Development of the fuel heating device for the component test of aerospace propulsion systems

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Abstract
For the next generation space launch vehicle, fully reusable spaceplane with rocket and ramjet combined propulsion system is proposed. That type of spaceplane can drastically reduce the cost per unit mass of the payload. One of the main technical challenges of the spaceplane is the propulsion system. Thus, many component tests have been carried out using hydrogen as fuel. On the other hands, in these days, some of the projects uses hydrocarbon (HC) fuel, because of the ease of treatment, and the high density Isp performance. Because of these backgrounds, pressurized high temperature HC fuel feeding device for the component tests of space propulsion system is required to simulate re-generative cooling. We started to develop the fuel heating device aiming to feed ethanol at supercritical condition for the component tests of the RBCC engine. The device is needed to heat up the fuel higher than 520 K and pressurize the fuel higher than 7 MPa. In the development process, we experienced some troubles, but we improved the composition of the fuel heating device, and most of the troubles were settled. We achieved the main goal of the development, to feed supercritical ethanol (7.5 MPa, 520 K at the exit of fuel heating device) to the test equipment of the dual-mode ramjet combustor. In this paper, we report the construction of the developed fuel heating device, the detail of the troubles and countermeasures, the result of the unit tests and the result of an actual use test.

Key words: Rocket, Scramjet, Hydrocarbon, Supercritical fluid, Combustion

1. Introduction
An integrated rocket and ramjet propulsion system i.e., rocket based combined cycle (RBCC) engine, with hydrocarbon fuel is proposed for the next generation space launch vehicle. The RBCC engine uses air as a part of oxidizer at flight Mach number 0 to 12. The oxidizer accounts for 50 to 80 % of the propellant mass of the conventional rocket powered space launch vehicle (Sutton, 2001). Thus, the RBCC engine can reduce the loaded propellant mass. In addition to this, more than two thirds of the propellant tank volume is accounted by the fuel for the liquid oxygen/liquid hydrogen propulsion systems. Then, the hydrocarbon (HC) fuel is proposed to reduce the tank volume. Hydrocarbon fuel has lower Isp performance of rocket propulsion system (about 280 to 350 sec.) than that of hydrogen (higher than 400 sec.), but the density of HC is high as ten times as that of hydrogen. Thus, the density Isp performance of HC fuel is higher than that of hydrogen. In other words, the fuel tank volume of the spaceplane using HC fuel is smaller than that of the spaceplane using hydrogen. For these reasons, the spaceplane using HC fueled RBCC engine reduces the propellant mass and volume per payload. The loaded propellant mass and volume have big influence on the performance of the spaceplane; because the loaded propellant occupy most of take-off mass and internal volume of the launch vehicle. Thus, to reduce the loaded propellant is one of the most important technical challenges of fully reusable spaceplane.

Many component tests of the RBCC have been running with this background (Tomioka, et al., 2014). Most of these tests used the hydrogen or ethylene in room temperature as the propellant (Nojima, et al., 2014a, 2014b). However, the
propellant in actual system would be liquid HC namely ethanol (Yoshida, et al., 2009). And, in actual system, the integrated rocket combustor and airflow pass (ramdact) were cooled by the propellant. In other words, the propellant flows in some sections of the RBCC components as a pressurized high temperature fluid. Thus, some of the component tests should use high temperature and high pressure fuel to simulate re-generative cooling.

For this reason, we started to develop a simple and safe fuel heating device for the component test of the aerospace propulsion systems. The main goal of the fuel heating device is to feed ethanol at supercritical condition (The critical point of ethanol is 6.3 MPa, 513 K). To satisfy the main goal, the fuel heating device needs to pressurize the fuel higher than 7 MPa and to heat up the fuel higher than 520 K. The specifications of the heating device drawn out from the goal are shown in Table 1. In addition to this, our fuel heating device aimed the followings.

1. Ability for the quick start and stop of the fuel feeding for the combustion test
2. Secure durability for the faults of the connected test equipment
3. Simplicity in the structure and the operation

The work time of combustion test equipment is often restricted within some seconds, because of its huge thermal load. Then, the fuel heating device has to start and stop within the restricted duration. Also, when something fault happened during a combustion test, the fuel flow should be immediately stopped. Thus, the fuel heating device has to cope with the sudden heat load change without damage to the heating tube. We wanted to attach the fuel heating device to the combustion test facility in service. So, the device should be small enough and simple to add in the limited space. Also, the operation of the heating device should be simplified enough to reduce the additional burden of the operator.

To satisfy the goal, we investigated some types of the heating device, and the discussion was mainly held about the heating method. The fuel heating system required 200 – 300 kW class heating capacity. Some previous studies used combustion heater (Takegoshi et al., 2011) or electric heater (Meyer et al., 1998). However, their fuel heating systems were large scale and complex. As another method, heat up stored fuel in high pressure vessel was suggested. Zhong et al. used that type of fuel heating system as the preheater for the test facility of thermal cracking (Zhong et al., 2011). However, the storage tank has risks entailed in the treatment of large amount of high temperature fuel. What is more, these studies aimed to investigate the heat transfer characteristics of fuel. So, these heating systems assume the downstream of the heater connect to the catch tank or to atmosphere. However, we considered that the construction of the fuel heating device for the combustion test should be deliberated about the treatment of the failure in the downstream of heating section. In other words, when a trouble happened at the downstream of heating section, the inlet fuel flow to the heating section should be terminated, and the high temperature fuel should be dumped immediately. Then, the fuel heating system should be able to follow the quickly heating

Table 1 Target capacity of the heating device

| Fuel type               | Ethanol, Kerosene, etc. |
|-------------------------|-------------------------|
| Fuel Pressure           | MPa                     |
| Fuel Temperature        | K                       |
| Fuel flow rate          | kg/s                    |
| Duration of supply      | sec                     |
| Fuel type               | Ethanol, Kerosene, etc. |
| Fuel Pressure           | MPa                     |
| Fuel Temperature        | K                       |
| Fuel flow rate          | kg/s                    |
| Duration of supply      | sec                     |

![Fig.1 Description of original construction of fuel heating device](image)
load decreasing to protect the heater from damage by the heat input. Therefore, these methods were unsuitable for the object of our study. Finally, we selected combined heating system with heat storage heater (storage heater) and electric heated tube heater (electric heated tube) for the fuel heating system. The storage heater load the almost all of the heating load by its heat capacity, and the electric heated tube compensate the fuel temperature change caused by the temperature drop of the storage heater. Then, the device could reduce the maximum electric consumption and minimize the electric power control system. As the fuel pressurize system, we selected a gas drive pressurizing system, because of the merits such as simple construction, good durability and ease to set the fuel pressure. The original construction of the fuel heating system is shown in Fig.1.

We experienced some troubles with the original fuel heating device (Soejima et al., 2014), but almost of them were improved. Then, we started to use the fuel heating device in actual component test of a dual mode ramjet combustor.

In this paper, we describe the improvement of the fuel heating device and the result of the test run of the improved fuel heating device.

2. Nomenclature

| Symbol | Description |
|--------|-------------|
| $A$    | Tube sectional area [m$^2$] |
| $d$    | Tube inner diameter [m] |
| $L$    | Pipe length [m] |
| $\dot{m}$ | Fuel mass flow rate [kg/s] |
| $P$    | Pressure [MPa] |
| $t$    | time [sec.] |
| $T$    | temperature [K] |
| $u$    | Fuel flow velocity [m/s] |

Greek symbols

| Symbol | Description |
|--------|-------------|
| $\lambda$ | Pipe friction factor |
| $\mu$   | Viscosity [Pas] |
| $\rho$  | Fuel density [kg/m$^3$] |

Subscriptions

| Symbol | Description |
|--------|-------------|
| D      | Fuel at the downstream of the throttling orifice |
| EATank | Fuel at the Pressure fuel cylinders |
| U      | Fuel at the upstream of the throttling orifice (at the heating section) |

3. Original organization of the fuel heating device and the trouble at the first test run

The original construction of the fuel heating device is drawn in Fig.1. The fuel in the fuel tank is pressurized by the nitrogen gas. The gas pressure is set by the pressure regulating valve. The pressurized fuel flows into the heating section through the main valve and a check valve. The storage heater and electric heated tube name heating section generically. We explain the details of our fuel heating device in the Chapter 4.

On the original construction of the fuel heating device, the inlet of heating section has a check valve, and the exit of the section is restricted by the throttling orifice. However, the section did not have the vent system. Therefore, the fluid in the section could flow out through only the throttling orifice and the flow rate was limited.

For this reason, we experienced some troubles at the first test run of the fuel heating device, such as the pressure surge in the heating section. The measured pressure and temperature data are shown in Fig.2. The pressure and temperature were measured at the inlet of the throttling orifice. The conditions of the first test are shown in Table 2, the pressurize gas pressure was set up at 2.0 MPa and heating section were preheated to 550 K. However, the measured fuel pressure in heating section above the pressurize gas pressure, and the fuel temperature at the exit of heating section did not get to the heater temperature.
We supposed to the cause of these malfunctions to be the excessive inlet fuel flow just after the device starting. Although the device did not measure the inlet fuel flow rate, we calculated it using the measured pressure data. The simplified calculation model is shown in Fig.3. The control volume was assumed to be filled with the fuel before the run. The equation of motion is below.

\[ \frac{\partial u}{\partial t} = \frac{1}{\rho L} (P_0 - P_1) - \frac{\lambda L}{d} \frac{u^2}{2L} - \frac{u^2}{2L} \]  

(1)

\[ \lambda = 0.0032 + \frac{0.221}{Re^{0.237}} \]  

(2)

where, $u$ is the fuel flow velocity, $t$ is the time, $\rho$ is the density of the fuel, $P$ is the pressure, $\lambda$ is the pipe friction factor, $L$ and $d$ is the length and the diameter of the flow pass in the control volume. The subscripts 0 and 1 indicate at fuel tank and heating section. In this calculation, $\lambda$ was calculated by Nikuradse equation Eq.(2) (Matsunaga et al., 1991), where $Re$ is Reynolds number. The pressure drop at the valves was omitted because they were very small (about 0.01 – 0.02 MPa).

The fuel mass flow rate, $\dot{m}$ was calculated by Eq. (3)

\[ \dot{m} = \rho u A \]  

(3)

The initial values and fixed values of the calculation are shown in Table 3. The values of $P_1$ were measured in the test run. Figure 4 shows the result of this calculation (The beginning of the horizontal axis corresponds to the point of pressure start increasing in Fig.2). The target fuel mass flow rate of the run was 0.05 kg/s, but the actual fuel flow rate was much high.

As a result of the excessive flow rate, large amount of fuel flow into the heating section, and they were boiled up. The fuel boiling should cause of pressure increase within heating section with some delay. Then, the pressure $P_1$ increased to be higher than the upstream pressure $P_0$ and the check valve closed just after starting the sequence.

On the first design concept of the fuel heating device, we expected the fuel flow rate could be calculated from the inlet temperature and the pressure ratio across the throttling orifice, because the fuel heating device were designed to control the fuel flow rate by the throttling orifice. However, according to the foregoing, throttling orifice did not work as expectation in the starting phase of the device, and we could not measure the inlet fuel flow rate into the heating section directly.

| Table 2 Heating device setting (Subcritical condition) |
|--------------------------------------------------------|
| Fuel tank set pressure | MPa  | 2.0 |
| Storage heater initial temperature | K   | 550 |
| Electric heated tube temperature | K   | 550 |
| Throttling orifice diameter | mm  | 3.4 |

| Table 3 The assumption values to calculate fuel flow rate |
|--------------------------------------------------------|
| Initial value | |
| fuel flow velocity | m/s  | 0 |

| Fixed values | |
| Fuel density | kg/m³ | 780 |
| Fuel viscosity | μPas | 1200 |
| $P_0$ | MPa  | 2.0 |
| $L$ | m    | 2.5 |
| $d$ | m    | 0.01 |
Furthermore, at the first test, we could not depressurize the heating section freely, because the section did not have a remote operating vent system.

Then, we clarified the problems on the fuel heating device as below.

1. The inlet fuel flow rate should be measured directly at the section before the storage heater.
2. The heating section should be pre-pressurized before main fuel valve open to check the excess fuel flow.
3. The heating section should have a vent system to depressurize it freely and quickly

We investigated the countermeasure to these troubles of the heating device based on the reasoning. Finally, we decided to add three components as below

1. Turbine flow meter
2. Priming valve and throttle system
3. Remote vent valve

The schematic of the improved fuel heating system is shown in Fig.5.

The improved system is more complex than the original system. Then, we paid attention to reduce the additional operating load of operators. For example, the components were unitized by the functional unit, pressurizing section, control and measuring section and heating section. As a result of this, the system improved the maintainability, flexibly to arrange the component. And the footprint of the improved system is almost same as that of the original system. Also, to simplify the control sequence, some of the additional valve functions were automated by the pressure switch, and the electric interlock was set to stave off the trouble about the mistake of valve sequence. As a result of this, the additional crux of the sequence were excluded.

In the following Chapter 4, the constitution of the improved fuel heating device was described by the section.

4 Improved organization of the fuel heating device

4.1 Pressurizing Section

The pressurizing section is composed of pressurized nitrogen gas feeding system and pressure fuel tank.

The nitrogen gas feeding system has 4 pressurized nitrogen gas cylinders, pressure regulating valve, safety valve and pressurizing gas shut off valve. The fuel pressure is controlled by the set point of the regulating valve. Figure 6 shows the overall view of the system.

The fuel tank has 6 pressure fuel cylinders and the total tank volume is about 22.7 liter. The pressurizing gas flows into the upside of the fuel cylinders through a check valve and branch tube. And the pressurized fuel flows out from the underside of the cylinders. The exits of each fuel cylinders have a few contraction of area to equalize the fuel flow rate of the cylinders.
From this section to the upstream of main fuel valve (include the most of control and measuring section) were pressurized prior to the experiment.

4.2 Control and measuring section

The control and measuring section was composed of control valves, a turbine flow meter and a purge gas injection valve as shown in Fig.7. The control valves were 3 remote valves and a manually throttle valve. The remote valve upstream of the section was called fuel cutoff valve. It cuts the fluid flow from the fuel cylinders when the downstream of the valve are failed. Also, the valve closes when fuel cylinders are scavenged using nitrogen gas to shut the gas from the turbine flow meter. The other remote valves are set in parallel at the downstream of the turbine flow meter. One of them is called main valve, it control switching the fuel when the fuel heating device is working. Another one is called priming valve. It operates in advance to the main valve. The priming valve is set in series with a throttle valve. When the fuel heating device is actuated, the line supplies the small amount of fuel to heating section. The fuel is boiled up in the heat storage heater and it pre-pressurizes the section from downstream of the main valve to the throttling orifice. Then, the excessive fuel flow occurred in the first test run should be restrained. In addition to this, control signal for the main valve and the priming valve is interlocked with the open or closed state of the vent system in the heating section by electrical interlocks. In other words, when the vent valve is open, the main valve and the priming valve are forced to close. Then, the massive dumping of the fuel caused by mistake of control sequence was avoided.

The purge gas injection valve operates and injects the purge gas to scavenging the fuel from the heating section and vent system, when the run of the experiment finished.

4.3 Heating section and throttling orifice

The heating section is composed of the storage heater, electric heated tube and a remote vent valve with pressure switch. The storage heater has the most of heating load. And, the electric heated tube has compensation for the fuel temperature change by the temperature drop of the storage heater. The heat storage unit of the storage heater is a copper block (a 250 mm cube). The block has four stages of inner fuel channels, and they are connected by vertical holes. A part of the inner fuel channel is shown in Fig.8 a). The channel inner diameter is 12 mm and the total length is about 6 meters. The block mass is about 130 kg, and the heat capacity of the block is 50 kJ/K. The copper block was covered by a 30 mm thickness ceramic heat insulator and stainless plate. Figure 8 b) shows the aspect of storage heater. This
block is preheated by 20 × 1 kW embedded electric heaters and the electric heaters are cut before the experiment. Then, the temperature of copper block keeps on decreasing during an experiment.

The electric heated tube is a 3 meters length 1/2 inches copper tube with 6 × 1.2 kW electric heaters. These electric heaters are governed to maintain the set temperature of the tube.

The vent valve is set to depressurize the heating section quickly when the run of the experiment are finished. And, the valve operates as a safety valve when the internal pressure of heating section rise excessively. This function is controlled automatically by the pressure switch.

The throttling orifice controls the relationship between fuel pressure and fuel flow rate corresponding to the conditions of experiment.

5 Result and discussion

5.1 Unit test of the improved fuel heating device using subcritical and supercritical pressurized ethanol

At the first step, we conducted the test run to confirm whether the fuel heating device could work as expectation. At this step, the fuel heating device ran with priming valve and main fuel valve same as the actual use (the fuel heating device work with the other test equipment, i.e. scramjet combustor). However, the valve sequence was built tentatively for these tests. Then, the starting phase of the device (during the phase, main fuel valve close) runs on about 15 seconds. Also, the downstream side of the throttling orifice was directly connected to vent stack. Thus, the pressure ratio across the throttling orifice was larger than that in actual use. As a result of this, the throttling orifice would maintain choked flow in any pressurized condition of the test. Thus, we could evaluate the function of the fuel heating device separating from the effect of the downstream conditions of throttling orifice.

We carried out the unit test run at some test conditions. In these tests, fuel temperature and pressure were measured upstream and downstream of the throttling orifice. The main fuel valve and priming valve sequence was fixed in this phase. At first, the priming valve opened from 15sec to 30 sec in Fig.9. Next, the main fuel valve opened from 30 sec to 42 sec. Figure 9 show the result of a test under subcritical condition (steady heated ethanol flow was supplied from 32 to 42 seconds). The heating device setting data are shown in Table 4. Small pressure surge happened with the priming valve opening, but with the main fuel valve opening, fuel pressure and temperature became stable. On the other hand, the fuel mass flow rate fluctuated somehow. We estimated that was due to boiling of flow in the electric heated tube, because this fluctuation was not observed in the test under supercritical condition. Figure 10 shows the result of the test run under supercritical condition (steady heated ethanol flow was supplied from

| Fuel tank set pressure | MPa | 4.0 |
|-----------------------|-----|-----|
| Storage heater initial temperature | K | 460 |
| Electric heated tube temperature | K | 530 |
| Throttling orifice diameter | mm | 2.0 |

Table 4 Heating device setting (Subcritical condition)

| Fuel tank set pressure | MPa | 7.5 |
|-----------------------|-----|-----|
| Storage heater initial temperature | K | 520 |
| Electric heated tube temperature | K | 520 |
| Throttling orifice diameter | mm | 2.0 |

Table 5 Heating device setting (Supercritical condition)

Fig.9 The result of unit test under subcritical condition

Fig.10 The result of unit test under supercritical condition
32 to 42 seconds). The representative heating device setting data are shown in Table 5. Comparing with the ethanol critical point (6.3 MPa, 513 K), the measured exit condition of the tests was 6.9 MPa, 520 K. Therefore, our fuel heating device achieved the main goal. However, the fuel mass flow rate changed about 10% during the run. We estimated that the storage heater’s temperature drop caused the flow rate change. That is, the decrease of the flow resistance to attendant on volume expansion by the heating caused the flow rate increasing in the test.

To summarize the result of these unit tests, the fuel heating device achieved the main goal, but there remained some issues. Especially, the duration of the starting time have to be shortened before proceed to the actual use.

5.2 Optimization of the starting sequence

Using the priming system, the fuel heating device settled the pressure surge at some test conditions. However, at the other test conditions, the pressure surge happened. In addition to this, the starting phase have to be shortened for the actual use, because the run time of test equipment (i.e. scramjet combustors) were restricted to very short time (5 – 20 sec.) by the huge thermal load. Thereby, we conducted test run to optimize effectiveness of the countermeasures to the pressure surge at various test conditions. In this phase, to focus the effect of the priming system, the heating device worked without main fuel valve working. We tried the various opening of the throttle valve, the duration to open the priming valve, pressurize gas pressure and heater temperature.

From the result of the unit test, the fuel heating device needs 15 to 20 seconds from the start till steady state. The latter half of the duration could be omitted simply by shortening the priming valve opening, but the first half of it depended on the fuel flow rate through the priming system. Thus, we tried to increase the flow rate. Figure 11 shows result of a test. The condition of this test was the pressurize gas pressure of 4 MPa, storage heater initial temperature of 480 K and heated tube set temperature of 540 K. In this test, the priming valve was repeatedly operated five times during the run. The priming valve opening duration was changed at each step in the styles of 3, 5, 7, 5 and 3 sec. The remote vent valve and purge gas injection valve worked between each steps of priming valve to depressurize and to scavenge the heating section. The valve sequence had 5 sec. of interval between the priming valve close and the vent valve open. Then, the test corresponds to five types of the test condition under same pressure, but different temperature of the storage heater (The heat storage temperature changed from 480 K to 450 K during the run by heat exchange with fuel) and the duration of the priming valve open. The effect of the storage heater temperature appealed as the peak pressure of the pressure surge shown in Fig.11. The peak pressure of the surge changed every steps of priming valve open. Although, the pressure surge was not settled in the test, the pressure decrease before the vent valve opening was more quickly than that of the tests expressed in Section 5.1. On the other hand, we could observe the effect of the priming valve opening duration on the pressure surge as the duration of the pressure surge.

As a result, it was shown that the peak pressure during the pressure surge was dependnet on the temperature of the storage heater. On the other hand, the duration of the surge was dependnet on the priming valve opening. Hence, we drew the inference that the action time tuning of the priming valve is effective as the countermeasure to reduce the pressure surge duration. In other words, we decided to permit pressure surge depending on the set of storage heater temperature, to focus on reducing the duration of pressure surge.

In the end of this phase, we tried an improved sequence under three different test conditions, and we achieved the goal to shorten the duration of starting phase. The result with the improved sequence is shown in Fig.12.

![Fig.11 A result of test to shorten the starting phase (Under subcritical condition)](image1)

![Fig.12 A result of test using improved valve sequence (Under supercritical condition)](image2)
5.3 An actual use test of the fuel heating device with a dual-mode ramjet combustor test component

Finally, we had an actual use test of the fuel heating device in combination with a dual-mode ramjet combustor (a key component of RBCC engine) test component. The combustor was used for many combustion tests using hydrogen and ethylene (Nojima et al., 2014a, 2014b). The combustor was set in a blowdown type supersonic wind tunnel with a vitiated air heater. The vitiated air heater makes high enthalpy air flow by the lean combustion of gaseous hydrogen. Also, gaseous oxygen were mixed into the air flow to maintain the oxygen mole fraction same as the normal air. The high enthalpy air flow is accelerated by the supersonic nozzle and flows into the dual-mode ramjet combustor test component. The supersonic nozzle and dual-mode ramjet combustor work without cooling system. Then, the work time of them were restricted within 20 sec. For this reason, the fuel heating device have to steady down within 7 sec from starting and cut the fuel feeding to the combustor after the test immediately. We built the sequence of the fuel heating device under this limitation.

When the fuel heating device works with the dual-mode ramjet combustor, the backpressure of the throttling orifice would be higher than that of the unit test. Thus, the choked flow at the orifice would be broken, and the flow fluctuation of the downstream of the throttling orifice would interfere with the fuel heating device. It might make some malfunctions of the fuel heating device. In this test, that influence was the major concern to us.

The test condition is shown in Tables 6 and 7. The pressure and temperature set was almost same as the test described in Sec 5.1. However, the throttling orifice diameter was changed to match the requirement fuel flow rate of the combustor. Figures 13 and 14 show the results of these tests. Both of them, the fuel fed through the main fuel valve from 22 to 32 sec. In the test shown in Fig. 13, the fuel heating device worked under subcritical pressure of ethanol. The fuel pressure at the downstream of the throttling orifice oscillated to some extent. In the inlet fuel flow rate measured at the throttling orifice would be lower than that of the unit test. Thus, the choked flow at the orifice would be broken, and the flow fluctuation of the downstream of the throttling orifice would interfere with the fuel heating device. It might make some malfunctions of the fuel heating device. In this test, that influence was the major concern to us.

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Table 6 Heating device setting (Subcritical condition)

| Parameter                  | Value   |
|----------------------------|---------|
| Fuel tank set pressure     | 4.0 MPa |
| Storage heater initial temperature | 480 K   |
| Electric heated tube temperature | 510 K   |
| Throttling orifice diameter | 1.8 mm  |

Table 7 Heating device setting (Supercritical condition)

| Parameter                  | Value   |
|----------------------------|---------|
| Fuel tank set pressure     | 8.0 MPa |
| Storage heater initial temperature | 530 K   |
| Electric heated tube temperature | 530 K   |
| Throttling orifice diameter | 1.8 mm  |

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6 Conclusions

In this paper, we report the development of the fuel heating device for the component test of aerospace propulsion systems, and the result of the test run of the improved fuel heating device. The experimental conditions of the test run using ethanol are at pressure ranging 4 to 8 MPa and at the temperature ranging 480 to 550 K. The pressure range is across the critical pressure of the ethanol. This study concludes as below.

1) The effectiveness of the countermeasures to the pressure surge was confirmed.
2) The heating device achieved the main goal to feed ethanol at supercritical condition to the test equipment.
3) Ethanol temperature and pressure was stabled in the test run under supercritical condition.
4) Ethanol mass flow rate increased gradually in the test run under supercritical condition.
5) The heating device worked without pressure oscillation at the heating section under subcritical condition.
6) At the downstream of throttling orifice, 10 – 20 % width of pressure oscillation was observed under subcritical condition.
7) Ethanol mass flow rate fluctuated somewhat under subcritical condition.
8) The fuel heating device could feed the high pressurized high temperature fuel to the combustion test of a dual-mode ramjet combustor test equipment.

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