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Processing of a thermal plasma flow in a tube

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Abstract - First, the behaviors of a thermal plasma flow in a water-cooled tube are shown according to both numerical and experimental results. Next, two examples of the processing of a thermal plasma flow in a tube are shown. One is the particle heating by a thermal plasma flow in a porous ceramic tube with a transpiration gas, and the other is the quenching effect of a water-cooled tube on the yield of CO from the decomposition of CO_2.

INTRODUCTION

A thermal plasma flow has been widely used in many fields because it has high energy and activity. For example, they are plasma cutting, plasma welding, melting of metals, refining of refractory materials, producing of fine particles, synthesis and decomposition by chemical reactions, plasma coating, surface treatment, etc. Some of these applications utilize a confined plasma flow such as a plasma reactor or a plasma furnace. So the behavior of an internal plasma flow needs to be investigated.

An internal plasma flow has some features as follows:

(1) the flow is confined and does not spread radially, and the plasma region becomes longer;
(2) the material, which is treated by a thermal plasma flow, resides in it for a longer time, and the heat exchange from the plasma to the material is more effective;
(3) the plasma flow comes into contact with the wall of a container, and the wall interaction problem becomes a subject of discussion.

So far there are some papers about an internal thermal plasma flow. They are mainly related to the temperature and velocity fields of the plasma flow in a tube or the heat transfer from the plasma flow to the wall. In the present paper, the characteristic behavior and the processing of an argon thermal plasma flow in a water-cooled or porous ceramic tube are described.

NUMERICAL CALCULATIONS OF A THERMAL PLASMA FLOW IN A TUBE

Procedure for numerical calculation

An axially symmetrical thermal plasma flow in a water-cooled tube can be solved numerically using the mass, momentum, energy and species conservation equations. In the present numerical analysis, the following assumptions are used: (1) the flow is steady and laminar; (2) the natural convection and radiation are neglected; (3) boundary-layer approximation; (4) the properties are calculated by the corrected simple kinetic theory; (5) the separation of the flow does not exist; (6) ambipolar diffusion; (7) LTE condition for $D > 1$ and frozen state for $D < 1$.

At the inlet of the tube, the temperature, velocity and pressure are uniform, and the condition is in LTE. The calculation was conducted for the inlet temperature of 10,000 K, 12,500 K and 15,000 K, and for the argon gas flow rate of 5.54×10^{-4} kg/s. The wall temperature is constant at 300 K and the wall is electrically floating.

Results and discussions

The normalized static pressure is shown in Fig. 1. At first, it decreases in the same manner as in an ordinary tube flow, but it increases downstream. The variation of the static pressure is dependent on the viscosity and momentum change. In the entrance region, the plasma has a higher velocity and viscosity, and the static pressure decreases along the axis. At downstream, the plasma flow is sufficiently cooled and the static

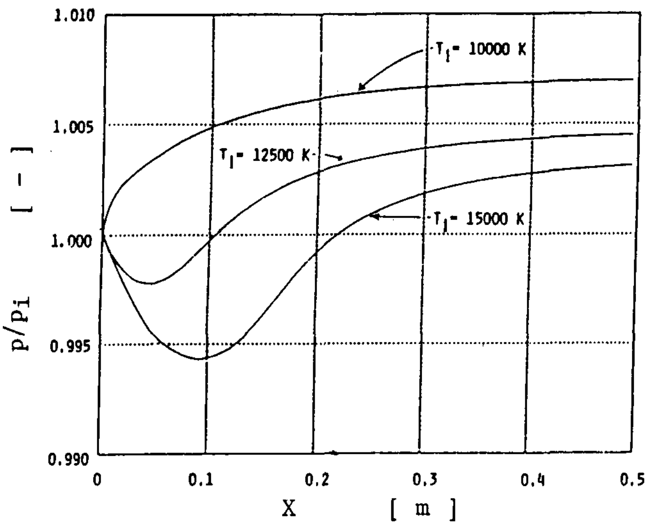

Fig. 1 Calculated pressure

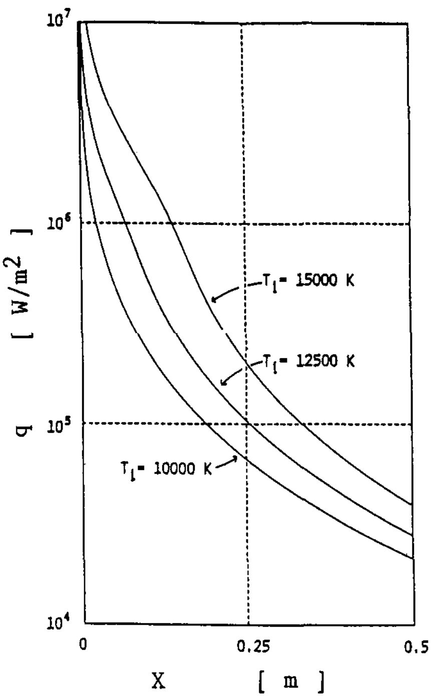

Fig. 2 Calculated heat flux

pressure is affected by the momentum change rather than by the viscosity.

The heat flux to.the tube wall is shown inFig. 2. The heat flux decreases gradually in the region where the recombination reaction is considered to take place.

PRESSURE AND HEAT FLUX MEASUREMENTS

Experimental apparatus

The test tube for the static pressure measurement is 8 mm i.d. and 550 mm long, which is made of copper and cooled by water. This tube is attached to the nozzle exit of the argon plasma torch generated by an arc discharge. The static pressure is measured using a water manometer connected to the pressure taps (1 mm i.d.) installed at the outside of the test tube at intervals of 2-10 cm.

The heat flux to the tube wall is calorimetrically measured using a transient method. The test tube which has the same size as that for the pressure measurement is attached to the plasma torch. The several probes for the heat flux measurements, consisting of copper, 8 mm i.d., 14 mm or 12 mm o.d., and 10 mm long, are installed along the tube. Each probe is insulated both thermally and electrically from the adjacent tubes using Teflon sheets.

Results and discussions

The measured static pressure is shown in Fig. 3. It is noticed that the static pressure does not vary monotonically, but the distributions show rather a minimum, as seen in the results of the numerical calculation.

The measured heat flux is shown in Fig. 4. This result shows that the heat flux is much higher than that in an ordinary gas, and increases with the increasing arc power.

EFFECTS OF GAS INJECTION ON A THERMAL PLASMA FLOW IN A TUBE

Experimental

An argon, helium or nitrogen gas is injected into the plasma flow through the small tube (1 mm i.d.) installed at the position of 5 - 6 cm from the cathode tip. The experimental apparatus and the method of the pressure and heat flux measurements are the same as mentioned in the previous section.

Figure 5 shows the static pressure for argon, helium and nitrogen injection together with no injection. The variation for helium injection is the largest and that for argon or nitrogen injection is less than that for no

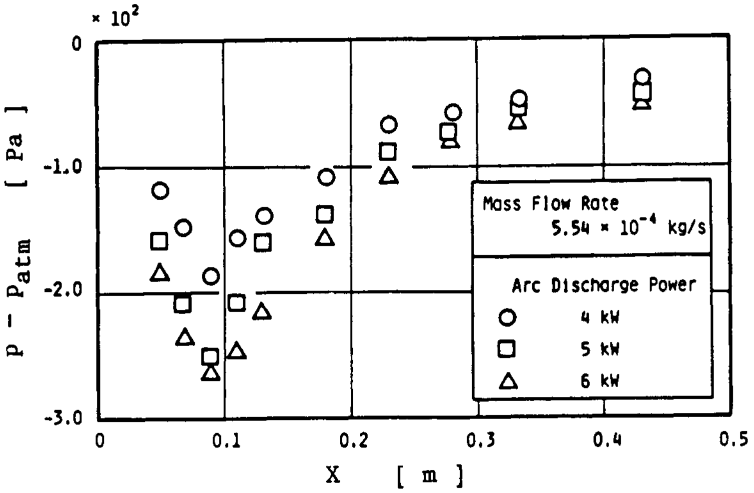

Fig. 3 Measured pressure

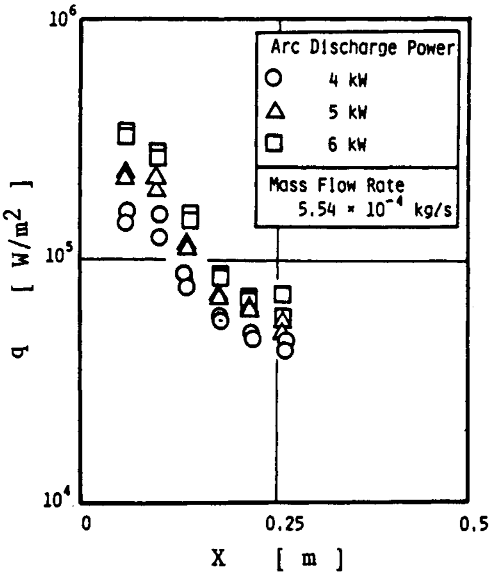

Fig. 4 Measured heat flux

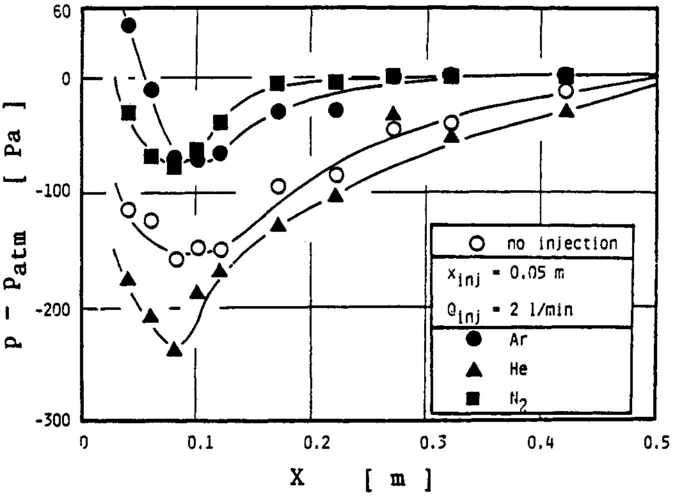

Fig. 5 Measured pressure with gas injection

gas injection. This is caused by the fact that the increasing rate of the static pressure downstream is dependent on the temperature decrease of the plasma flow.

The heat flux is shown in Fig. 6 for argon, helium and nitrogen injection. The difference between heat fluxes with and without injection is not so obvious as a whole.

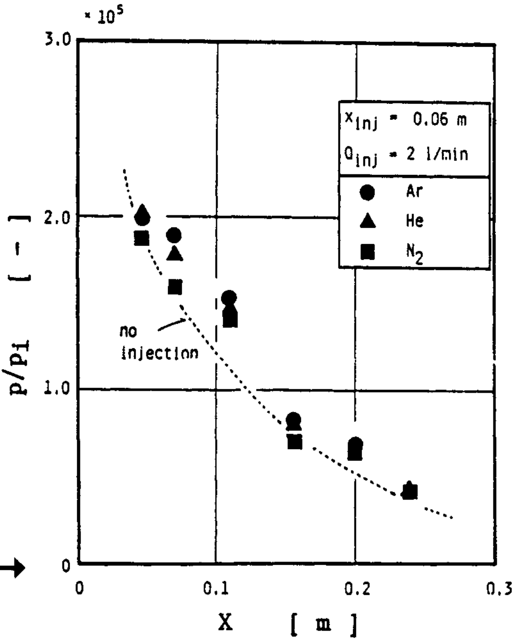

Fig. 6 Measured heat flux with gas injection →

Calculated

Numerical calculations are carried out assuming that the injection gas is completely mixed at the section of the injection. Argon, helium and nitrogen gases are also used as the injection gas.

The calculated normalized static pressure is shown in Fig. 7. The static pressure for helium injection increases rapidly in the same manner as the experiment.

The calculated heat flux is shown in Fig. 8. The enthalpies at the injection position are assumed to be uniform in the radial direction and so the heat fluxes increase there. However, the distributions of the heat fluxes show little differences between the cases with and without injection in the same manner as the experiment.

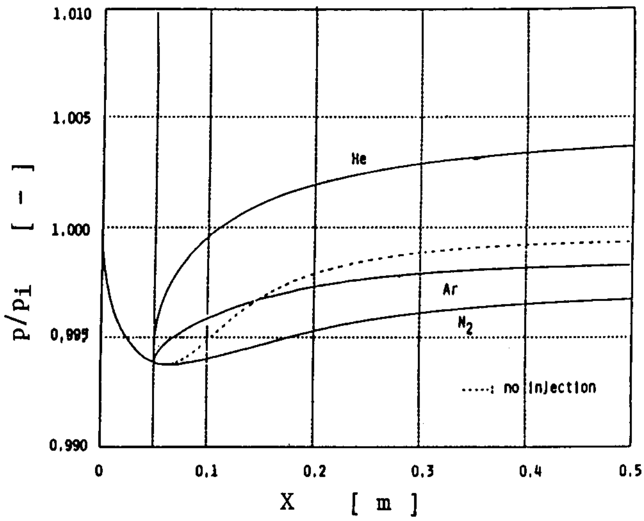

Fig. 7 Calculated pressure with gas injection

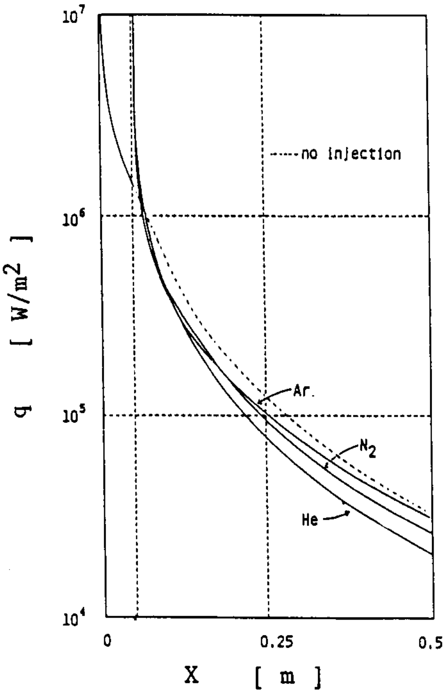

Fig. 8 Calculated heat flux with gas injection

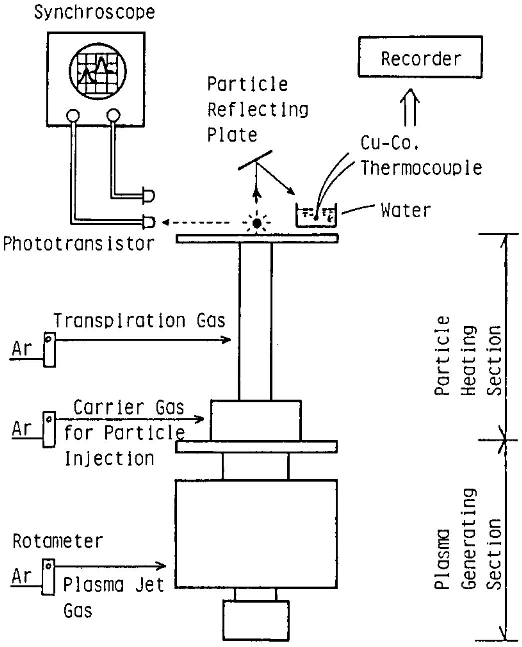

Fig. 9 Particle heating apparatus

PARTICLE HEATING BY A THERMAL PLASMA FLOW IN A TUBE

Experimental apparatus

A schematic drawing of the experimental setup is shown in Fig. 9. The experimental setup consists of a plasma generating section and a particle heating section. The particle heating section consists of a particle feeder and a ceramic porous tube. An alumina particle of 1 mm diam. is injected into the thermal plasma flow with a carrier gas and is heated there. The temperature of the particle is measured calorimetrically at the exit of the heating section.

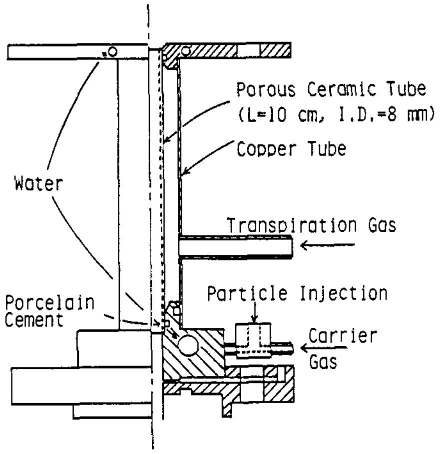

Fig. 10 Porous ceramic tube

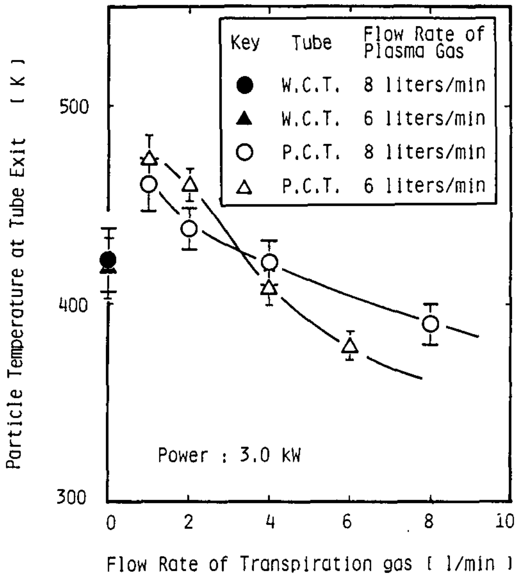

Fig. 11 Particle temperature

Figure 10 shows the detail of the porous ceramic tube. An argon gas is transpired through the wall of the tube to enhance the heating of the particle.

Results

Figure 11 shows the particle temperature of the exit of the tube. It is noted that the porous tube is more effective for the heating of particle.

QUENCHING OF A CHEMICAL REACTION IN A THERMAL PLASMA TUBE FLOW

Experimental apparatus

The decomposition of carbon dioxide to carbon monoxide is used as a typical reaction to study the quenching mechanism.

The schematic diagram of the apparatus is shown in Fig. 12. The reaction tube has 8 mm i.d. and 12 cm long, and the water-cooled quenching tube has 4, 6 and 8 mm i.d. and 40 cm long. Carbon dioxide gas is injected at the inlet of the reaction tube and decomposed into carbon monoxide. Product gases are analyzed and measured by gas chromatograph to determine the conversions.

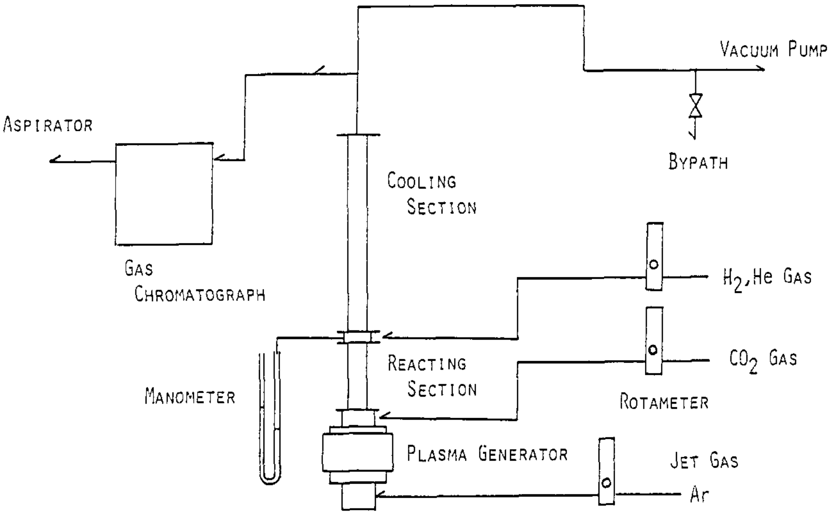

Fig. 12 Quenching apparatus

Results

Figure 13 shows the results of the conversion obtained by changing the quenching tube diameter. The conversion is higher in the smaller diameter of the tube because the higher heat transfer rate.

<Nomenclature>

D	Damkohler number
P	pressure
P.C.T.	porous ceramic tube
q	heat flux
T	temperature
W.C.T.	water-cooled tube
x	distance from tube inlet, distance from cathode tip

<suffix>

atm	atmospheric
i	initial

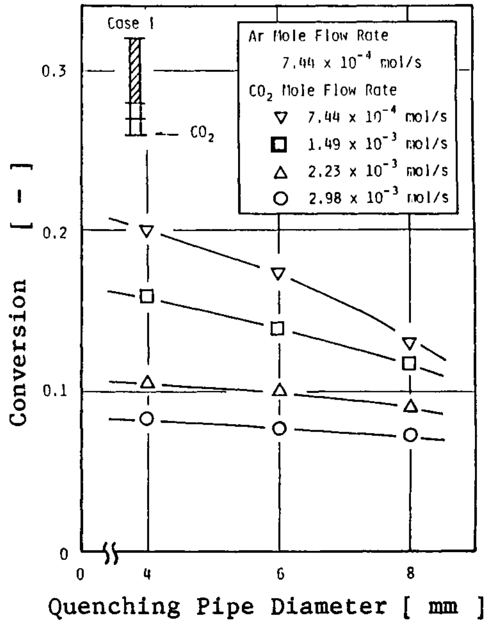

Fig. 13 Conversion to CO