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Development of Performance Test Rig for Heat Exchanger of a Supersonic Regenerative Cooling Combustor

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Abstract

A performance test rig for heat exchanger of a supersonic regenerative cooling combustor was developed in Korea Aerospace Research Institute. The 500 hp compressor was used to supply air of more than 2 bar and the air was heated through two electric air heaters, which had a capacity of 300 kW and 400 kW, respectively. Max. air flow is about 0.7 kg/s and max. air temperature is about 600 °C. The heated air is accelerated up to Mach 2 with supersonic nozzle. A preliminary performance test was carried out with heat exchanger of a supersonic regenerative cooling combustor model at Mach 2 air flow and air temperature was varied from 300 to 500 °C. And room temperature water was supplied as a fuel and coolant of heat exchanger instead of real fuel for safety reason.

Keywords: Supersonic Combustor, Regenerative Cooling Test Rig, Heat Exchanger

1. Introduction

The high-pressure turbine of the gas turbine engine is operated at a temperature of more than 1,500 °C. For stable operation of hot section, the turbine is cooled by air supplied from the rear of the compressor. In scramjets, however, the air temperature behind the compressor is heated up to 1,000 °C, making it difficult to utilize for cooling. In order to solve this problem, the regenerative cooling technique has been applied to the US X-51A. Regenerative cooling is a method of cooling the combustor wall with fuel, and it is possible to increase combustion efficiency as the temperature of the fuel utilized for cooling increases.

The Korea Aerospace Research Institute (hereinafter referred to as KARI) is working with the Korea Research Institute of Standard and Science (hereinafter referred to as KRISS) and the Korea Institute of Energy Research (hereinafter referred to as KIER) to develop supersonic regenerative cooling combustor technology with a combustor inlet flow of Mach 2 or higher. KARI is conducting design and experiment of supersonic combustor and heat exchanger, KRISS is developing accurate measurement technique and KIER is studying carbon fiber composite technology for light weight of supersonic combustor. In this paper, only the contents of the rig development and test run results will be discussed.

2. Main

2.1. Development of Test Rig

For the development of regenerative cooling technology, KARI was in charge of designing and testing supersonic combustors and heat exchangers. Prior to the final test of the supersonic combustor, the

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heat exchanger was tested to determine the performance of regenerative cooling. The following design requirements were derived for the design of the heat exchanger's test rig.

1. Combustor Test Only (without Intake and Nozzle)
2. Direct-Connected Type
3. Test Duration = Continuous
4. Test Article Size = 70 mm (W) x 32 mm (H)
5. Combustor inlet Mach number ≈ Mach 2.0
6. Total Pressure: More than 2 bar (Absolute)
7. Easy to Optical Access

Since the research is underway with the goal of developing a heat exchanger for regenerative cooling, the intake and nozzle parts of the scramjet engine are not subject to research. For this reason, only the supersonic combustor should be tested, and since there is no intake, the test should be performed in the test equipment of direct connected type. In order to confirm the phenomenon due to heat transfer during the test, the test time should be sufficiently long, and the application of a test specimen of 70 mm (W) x 32 mm (H) shape should be possible. As for the shape of the test body, the shape of the supersonic combustor under development was applied. Since the inlet Mach number of the supersonic combustor under development is about Mach 2.0, similar speeds were simulated in Mach 2.0 in the test league, and the total pressure of the air supplied to simulate the speed similar to Mach 2.0 was 2 barA or more. Finally, in addition to the heat exchanger test in the test facility, fuel injection test is also planned, so optical access should be convenient. So, we considered the test at the Scramjet Combustor Test Facility (SCTF) where a supersonic combustor with actual regenerative cooling was tested.

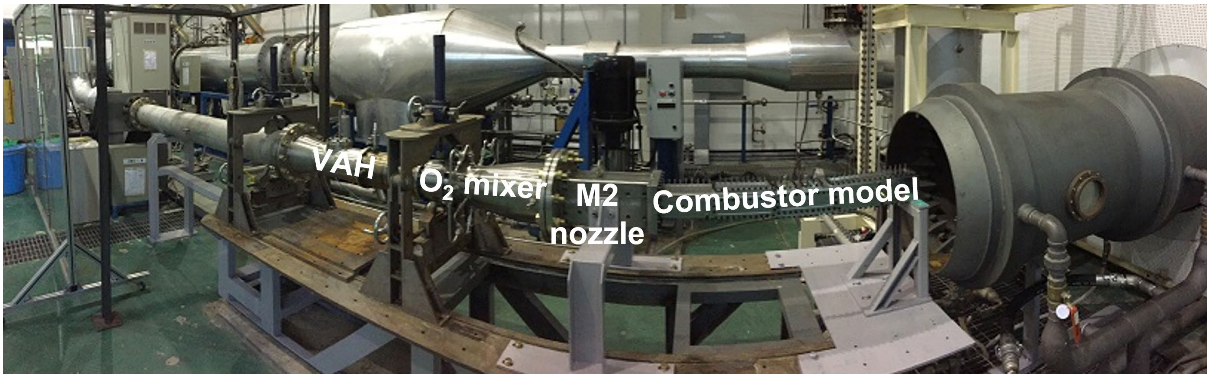

Fig. 1 Scramjet Combustor Test Facility

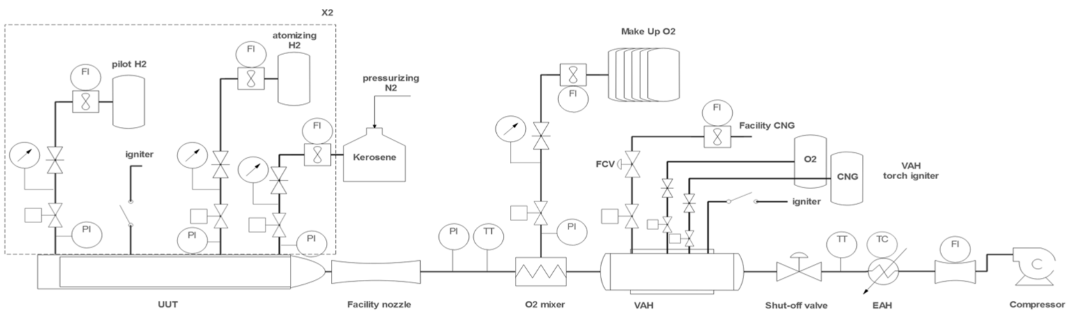

Fig 1. Schematic of Scramjet Combustor Test Facility

The figure above is an illustration of the SCTF where the actual test was conducted. A compressor of 2250 HP is installed to supply air, and two electric air heaters (hereinafter referred to as EAH) and one Vitiation Air Heater (hereinafter referred to as VAH) are applied to simulate the high temperature of supersonic air flow. The 2250 HP compressor can supply about 4 barA of air and has a flow rate of 1 kg / s. Each of the two EAHs has a capacity of 1.2 MW, so that the supplied air can be primarily heated to about 600 K. VAH is driven by LNG as a fuel, and becomes an ignition by a torch using CH_4. At the rear of the VAH, an O_2 supply system and an O_2 mixer are applied to compensate for O_2 consumed during combustion of the VAH. Finally, air heated to 1,300 K or more through VAH is accelerated to Mach 2.0 through M2 nozzle and supplied to the combustor model behind the nozzle. The Combustor Model is equipped with an optical window for measuring the combustion phenomenon with a laser, and is designed to easily test by replacing the heat exchanger.

SCTF satisfies all the design requirements of the heat exchanger test rig. However, during the test, about 1.7 MW of electric power was required to drive the compressor, and about 2.4 MW of electric power was required to drive the EAH, and a total of 4 MW of electric power was required. In addition, a total of 5 test personnel were required, including data acquisition and facility control. In order to simply perform the performance test of the heat exchanger, a lot of resources were needed, so a small test facility was needed to test with a small capacity and a small number of people.

The requirements for the design of the test rig of the heat exchanger for regenerative cooling were newly defined as follows.

1. Combustor Inlet Mach Number: Mach 2.0
2. Air flow = 0.7 kg / s
3. Air Temperature: more than 200 ℃
4. Fuel Pressure: more than 40 barA

The inlet Mach number and air flow of the test model to be equipped with the heat exchanger were defined in consideration of the combustor inlet Mach number and air flow of the supersonic combustor to which regenerative cooling is being considered. A 500 HP class compressor was selected to satisfy the Mach 2.0 combustor inlet Mach number and air flow of 0.7 kg / s. The air temperature was defined as 200 ° C or higher, and since the performance of the heat exchanger was simply compared during the test, a temperature lower than the temperature at which the actual supersonic combustor was operated was selected as the test condition. EAH having a capacity of 300 kW and 400 kW was selected to heat the air flow of 0.7 kg / s to a temperature of 200 ° C or higher. EAH of 300 kW and 400 kW can be driven and controlled respectively, and when both EAHs are operated, air of about 500 ° C or higher can be supplied. The fuel pressure was defined as the design requirement of a high 40 barA pressure in consideration of an increase in the pressure of the heated fuel due to heat exchange when the actual supersonic combustor is operated in the future. The conceptual design results for test rig that can implement these design requirements are as follows.

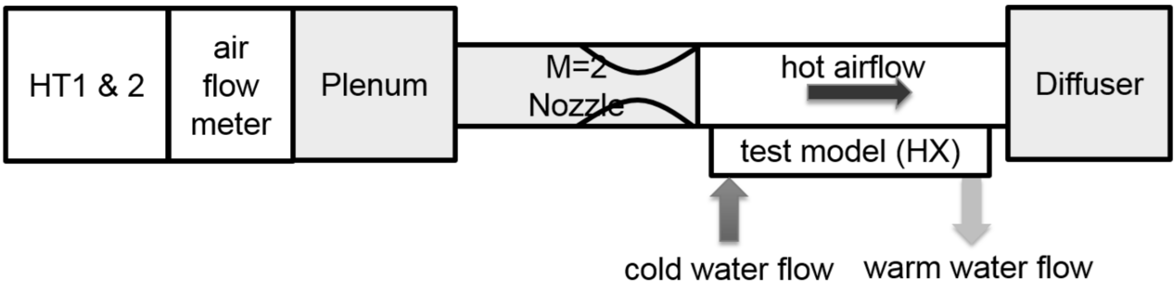

Fig 2. Conceptual Design of New Test Rig for Heat Exchanger

The test rig was designed to operate in three types of modes. The first mode is the spray visualization test of hot fuel. The fuel can be heated through a coil-type heat exchanger installed in a straight pipe in front of the supersonic nozzle, and the fuel line branched in front of the fuel spray position before the test to prevent a decrease in fuel temperature due to heat transfer in the fuel line. Through the operation of the valve, the heated fuel can be injected into a hot airflow accelerated by Mach 2.0. However, considering the danger of the heated fuel, in the initial test, the facility was configured to supply water instead of fuel.

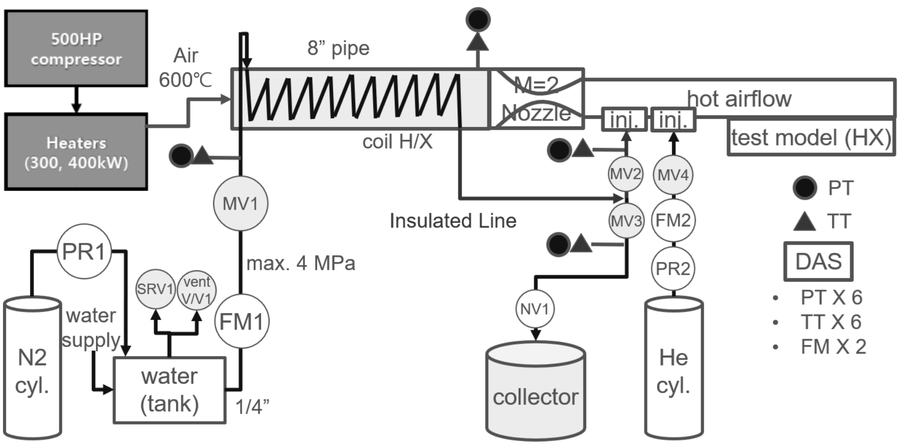

Fig 3. Mode 1 of New Test Rig for Heat Exchanger

The second mode is the spray visualization test of room temperature fuel. The difference between the spray visualization test rig of room temperature fuel and high temperature fuel is whether or not to use a coil-shaped heat exchanger installed in front of the supersonic nozzle. In the room temperature fuel test rig, the fuel at room temperature without going through the coil heat exchanger was configured to be supplied to the test section.

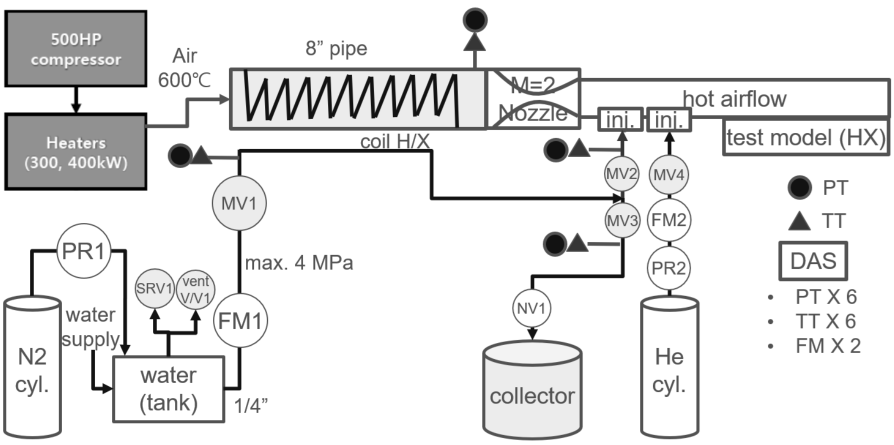

Fig 4. Mode 2 of New Test Rig for Heat Exchanger

The last mode is a rig for the performance test of the heat exchanger for regenerative cooling. Since it is a rig for testing the performance of a heat exchanger, it is possible to supply fuel at room temperature without controlling the temperature of the supplied fuel, and heat exchanger is heated to 500 ℃ to measure the amount of heat exchanged with the supplied air. A sensor that can measure pressure and temperature was applied to the fuel outlets.

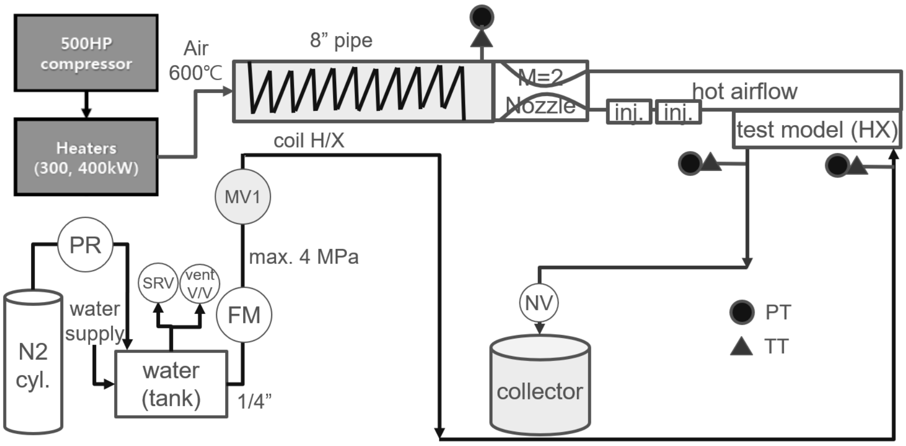

Fig 5. Mode 3 of New Test Rig for Heat Exchanger

The below is a picture of the actual test model and rig. A water supply tank was installed to supply water instead of fuel, and the water supply system was constructed in a pressurized manner. The heat exchanger for regenerative cooling was manufactured in a plate shape to be installed on the wall of a supersonic combustor, and a port capable of measuring pressure and temperature was applied to the inlet and outlet where the coolant is supplied. A coil-type heat exchanger was applied to the straight pipe located in front of the supersonic nozzle to heat the fuel with air at 400~500 ° C.

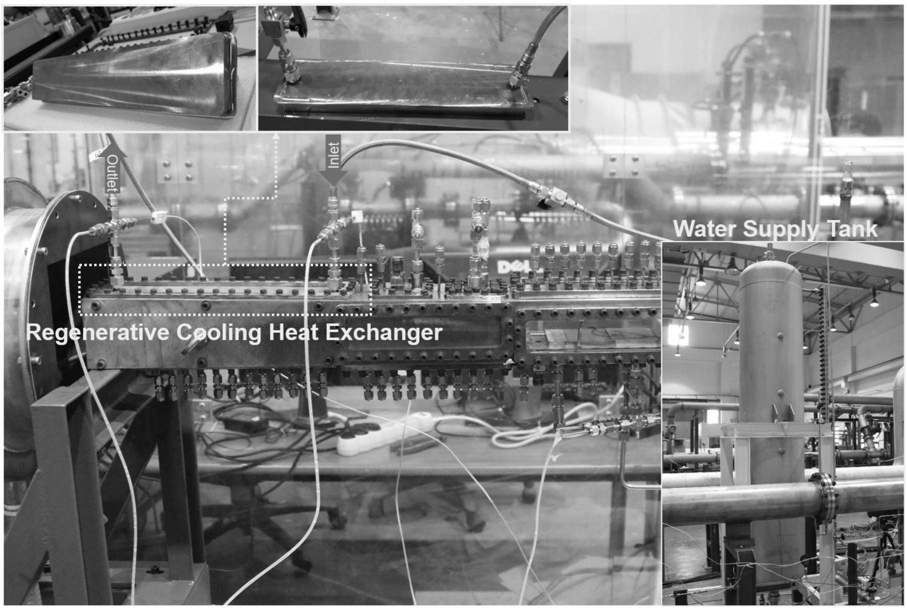

Fig 6. Test rig of Heat Exchanger for Regenerative Cooling

2.2. Preliminary Performance Test

The test results were analyzed using the following equation.

$$Q = \dot{M}_{cold} \times Cp_{cold} \times \ Delta\ T \quad (1)$$

Here, Cp_{cold} is taken from Yunus A. Cengel's "Heat Transfer". The test conditions were selected as follows.

Table 1. Test Conditions

Air Temperature [℃]	Pressure [bar]	Fuel Flow [g/s]
300	5	5
400	10	10
500	15	15

The performance test of the heat exchanger was performed according to the test conditions, and the test results are shown in the graph and table below.

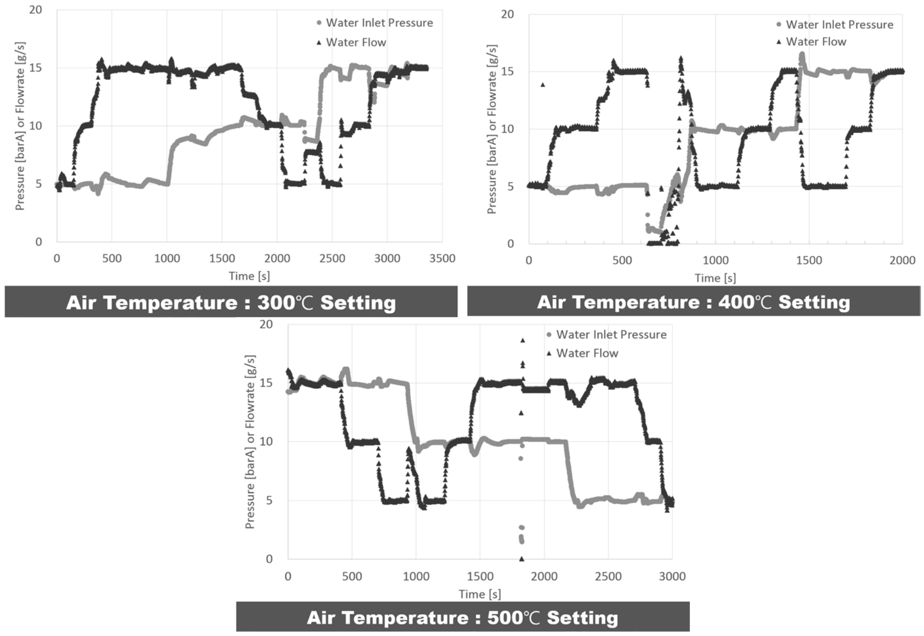

Fig 8. Test Results of Heat Exchanger with Heated Air

Table 2. Test Results of Heat Exchanger

Test No.	Air Temperature [°C]	Water Pressure [barA]	Water Flow [g/s]	Delta T [°C]	Deviation of Delta T
1			5	77.98	0.47
2		5	10	46.51	0.42
3			15	30.31	0.14
4			5	83.02	1.23
5	300	10	10	48.35	0.16
6			15	30.74	0.37
7			5	84	4.06
8		15	10	50.14	0.22
9			15	31.98	0.1
10	400	5	5	90.66	60.91

11			10	60.57	0.25
12			15	38.43	0.11
13			5	107.47	1.06
14		10	10	64.34	0.86
15			15	40.15	0.17
16			5	108.49	1.07
17		15	10	65.44	0.79
18			15	40.4	0.12
19			5	-	-
20		5	10	77.91	1.09
21			15	49.02	0.2
22			5	135.72	3.48
23	500	10	10	77.09	0.81
24			15	47.88	0.13
25			5	137.91	3.04
26		15	10	74.38	0.45
27			15	45.2	0.5

The test of supplying air at 500 ° C and water at a flow rate of 5 g/s with 5 barA was not performed. All the water supplied was immediately vaporized as a small amount of water was supplied, and the pressure of the water supply pipe increased due to this. Among the above result tables, there are test results showing one special value. At the results of test 10, the deviation of delta T was 60.91, showing a very high value. This means that there was fluctuation in the outlet pressure of the supplied water, and this phenomenon is thought to be due to the simultaneous presence of water and water vapor under the corresponding conditions. Based on the above test results, various analyzes have been performed, and the results are as follows.

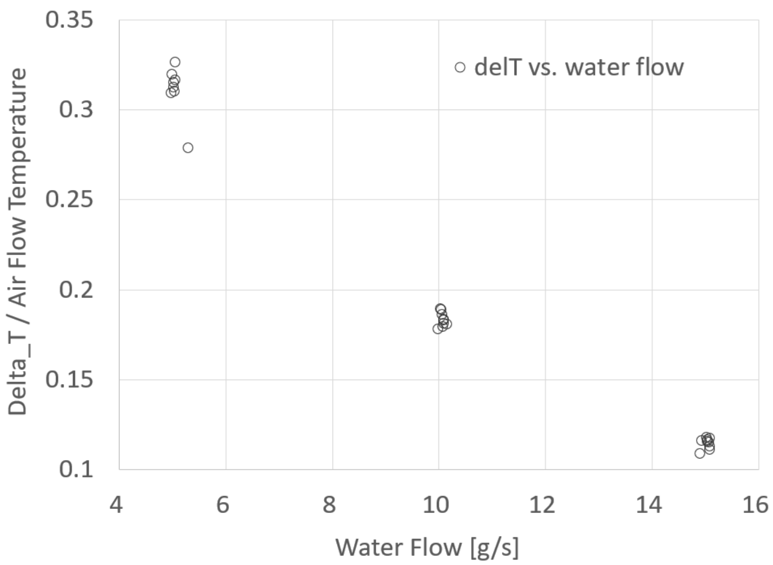

Fig 9. Performance of Heat Exchanger

Figure (9) is a graph that analyzes how the temperature difference changes depending on the pressure of the supplied water. Looking at the figure, it can be seen that delta T is similar if the flow of water supplied is similar. Through this, it was found that the temperature difference is related to the flow rate of the supplied fluid. Judging from the test result values shown above, the pressure of the supplied fluid does not significantly affect the temperature difference compared to the flow rate, but it affects the boiling point of the fluid.

Based on the previously measured test results, the heat transfer coefficient was calculated. The heat transfer coefficient was calculated by the following equation.

$$\mathrm{Q_{tot}} = (\dot{M}_{cold}) \times (Cp_{cold}) \times (T_{cold\_out} - T_{cold\_in}) \tag{2}$$

$$\mathrm{Q_{tot}} = hA(T_{hot\_aw} - T_{cold\_avg}) \tag{3}$$

In the above equation, A is the heat transfer area. Assuming the inside of a heat exchanger composed of a rectangular cooling channel as shown in the figure below, A can be calculated as follows.

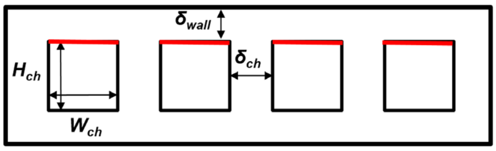

Fig 7. Cooing Channel

$$\mathrm{A} = \mathrm{W_{ch}} \times H_{ch} \times N_{ch} \tag{4}$$

In the above equation, N_{ch} represent the heat transfer channel number. And T_{hot_aw} can be calculated by assuming the adiabatic wall temperature as follows.

$$\mathrm{T_{aw}} = T_g\left[1 + (Pr_g)^{\frac{1}{3}}\left(\frac{r-1}{2}\right)M^2\right] \tag{5}$$

In the above equation, Pr_g is the number of Prandtl of Air and has a value of 0.71. The Mach number can be calculated from the total pressure and static pressure values at the supersonic nozzle exit. The Mach number calculated as above is not the same as the combustor inlet Mach number because it is the Mach number of the supersonic nozzle exit. However, the difference was assumed to be negligible. T_g was calculated as follows.

$$\mathrm{T_g} = \frac{T_t}{1 + \frac{(\gamma-1)M^2}{2}} \tag{6}$$

In the above equation, Tt is assumed to be combustor inlet temperature. In the test model, the temperature at the inlet and outlet may be different due to the heat loss in the model, but it is assumed that the heat loss value is not large and the temperature in the entire test model is the same. T_{cold_avg} was calculated as follows.

$$T_{cold\_avg} = \frac{T_{cold\_in} + T_{cold\_out}}{2} \tag{7}$$

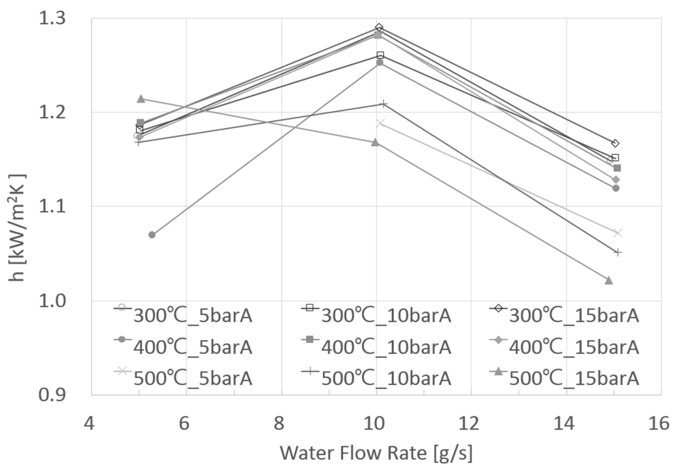

Fig 8. Heat Transfer Coefficient

As can be seen from the calculation results, the heat transfer coefficient does not increase in proportion to the flow rate of the supplied fluid, but shows the maximum value from the intermediate value. These results will be reflected in the design of the heat exchanger in the future and can be used for design optimization.

3. Summary and Conclusion

A test rig was developed to carry out the performance test of the heat exchanger of a supersonic regenerative cooling combustor and the preliminary performance test was performed. The test rig was configured to supply fuel at various pressures and flow rates, and preliminary performance tests were conducted with water instead of fuel for safety reason. It was confirmed that the heat transfer coefficient does not increase in proportion to the flow rate of water supplied instead of fuel, and this result can be used to optimize the design of the heat exchanger. In the future, tests will be conducted using actual fuel instead of water, and a pump will be applied to utilize a system that can control the flow rate regardless of fuel pressure.

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