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Technical Notes

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Effect of Regenerative Cooling on Rocket Engine Specific Impulse

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I. Introduction

REGENERATIVE cooling (R.C.) is a well-known engine cooling method, first conceived in 1942[1] and presently used in many liquid rocket engines. In regenerative cooling propellant is used as engine coolant and the heated coolant is injected into the combustion chamber. This mechanism is called enthalpy pumping.[2] Regenerative cooling does not necessitate excess propellant to cool an engine, in contrast with other cooling methods such as film cooling and dump cooling.

In the beginning of the liquid rocket engine study, several basic and suggestive thermodynamical investigations[3-5] were carried out. It was described in Ref. 4 that regenerative cooling increases specific impulse with discussion of the role of entropy changes. The investigation was based, however, only on the combustion gas flow, and did not take the entropy increment of the coolant into consideration as a part of the whole engine. Engine cycle performance is specified by the net entropy increment in an engine: the smaller the net entropy increment, the better the engine performance in the Mollier diagram. The relation between engine performance and entropy increment must be discussed in a whole engine system. When a part of the whole engine is isolated, the entropy may decrease in it. For example, in a water-cooled nozzle skirt, entropy decreases because of cooling. To date, there has not been sufficient discussion of the difference of entropy increment in a subsonic flow and in a supersonic flow.

In this Note, to investigate the effect of regenerative cooling on rocket engine specific impulse, a whole liquid rocket engine was studied with quasi-one-dimensional simulation, taking the entropy increment of coolant into consideration.

II. Model Engine and Simulation Procedure

Figure 1 is a schematic of the model engine used. Propellants were hydrogen and oxygen. In this Note, an engine with regenerative cooling only at the nozzle skirt is termed a "N.S. cooled" engine, and the exchanged heat and the hydrogen flow rate were Q_{NS} and $\dot{m}_{NS}$, respectively. An engine with

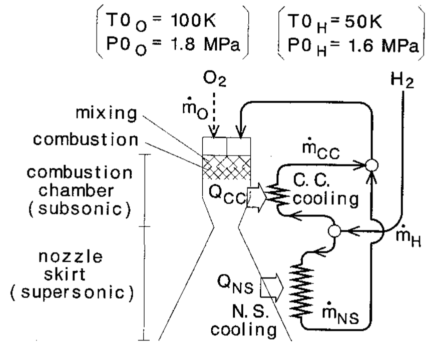

Fig. 1 Engine schematic.

regenerative cooling only at the combustion chamber is termed a "C.C. cooled" engine, and properties were specified with a subscript of CC. An engine without regenerative cooling is termed a "no R.C." engine. Supplied propellant properties, i.e., total temperature, $T0$, and total pressure, $P0$, were specified at the engine entrance as shown in Fig. 1. The hydrogen flow rate was 40 kg s^{-1} and the mixture ratio was O/F = 6. Fluids in the engine were compressible, calorically perfect gases. There was no total pressure loss in bends, or in manifolds.

The combustion chamber diameter was 0.4 m, and the length was 0.4 m. The nozzle skirt was conical with a length of 2.5 m, and the nozzle expansion area ratio was 60. There were 288 cooling channels around the combustion chamber, and there were 721 channels around the nozzle skirt. The mean height of the cooling tubes was 10 mm, the mean width of the tubes around the combustion chamber was 2 mm, and the mean width of the tubes around the nozzle was 10 mm. The engine was nominally the same size as the LE-7,[6] the booster engine of the Japanese rocket vehicle, H-II.

There were two kinds of simulations in this Note. One type, Simulation A, is a very simple way to examine the effect of heat exchange. Regeneratively exchanged heat was an input parameter, combustion gas was inviscid, and the heat flux was distributed uniformly along the combustion gas flow. The other, Simulation B, is a relatively complicated way to discuss the effect of heat exchange in a real engine. Regenerative heat exchange was calculated assuming a uniform temperature engine wall and viscous combustion gas. The wall temperature was calculated to balance the total heat flux from the combustion gas and that to the coolant. The heat transfer coefficient and the friction coefficient of the combustion gas were calculated with the Blasius formula[7] and Reynolds analogy. In both kinds of simulations, hydrogen was viscous in the cooling tubes. The friction coefficient and the heat transfer coefficient were calculated with the universal resistance law for smooth pipes[8] and Reynolds analogy.

III. Simulation Results and Discussion

The relation between the vacuum specific impulse ($Isp_{,v}$) and the regeneratively exchanged heat nondimensionalized with the combustion heat release (Q_{ex}/Q_c) is shown in Fig. 2. The total temperature of hydrogen after regenerative cooling is also shown as abscissa. The results of Simulation A are

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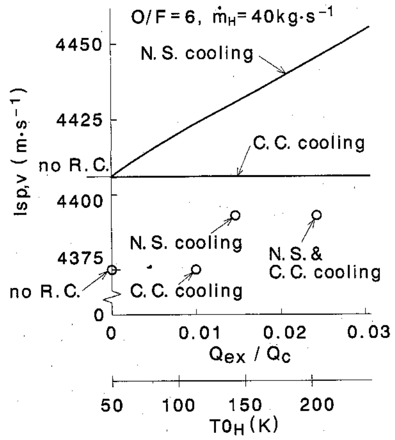

Fig. 2 Effect of regenerative cooling on specific impulse. Solid lines are by Simulation A and circles are by Simulation B.

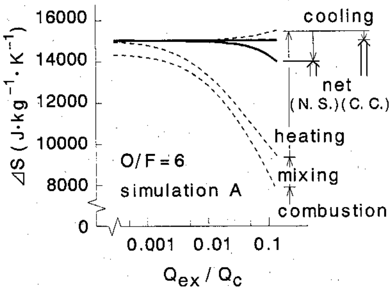

Fig. 3 Entropy change with regeneratively exchanged heat.

shown with solid lines. The results of Simulation B are also indicated with circles, and they were smaller than those of Simulation A due to friction. Pressures in the combustion chamber were around 15 MPa in all the simulations. The results of both simulations showed that the engine specific impulse increased only when a nozzle skirt was cooled regeneratively. Regenerative cooling of the combustion chamber did not affect the specific impulse.

Figure 3 shows the net entropy increments in the N.S. cooled engine and in the C.C. cooled engine. Due to regenerative cooling, the entropy increment of combustion decreases very much because of the increment of total temperature of the mixed propellants. At around 0.01 of Q_{ex}/Q_c, the entropy increment of mixing becomes smallest. The entropy increment associated with heating the hydrogen increases with the regeneratively exchanged heat. Overall, the net entropy increment of the N.S. cooled engine with the regeneratively exchanged heat is small. In contrast, the net entropy of the C.C. cooled engine does not change, even though the combustion chamber was regeneratively cooled. In Rayleigh flow, the higher the entrance Mach number, the larger the entropy decrement by cooling in a supersonic flow.[9] In a subsonic flow, the entropy decrement is roughly constant. The difference of specific impulse seems to be caused by the difference of this net entropy increment. Figure 4 shows the comparison of the model engine operations by Simulation A in a Mollier diagram. The net entropy increment became smaller, the enthalpy at the cycle end point, which corresponds to the nozzle skirt exit, was lower, and the kinetic energy was greater in the N.S. cooled engine than in the other two engines.

The engine vacuum thrust can be discussed with the impulse function at the engine exit when the entrance conditions of propellants are specified. The impulse function is a function of Mach number, flow rate, and total temperature, and it increases with Mach number in a supersonic flow. The total temperature at the exit of the regeneratively cooled engine is the same as that of the no R.C. engine. However, in the N.S. cooled engine, the total temperature at the throat is higher than that of the no R.C. engine, and the combustion gas is

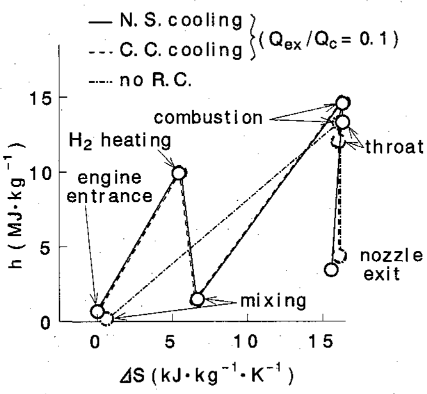

Fig. 4 Mollier diagram.

accelerated by cooling in the supersonic component, i.e., in the nozzle skirt, as well as by divergence in the nozzle. The Mach number and impulse function at the exit of the N.S. cooled engine become greater than those of the no R.C. engine. In Ref. 2, there was a description that the increment of specific impulse was due to the increment of temperature at the throat in the regeneratively cooled engine. This may indicate the above mechanism.

When a rocket engine is used in an orbital transfer vehicle, or in an aerospace plane, it may often be throttled. The velocity, the temperature, and the viscosity of the combustion gas do not change very much in a specified engine, so the change in flow rate causes the Reynolds number to change. The friction coefficient is proportional to -0.2 power of the Reynolds number according to the Blasius formula.[7] On the other hand, the specific impulse increment is proportional to the regeneratively exchanged heat as seen in Fig. 2. With Reynolds analogy, the regeneratively exchanged heat is proportional to the friction coefficient, so the specific impulse increment by regenerative cooling of the nozzle skirt is proportional to the -0.2 power of the flow rate.

The area where heat flux is large corresponds to the area where friction force is large, so it is not useful to enlarge the nozzle surface area, e.g., with fins, to obtain greater heat flux. As a result, the specific impulse is increased by 10 or more m/s by regenerative cooling, according to the simulations with a nozzle expansion area ratio of 60–1000.

IV. Conclusions

The effect of regenerative cooling on specific impulse in a whole engine system was investigated, and the effect was confirmed with consideration of the entropy increment of the coolant.

1) When a supersonic component, i.e., a nozzle skirt, is cooled regeneratively, engine specific impulse becomes larger than that of an adiabatic engine by 10 ms^{-1} or more. When a subsonic component, i.e., a combustion chamber, is cooled, however, specific impulse does not change.

2) This effect is explained by the larger entropy reduction due to cooling a supersonic flow in the nozzle skirt in comparison with that due to cooling a subsonic flow in the combustion chamber.

3) The effect becomes larger at lower Reynolds numbers.

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Performance Evaluation of LE-7 High-Pressure Pumps

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I. Introduction

A LARGE launch vehicle, the H-II, has been developed in Japan. The launch vehicle uses a LOX/LH_2 engine, the LE-7, the thrust of which is about 1000 kN. The cryogenic propellant feed pumps of the LE-7 engine are characterized by high delivery pressure and large flow rate. The hydrodynamic performance of these pumps was thermodynamically evaluated mainly for the following reasons:

1) With regard to compressible fluids, the pump performance evaluations, which are based on assumptions of incompressibility, do not necessarily show the true pump performance because a fair amount of energy input to a pump is spent on increasing the internal energy.

2) With regard to pump efficiency measurement, a torquemeter could not be installed between the pump and the turbine of a turbopump. The installation of a torquemeter complicates turbopump assemblies to such a degree that they are not able to operate at the rated rotational speed.

The efficiency of the LOX pump was evaluated based on the adiabatic efficiency[1,2] because LOX is not so compressible. However, the efficiency directly determined from the measured pressures and temperatures was corrected for internal leakage from the split pump to the main pump.

With regard to the LH_2 pump performance, the polytropic head and efficiency which has been used as the true aerodynamic efficiency[3] were examined, because LH_2 is much more compressible than LOX. Since it was impossible to know the detailed compression process in a pump, a simplified calculation was carried out to determine the polytropic head and efficiency.

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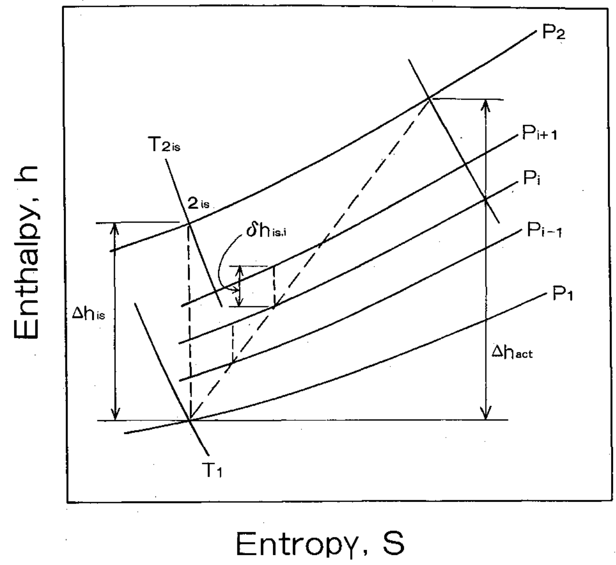

Fig. 1 Compression process of pump fluid.

II. Polytropic Head and Efficiency

A typical compression process of cryogenic fluids is presented in Fig. 1 using an enthalpy h—entropy s diagram. p_1 and p_2 represent the pump inlet and outlet pressure, respectively. The isentropic and actual compression processes are indicated by dotted lines. The adiabatic efficiency is presented by the following equation in which both the kinetic and geodetic heads are neglected:

$$\eta_a = (\Delta h_{is}/\Delta h_{act}) \tag{1}$$

where Δh_{is} and Δh_{act} are the increase of enthalpy in the isentropic compression process and the energy input to the pump, respectively. Since it was impossible to know the detailed compression process in a pump, the polytropic head and efficiency are calculated by the following expedient procedures. An isentropic compression process with a fixed efficiency is assumed between all the adjacent isobaric lines which are drawn between the two isobaric lines of pressures p_1 and p_2 as shown in Fig. 1. The polytropic head Δh_{tr} is obtained as the sum total of all isentropic enthalpy increments between the adjacent isobaric lines:

$$\Delta h_{tr} = \Sigma\delta_{is,i} \tag{2}$$

The polytropic efficiency is defined as follows:

$$\eta_{tr} = (\Delta h_{tr}/\Delta h_{act}) \tag{3}$$

As shown in Fig. 1, the enthalpy increment between the adjacent isobaric lines increases with the increase of entropy. So both the polytropic head and efficiency result in larger values than those of the adiabatic head and efficiency.

III. Test Pumps and Test Procedures

The major design parameters of the LOX and LH_2 pumps of the LE-7 engine are presented in Table 1. The impellers of the main pump and the split pump are arranged on a common shaft with the LOX pump. The main pump has an inducer with three swept-back blades. The split pump sucks in about 20% of the delivery of the main pump. There is internal leakage from the split pump to the main pump through the wearing ring seal. The LH_2 pump is a two-stage centrifugal pump with an inducer which is similar to that of the LOX pump. Each of the main impellers has 10 full vanes and 10 partial vanes.