Performance analysis of a supersonic plasma wind tunnel equipped with a 400 kW class segmented type arc heater

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Abstract: Performance tests on a supersonic plasma wind tunnel constructed at CBNU (Chonbuk National University) were carried out. In this facility, a segmented type arc heater was employed as a plasma source and operated at the gas flow rates of 14.0 g/s and the input power of ~359 kW for the performance test. The test result reveals that the thermal efficiency of the arc heater reached 46.4 %, which corresponds to the mass-averaged enthalpy of ~11.9 MJ/kg. For the generated supersonic plasma jet, heat flux and total pressures were also measured along the centerline of jet stream by using a Gardon gauge and an enthalpy probe, respectively. From the measured data, the generated supersonic plasma jet can transfer an average heat flux of 7.7 MW/m² to the target materials due to the high local enthalpy of the supersonic plasma jet higher than 15 MJ/kg.

Keywords: supersonic plasma, heat flux probe, enthalpy probe, plasma wind tunnel

1. Introduction

As described dramatically in the movies treating space exploration, a spacecraft is subject to be wrapped in hot flames (> 3000 K) due to the aerodynamic heating during its re-entry to the Earth[1]. As a basic research facility for exploring the aerodynamic heating phenomena, Chonbuk National University (CBNU) has constructed a small-scale plasma wind tunnel. This CBNU’s plasma wind tunnel was designed to produce a supersonic plasma jet with an enthalpy higher than 10 MJ/kg at the power level of 0.4 MW and fabricated by Tekna Co. Canada.

In this paper, we report the main performance of the CBNU’s facility in terms of heat flux transferable to the test sample, thermal efficiency of the arc heater, mass-averaged and local enthalpies produced at a typical operation condition. For example, the mass-averaged enthalpy was calculated from the thermal efficiency of the arc heater, which is defined as the ratio of the total enthalpy to the input power. However, the intrinsic interference of shock waves causes the non-uniform distributions of the local enthalpy along the supersonic plasma jet stream, which results in the different heat flux to the test sample. In order to obtain the distribution of the heat flux, the stationary heat flux probe was introduced along the plasma jet in this paper and the measured heat flux results were also used to obtain the distribution of the local enthalpies according to the well-known relation suggested by Pope et.al. [2] as follow.

\[ h_e = \frac{q}{K \sqrt{P_{tot}/R_{eff}}} \]  

In the above equation (1), the term of \( K \) in right hand side is the constant set as 368 W/(MJ/kg Pa^{0.5} m^{1.5}) for air [2] while \( P_{tot} \) and \( R_{eff} \) mean the total pressure measured at stagnation point of the probe and its effective radius, respectively. For the measurements of the total pressure, the enthalpy probe was employed in this work.

2. Experimental Details

Fig. 1 shows the picture of the CBNU’s plasma wind tunnel used in this study. As shown in this figure, the installed plasma wind tunnel mainly consists of a MW class DC power supply, a segmented type arc heater, a vacuum chamber to keep the supersonic state of the generated plasma, a gas supply cabinet to provide with the plasma forming gases and a water supply system to cool down the plasma heater and others.

Fig. 1. A picture of CBNU’s supersonic plasma wind tunnel
In the inside of the vacuum chamber (not seen in Fig. 1), a substrate manipulator with four arms is installed. These arms can take the probes for measuring the enthalpy and the heat flux transferred from the plasma to the total points of each probe. Fig. 2 (a) and (b) present the cross-section of a Gardon gauge (Medtherm, USA) and an enthalpy probe (Tekna, Canada) used to measure the heat flux and enthalpy, respectively, in this work.

As shown in Fig. 2 (a), the Gardon gauge consists of a water-cooled copper tube and the metal bulk blocking the front of the copper tube, which is connected to the thermocouples in order to measure the temperatures at the inner side of the copper tube and the center of the metal bulk, respectively. Then, the heat flux transferred from the plasma flow can be determined from the difference between these two temperatures according to the heat transfer equation. It is well-known that the enthalpy probe designed as Fig. 2 (b) is very useful for measuring the velocity, enthalpy and the gas composition of the plasma jet, simultaneously [3]. In the diagnostics of supersonic plasma jet, however, the enthalpy probe has a limit in obtaining the velocity of the plasma jet because it can measure the total pressure only through the central tube due to its water-cooling jacket as shown in Fig. 2 (b). In supersonic plasma jet, the static pressure is normally different from the chamber pressure, and accordingly, the dynamic pressure cannot be extracted from the measured total pressure. In addition, it is also difficult to measure the local enthalpy of the supersonic plasma jet due to the shock wave formed in front of the probe tip. In other words, the measured values indicate the enthalpy of plasma after shock wave instead of the unperturbed supersonic plasma before the shock wave. Considering these limitations in the conventional usage of the enthalpy probe, we carried out only the measurement of the total pressure by using the enthalpy probe and the obtained data were employed to estimate the local enthalpy according to Eq. (1) with the heat flux values.

The details on the experimental conditions are listed in Table 1.

### Table 1. Experimental condition for the performance test of the CBNU’s supersonic plasma wind tunnel

<table>
<thead>
<tr>
<th>Operating Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma forming gas flow rate [g/s]</td>
<td>Ar: 0.8, Air: 13.2</td>
</tr>
<tr>
<td>Operating pressure [bar]</td>
<td>Pressure of Arc Heater: 4, Pressure of Chamber: 0.04</td>
</tr>
<tr>
<td>Input power [kW]</td>
<td>−359</td>
</tr>
<tr>
<td>Total Current [A]</td>
<td>350</td>
</tr>
</tbody>
</table>

### 3. Results and Discussion

We measured the input power and heat loss to cooling water by using the PLC (Programmable Logic Controller) system. From the PLC record, the heat loss to cooling water including both of arc heater and the Laval nozzle was measured as 192 kW, which is referred to the arc heater efficiency of 46.4% for the input power of 359 kW. According to the definition of arc heater efficiency, $\eta$, these values of input power and arc heater efficiency result in the mass-averaged exit enthalpy of 11.9 MJ/kg for the gases with the gas mass flow rate of 14.0 g/s.

Fig. 3 presents the measurement results obtained along the centerline of plasma jet from $z = 165$ mm to $z = 85$ mm. Here, the values of $z$-axis mean the distances away from the nozzle exit. In this figure, one can see that the measured heat fluxes were undulated around the average heat flux of 7.7 MW/m$^2$ along the plasma jet. This undulation indicates that the shock waves can have an effect on the jet stream away from the nozzle.

![Fig. 3 Heat fluxes measured by Gardon gauge along the centerline of the supersonic plasma jet from $z = 165$ mm to $z = 85$ mm. The plasma jet was generated at the input powers of 350 kW and the gas mass flow rate of 14.0 g/s.](image)
Fig. 4 shows the distribution of total pressure obtained along the centerline of plasma jet by the enthalpy probe. In this figure, one can see that the measured total pressures were decreased from $z = 85$ mm to $z = 125$ mm and increased from $z = 85$ mm to $z = 165$ mm. As predicted in Fig. 4, this distribution of total pressures results from the deceleration and acceleration of the plasma jet in the compressed and expanded zones, respectively, due to the interference of shock waves.

Finally, each value of the measured heat fluxes and the total pressures in Fig. 3 and 4 can be used to find the local enthalpy of the supersonic plasma jet at the measured position. By substituting the measured heat flux and total pressure of 7.88 MW/m² and 57.9 kPa at $z = 145$ mm, respectively, and the value of $R_{eff}$ corresponding to 2.3 times the radius of enthalpy probe of 12.7 mm into Eq. (3), for example, the local specific enthalpy can be calculated approximately as $\sim 16.3$ MJ/kg. As investigated in other papers [2], the local enthalpy of the supersonic plasma jet has a maximum value at the centerline due to the parabolic distributions of radial local enthalpy, and accordingly, the measured value should be larger than two times the mass-averaged enthalpy if the heat loss by radiation and radial diffusion are negligible at downstream. Compared with the mass-averaged enthalpy of 11.9 MJ/kg, this value of $\sim 16.3$ MJ/kg is as $\sim 1.4$ times the mass-averaged enthalpy, then, the generated supersonic plasma jet seem to experience not only a heat loss but also radial diffusion at downstream ($\geq z = 85$ mm).

**Conclusion**

In this work, we conducted a performance analysis on the CBNU’s supersonic plasma wind tunnel with a 400 kW class segmented type arc heater. From the basic performance test, thermal efficiency of 46.4 % can be achieved at the input power of 359 kW and gas flow rate of 14.0 g/s, which was attributed to the mass-averaged enthalpy of 11.9 MJ/kg. In addition, heat fluxes and the total pressures were measured along the generated plasma flow by using a Gardon gauge and an enthalpy probe, respectively. The measurement results revealed that the generated supersonic plasma jet can transfer an average heat flux of 7.7 MW/m² to the target materials due to the high local enthalpy of the supersonic plasma jet higher than 15.0 MJ/kg.

**References**


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