 600 | 0 |
| Composition of detonable gas | $1.1C_2H_4$+$3O_2$ +6.4Ar | $1.1C_2H_4$ +$3O_2$ |
| Temperature at CJ surface [K] | 3597 | 3968 |
| Pressure at CJ surface [MPa] | 2.512 | 3.496 |
| Gas speed at CJ surface relative to the unburned gas [m/s] | 857 | 1114 |
| Mass of injected water per cycle [mg] | – | 25 |

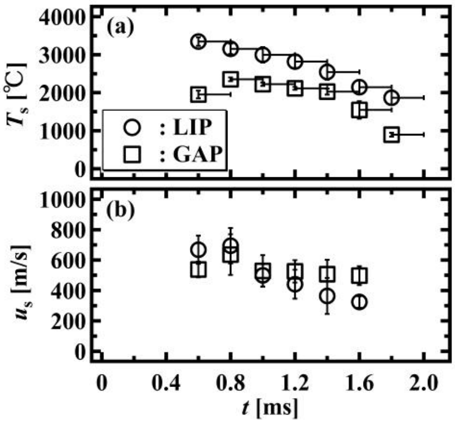


Fig. 4 Measured temperature (a) and speed (b) of CoNiCrAlY powder.

about 1000 K. On the other hand, the CJ temperature for the LIP-mode operation was higher than that for the GAP-mode operation by about 380 K as shown in Table 1. Although the difference in the CJ temperature between two operation modes seems to have the largest influence on the difference in the particle temperature between two operation modes measured at the time when the self-emission of the particles starts to be observed, namely at $t$=0.6 ms, the particle temperature measured at that time for the LIP-mode operation was higher than that for the GAP-mode operation by about 1400 K. On the particle speed, the gas-flow speed induced by CJ detonation for the LIP-mode operation was higher than that for the GAP-mode operation by about 260 m/s as shown in Table 1. However, the particle speed measured at $t$=0.6 ms for the LIP-mode operation was higher than that for the GAP-mode operation by only about 130 m/s. And further, the highest particle speed measured for the LIP-mode operation was higher than that for the GAP-mode operation by only about 50 m/s. Summarizing the experimental results, the differences in the measured particle temperature and speed between two operation modes were qualitatively what we expected, but quantitatively not.

## 3 Model calculations

We briefly describe the calculation methods for the particle temperature and speed measured at the time when the self-emission of the particles starts to be observed, namely at $t$=0.6 ms. We set the $x$-axis on the central axis of the PDC, whose direction is from the closed end toward the exit and origin ($x$=0) is at the PDC exit, and calculate the temperature and speed of the particles only on the $x$-axis. The boundary conditions for the particle temperature and speed are that $T_s$=300 K and $u_s$=0 at $x = -150$ mm corresponding to the powder-feeding nozzle. The initial conditions for the thermodynamic state of all gaseous media are that 1 atm and 300 K. Because the objective of the model calculations is to calculate the particle temperature and speed measured at the time when the self-emission of the particles starts to be observed, the following situation is assumed. Initially, the fresh detonable gas flows through the PDC toward the exit, and a spherical particle of specified diameter is accelerated by its flow. After the ignition, a CJ detonation propagates toward the PDC exit. At a certain instant, both of the particle and the detonation arrive simultaneously at the PDC exit. After that time, the particle is heated and accelerated by the burned-gas jet outside the PDC.

We calculate the position $x_s$, speed $u_s$=d$x_s$/d$t$, and temperature $T_s$ of a spherical particle of specified diameter as a function of time $t$ by using the following formulas.

$$x_s(t+\Delta t) = x_s(t) + u_s(t)\Delta t \quad (1)$$

$$u_s(t+\Delta t) = u_s(t) + C_D \rho_g (u_g - u_s)^3 |u_g - u_s|^{-1} (\pi d_s^2)(8m_s)^{-1} \Delta t \quad (2)$$

$$T_s(t+\Delta t) = T_s(t) + \alpha (T_g - T_s)(\pi d_s^2)(m_s c_s)^{-1} \Delta t \quad (3)$$

In the above formulas, $\Delta t$ is a small time interval actually set to 1 μs, $C_D$ is the drag coefficient for the particle, $\rho_g$ is the mass density of gas, $u_g$ is the gas-flow speed, $m_s$ is the particle mass, $\alpha$ is the heat-transfer coefficient for the particle, $T_g$ is the gas temperature, and $c_s$ is the specific heat of the particle. We ignore the temperature nonuniformity in the particle. When the particle temperature is equal to the melting point, we evaluate the heat flow to the particle by $\dot{Q} = \alpha\left(T_g - T_s\right)\pi d_s^{\,2}$, and keep the particle temperature to be equal to the melting point until the particle fusion finishes. The drag coefficient $C_D$ is evaluated according to Refs. [5,6]. The heat-transfer coefficient $\alpha$ is evaluated according to Refs. [6-9]. We treat the fresh detonable gas and the burned gas as different kinds of calorically perfect gases. We simplify the chemical composition of the burned gas to be the same as that of the CJ state. The thermal conductivity of gas $\lambda_g$ is simply evaluated by the following modified Eucken correlation [10] from the viscosity of gas $\mu_g$ which is evaluated by the same method as CHEMKIN [11].

$$\lambda_g = R_u\left[1.77 + 1.32\left(\gamma_2 - 1\right)^{-1}\right]W_g^{-1}\mu_g \tag{4}$$

In the above formula, $R_u$ is the universal gas constant, $\gamma_2$ is the effective specific-heat ratio of the burned gas, and $W_g$ is the average molar mass of the burned gas.

The gas-flow state of the fresh detonable gas inside the PDC is given by the uniform steady flow of 1 atm and 300 K with the flow speed $u_{g,\,x<0}$, which is evaluated so that $u_{g,\,x<0} = 228\ \mathrm{m/s}$ for the GAP-mode operation and $u_{g,\,x<0} = 110\ \mathrm{m/s}$ for the LIP-mode operation, taking account of the principle of the valveless-mode gas supply and the pressure history inside the PDC [12]. A particle that is accelerated by the flow of the fresh detonable gas until arriving at the PDC exit is heated and accelerated by the burned-gas jet outside the PDC. In the model calculations, the gas-flow state at the PDC exit is simplified to be constantly equal to that at the CJ surface of the detonation because the objective of the model calculations is to calculate the particle temperature and speed measured at the time when the self-emission of the particles starts to be observed. The flow speed and temperature of the burned-gas jet on the *x*-axis outside the PDC are evaluated according to Refs. [13,14]. The burned-gas-pressure distribution on the *x*-axis outside the PDC is assumed to be linear in the potential core.

The model calculations are carried out for the particles with diameters of 7.5, 15, 20, and 29 μm, where 15, 20, and 29 μm are the representative diameters of the particles having dominant contributions to the present measurements, and 7.5 μm is for comparison.

## 4 Comparison between experiments and model calculations

Figure 5 shows the results of the model calculations (the histories of the calculated particle temperature and speed as functions of the particle position) together with the corresponding experimental data for the GAP-mode operation. Experimentally, at $x$=0.1 m, we could not observe the self-emission from the particles at $t$=0.4 ms, and the self-emission from the particles started to be observed from $t$=0.6 ms. In the model calculations, the particles did not reach $x$=0.1 m at $t$=0.4 ms, but the particles with diameters of 15 and 20 μm, which must have dominant contributions to the measurements by SprayWatch 2i, reached the observation region at $t$=0.6 ms. And the calculated temperature and speed of the particles with diameters of 15 and 20 μm were close to the experimental data. Figure 6 shows similar comparison for the LIP-mode operation. Also in this case, the experimental fact that the self-emission from the particles started to be observed from $t$=0.6 ms was reproduced by the model calculations for the particles with diameters of 15, 20, 29 μm. And the calculated temperature and speed of the particles with diameters of 15, 20, 29 μm were close to the experimental data also for the LIP-mode operation. From these comparisons, we consider that the present model calculations are valid.

Analyzing the calculation results in detail, the following was found out. The increase of the particle speed due to the acceleration by the burned-gas jet outside the PDC intensively reflected the difference in the gas-flow speed at the CJ surface of detonation. However, the difference in the increase of the particle speed due to the acceleration by the flow of the fresh detonable gas inside the PDC reduced the difference in the particle speed at $x$=0.1 m to only 27% of the difference in the gas-

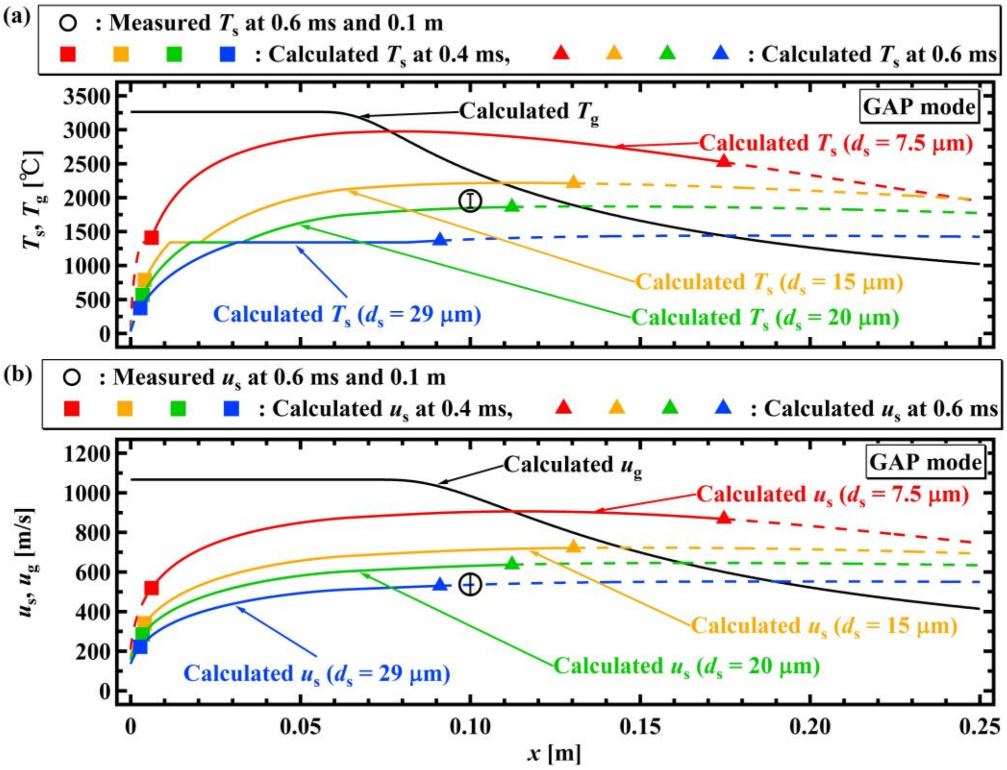


Fig. 5 Comparison of the calculation results with the experimental data for the GAP-mode operation.

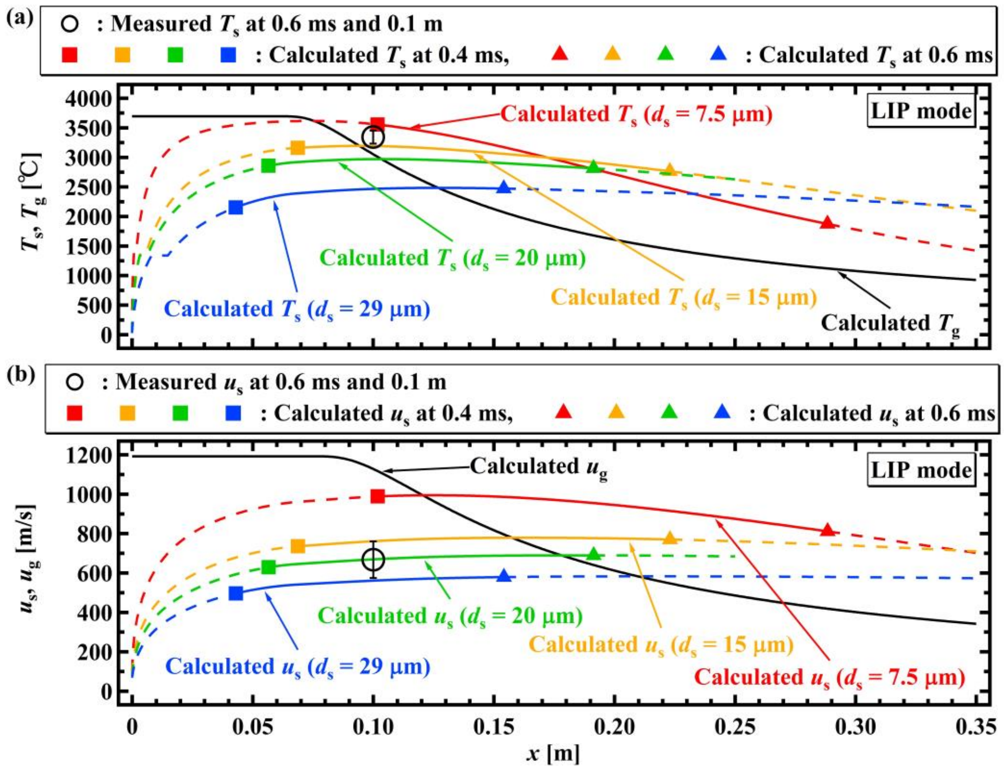


Fig. 6 Comparison of the calculation results with the experimental data for the LIP-mode operation.

flow speed at the CJ surface of detonation. The large difference in the particle temperature at $x$=0.1 m between two operation modes was due to the difference in the thermal conductivity of gas between two operation modes. That is, the thermal conductivity of gas for the GAP-mode operation was smaller than that for the LIP-mode operation because the mole fraction of argon, which is a monatomic molecule with a large molar mass, was large (54%) in the burned gas for the GAP-mode operation.

# 5 Conclusions

Pulse-detonation combustors were operated in the inert-gas-purge mode (GAP mode) and the liquid-purge mode (LIP mode) at 150 Hz. We measured the temperature and speed of CoNiCrAlY particles heated and accelerated by the pulsed detonations. As a result, the particle temperature in the LIP mode was higher than that in the GAP mode by about 1000 K. The experimental results were analyzed by using simple model calculations. It was found that the difference in the chemical composition of the burned gas between the GAP and LIP modes strongly affected the values of the thermal conductivity of gas, and altered the particle temperature heated by the pulsed detonations.

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