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Velocity measurement in critical flow nozzle and its response using recovery temperature anemometry (RTA)

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Abstract

Gas flow measurement is indispensable for social activities. Critical flow nozzles used for flow standards have been improved in ISO 9300 in 1990 and 2005. However, there are still issues regarding their rational shape. The main reason is that it is difficult to measure the flow velocity in the nozzle with low disturbance and high accuracy, although various velocity measurement methods have been proposed.

In this paper, we developed a recovery temperature anemometry (RTA) to measure the flow velocity from micrometer-order temperature sensors. The validity of RTA was verified through experiments and numerical simulations. It was confirmed from the experimental results that the difference between RTA and the reference was within 5% in the velocity range from 60 to 95 m/s. The supersonic flow in the critical flow nozzle measured using RTA agrees with the numerical simulations. In addition, the sensor part of the thermometer has a small heat capacity, and a test to confirm the temperature response was also conducted. As a result, a temperature response of about 30Hz was confirmed.

1. Introduction

Gas flow measurement is used in a wide range of fields and is an essential part of social activities. In Japan, critical flow nozzles are commonly used as transfer standards for gas flow standards. Although the utilization of nozzles is described in ISO 9300 [1], there are still issues [2] regarding the design of reasonable shapes due to the difficulty of measuring flow velocity in the nozzle.

In this study, we focused on the method (RTA, Recovery Temperature Anemometry) proposed by Ishibashi et al [3] to measure flow velocity from a micrometer-order thermometer and conducted flow velocity measurement experiments using RTA. Furthermore, the time response of the thermometers was verified from simple experiments, and the time response of RTA was estimated.

2. Flow velocity measurement using RTA

2.1 Measurement principle of RTA

Because of the effect of thermal diffusion in gas flows where the Prandtl number is less than 1.0, the wall surface temperature of an object that does not impede flow exhibits a smaller value than the stagnation temperature T_0 (Equation (1)). This temperature is called the recovery temperature T_r (Equation (2)) where M, γ and r denote the Mach number, specific heat ratio, and recovery temperature coefficient respectively. Since this temperature difference is proportional to the square of the mainstream flow velocity, it is possible to measure the flow velocity based on the temperature field. In this paper, recovery temperature coefficient of 0.83 was used for probe-type thermometers. The sensor diameter of thermometers used in this study is about 300 μm, which enables the realization of flow velocity measurement with high spatial resolution without disturbing the flow.

$$\frac{T_0}{T} = 1 + \frac{\gamma - 1}{2} M^2 \quad (1)$$

$$\frac{T_r}{T} = 1 + r\frac{\gamma - 1}{2} M^2 \quad (2)$$

2.2 Comparison between RTA and reference standard

In this experiment, two types of thermometers were used for recovery temperature measurement: the thermocouple and platinum thermometer. The diameter of each sensor is approximately 300 μm. Figure 1 shows the thermocouple used. Figure 2 shows the results of evaluating the accuracy of RTA with a flow velocity reference with an expanded uncertainty of 0.63% owned by NMIJ. For detailed experimental conditions, please refer to [4] [5] [6]. Each measurement was taken three times, the plots represent mean values, and the error bars represent standard errors. Figure 2 shows that the maximum difference between the reference value of the flow velocity and the value measured by RTA is about 30% near the 40 m/s, and the standard error is also large compared to other flow velocity points. This is due to the small difference (about 0.13 °C) between the stagnation temperature T_0 and the recovery temperature T_r in the flow velocity of 40 m/s. In the range of flow velocity from 60 to 95 m/s, the temperature difference between T_0 and T_r extends to about 0.75 °C, and the difference between the reference value of flow velocity and the value measured by RTA is within 5%. Therefore, RTA is expected to have high measurement accuracy in the range where the flow velocity is large, i.e., where the temperature difference between T_0 and T_r is large.

2.3 Measurement of flow velocity in critical flow nozzle

An overview of the experiment to measure the flow velocity in the critical flow nozzle is shown in Figure 3. A quarter-circle nozzle (diameter: 13.4 mm) without a diffuser with a known discharge coefficient is installed. A vacuum pump is used to provide sufficient differential pressure at the nozzle to generate a sonic flow at the throat. The thermometer installed upstream of the nozzle calculates the stagnation temperature T_0. The same thermocouple or platinum thermometer as in 2.2 was installed downstream of the nozzle to measure the recovery temperature T_r. The velocity distribution downstream of the throat was calculated from T_0, T_r, equations (1) and (2). To validate the experimental results, unsteady three-dimensional numerical simulations were also performed using the software of OpenFOAM [7]. Figure 4 shows the analysis domain. In the simulations, although the nozzle geometry has the same dimensions as in the experiment, it does not accurately reproduce the geometry of the experimental system upstream and downstream of the nozzle. For example, a rectification section is provided downstream of the nozzle to equalize the flow velocity and to reduce the number of meshes. The upstream pressure and the pressure inside the nozzle were set to 101 kPa and the back pressure ratio to 0.4. The average value of the flow velocity after 0.005 seconds was used as the calculation result. The time variation of the mass flow rate at each back pressure ratio is shown in Figure 5 for reference.

Figure 6 shows the results of traverse measurements from the center of the throat to x_{axial} = 25 mm in the downstream axial direction. The back pressure ratio in both the experiment and the numerical simulation is 0.4. The RTA and numerical simulations were in good agreement up to x_{axial} = 10 mm, and the validity of the RTA was confirmed even in the supersonic region where the flow velocity increased to about 420 m/s. The flow velocity decreases after x_{axial} = 7 mm, and the shock wave phenomena generated in the nozzle

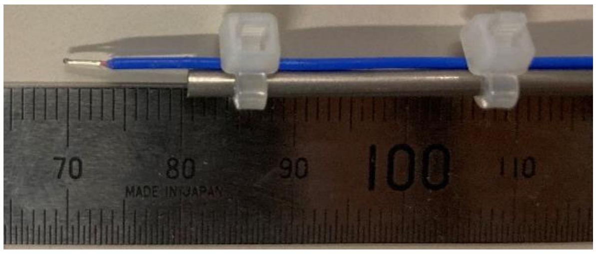

Figure 1: Thermocouple used in experiments (Wire diameter: approximately 300 μm).

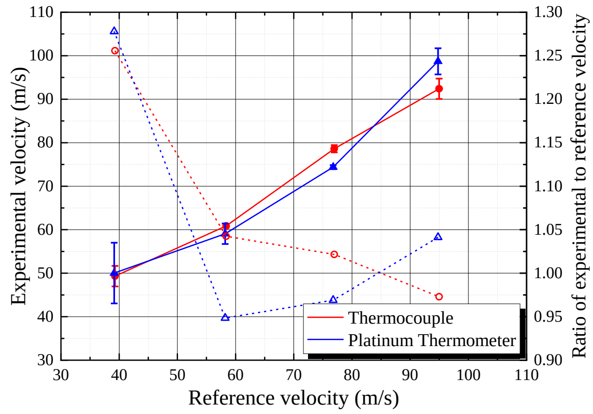

Figure 2: Comparison results between RTA and reference velocity.

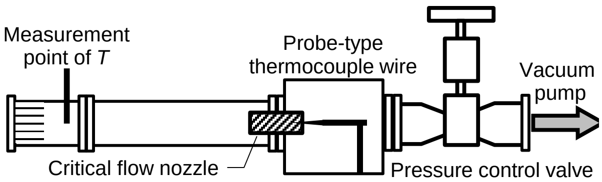

Figure 3: Overview of experiment to measure flow velocity inside critical flow nozzle.

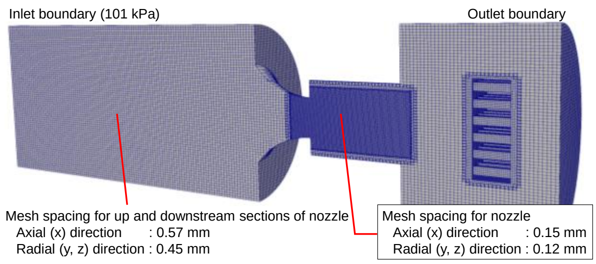

Figure 4: Simulation area (left: inlet, right: outlet).

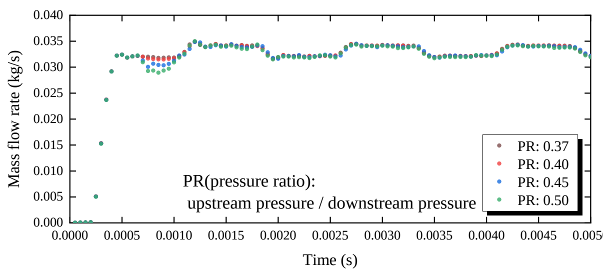

Figure 5: Variation of mass flow rate in numerical simulation.

can also be captured. On the other hand, a large difference in the flow velocity is observed after x_{axial} = 10 mm. The numerical simulation does not fully reproduce the space downstream of the nozzle, which may be a different pressure field at the nozzle outlet than in the experiment.

3. Experiments on temperature response of RTA

Understanding the responsiveness of RTA is important when considering the utilization. Since it is difficult to generate accurate turbulent flow, simple experiments were performed to evaluate the response of RTA from the response of the thermometers. The thermocouple and platinum thermometer used in Chapter 2 were rapidly inserted into a high-temperature bath at 100°C and temperature changes were recorded. In this study, 90% response time is used as the response characteristic. Figure 7 shows the experimental results. The 90% response time is about 30 msec for both thermometers.

A comparison between the tests conducted by Hoshi et al. [8] and the present experiments is shown in Figure 8. In the study by Hoshi et al. [8], the response of thermocouples was reported to be proportional to the 1.03 to 1.34 power of the wire diameter, and it can be seen that the present results are also in harmony with those of Hoshi et al [8]. Note that a rigorous discussion of the above proportionality requires consideration of the thermal conduction properties of the thermometer and the fluid. Since the 90% response time of the thermocouple and platinum thermometer used in this study is about 30 msec, it is estimated to have a response time of about 30 Hz with respect to flow velocity measurement. The use of smaller temperature sensors is expected to improve the response time. It is noteworthy that the flow velocity measurement with high resolution and high response can be easily performed using a commercially available thermometer.

4. Conclusion

In this paper, we developed RTA to measure the flow velocity from micrometer-order temperature sensors installed at two points without disturbing the flow in a micro space. From the experimental results, it was confirmed that the difference between the RTA and the velocity reference was within 5% in the flow velocity range from 60 to 95 m/s. In the 10 mm range downstream of the nozzle throat, the supersonic flow measured using RTA agreed well with the results of the 3D numerical simulation. In addition, we also conducted responsiveness confirmation experiments for

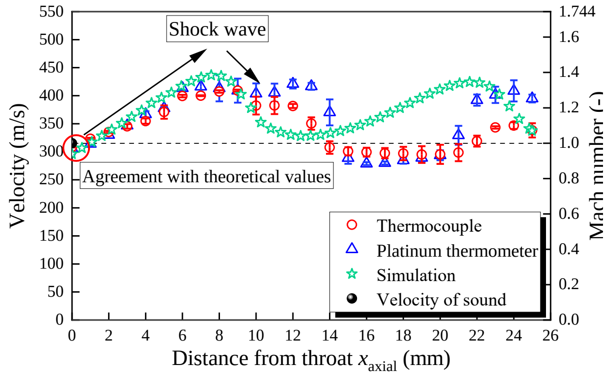

Figure 6: Axial velocity distribution from the center of the throat to 25 mm downstream.

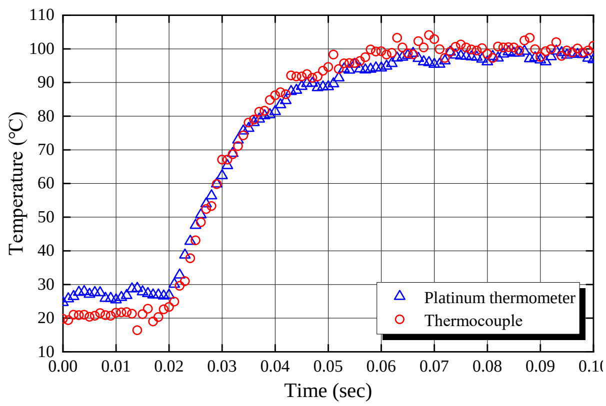

Figure 7: Time response of thermometer.

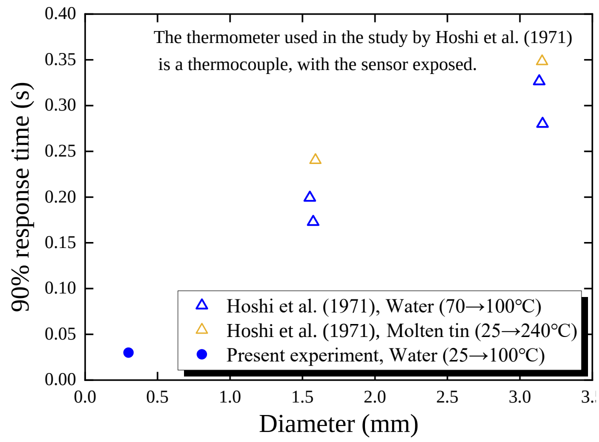

Figure 8: Relationship between wire diameter of thermometer and response time.

thermometers. As a result, a temperature response of about 30 Hz was confirmed, and it is expected to be applied to turbulence measurement. As a future prospect using the RTA, since the measurement range of the thermocouple extends to the high temperature range, it is considered to be applicable to the high-enthalpy flow that is characteristic of the aerospace field.

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Acknowledgements

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