Study on the Fundamental Technologies of ATREX Engine

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Abstract

This paper reviews the latest studies of the expander cycle Air Turbo Ramjet engine (ATREX) conducted in JAXA. First, a system analysis including the vehicle and trajectory was conducted to optimize the engine cycle and turbo-machine configuration. We selected the precooled turbo-jet cycle for a prototype engine using the near term technologies. Second, a system ground-firing test was conducted to verify a defrosting system for the precooler. Methanol injection with its particles atomization could compensate 80 % of pressure loss caused by the frost. Thirdly, a feasibility of carbon/carbon composites for the engine components was investigated by making complex shapes such as a heat exchanger and a plug nozzle. Basic technologies on the gas leakage, the junction and bonding were also studied. The end of the paper, some basic studies such as wind tunnel tests of a new type air inlet and a plug nozzle are described.

Introduction

Low cost, high reliable and routine access to space is required for the future space transportation system. One of the promising solutions is a space plane operated like an airplane by using air-breathing engines with high specific impulse. We have proposed a two-stage-to-orbit (TSTO) space plane, which employs the Air Turbo Ramjet engine with EXpander cycle. The typical characteristic of the ATREX is to employ the precooler, which can expand the engine flight envelope to Mach 6 and improve the engine performance.

A development study on the ATREX has been conducted by ground firing tests and wind tunnel tests since 1988. Now we are getting ready for the next development phase in a new organization, JAXA. This paper shows several topics in the current fundamental studies such as reconsideration of the core engine cycle using the current and near term technologies, engine firing tests for the precooler defrosting, a feasibility study of carbon/carbon composites and wind tunnel tests on the air inlet and the nozzle.

Table 1. History of the ATREX Engine Development

	'88	'89	'90	'91	'92	'93	'94	'95	'96	'97	'98	'99	'00	'01	'02	'03
ATREX-500 Firing Test																
-Design and Fabrication	■	■														
-without Precooler			■	■	■											
-with Precooler								■	■		■	■		■	■	■
Component Studies																
-Forebody Precompression									■							
-Axisymmetric Air Intake						■	■	■	■	■	■	■	■	■	■	■
-Precooler						■	■			■	■	■	■	■	■	■
-Mixer and Combustor		■		■		■	■		■				■			
-Plug Nozzle						■				■	■	■	■	■		■
Study on C/C Composite					■	■	■	■	■	■	■	■	■	■	■	■
Design of Flight Test						■	■	■	■	■	■	■	■	■	■	■
Conceptual Study on TSTO									■	■	■	■	■	■	■	■

Engine System Analysis

The conceptual design of a prototype engine used for the next flight demonstration is now in progress. This engine size corresponds to a 1/3-scaled model of that for the TSTO, which makes a development cost minimum and convenience. The ATREX engine introduces a precooled expander cycle that makes best use of characteristics of liquid hydrogen as the fuel and a low temperature heat source. The expander cycle engine is also suitable in the viewpoint of the reusability by its system simplicity and lightweight. However, it has a difficulty on the high temperature material technology for the heat exchanger. So we reconsidered the engine cycle for a prototype engine [1] using near term technologies.

First, a trade-off analysis was performed between two alternatives such as the expander cycle (ATREX) and the precooled turbojet engine cycle (PCTJ) shown in Fig.1. In case of the expander cycle engine, two turbines, which drive a fan and a propellant pump (fan-turbine and FTP-turbine), are driven by regenelatively heated hydrogen gas. In case of PCTJ, only the FTP-turbine is driven by hydrogen gas and the fan-turbine is driven by combustion gas from the gas generator arranged upstream of the fan-turbine. As the result, PCTJ was selected for the prototype engine from the viewpoints of higher Isp and low propellant system pressure and temperature. The expander cycle has a potential for improving its performance if the technology of composite material for the heat exchanger would be matured.

Second, several types of the PCTJ core engines were compared by a detailed analysis. Figure 2 and Table 2 show the basic configuration of three kinds of engine concepts with different compressor styles. The evaluation function is the vehicle structural weight ratio as well as the engine thrust and specific impulse.

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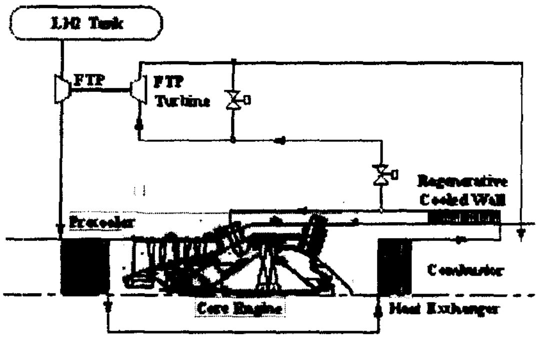
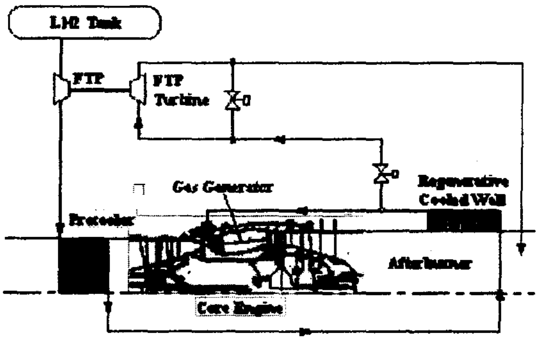
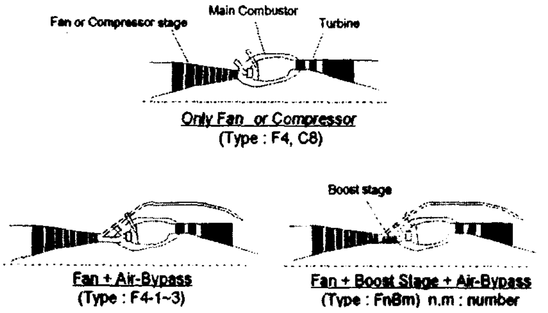


a) Full Expander ATR Cycle (ATREX)



b) Precooled Turbojet Cycle (PCTJ)

Fig. 1 Engine Cycle for TBCC Engine



Only Fan or Compressor
(Type : F4, C8)

Fan + Air-Bypass
(Type : F4-1~3)

Fan + Boost Stage + Air-Bypass
(Type : FnBm) n,m : number

Fig.2 Basic Configuration of Engine Core

Table 2 Engine Core Configuration List

Type	Engine Style
F-4	4-stage fan
F4-1	4-stage fan and air bypass ratio 0.11
F4-2	4-stage fan and air bypass ratio 0.25
F4-3	4-stage fan and air bypass ratio 0.43
F4B2	4-stage fan, 2-stage boost and air bypass
F4B4	4-stage fan, 4-stage boost and air bypass
F3B4	3-stage fan, 4-stage boost and air bypass
F2B4	2-stage fan, 4-stage boost and air bypass
F2B7	2-stage fan, 7-stage boost and air bypass
C8	8-stage compressor
F4EXP	4-stage fan, expander cycle

The simplest style, “F4” is not applicable because of not only poor performance but also weak structural strength due to small hub ratio of the turbine. In addition, the pressure loss through the turbine is large due to the high axial flow velocity. So, we added the bypass passage system to improve the turbine efficiency. Approximately 30% of the airflow bypass increases the turbine efficiency by 5%. We also found that the introduction of the boost stage or 8-stage compressor can decrease the amount of bypass air to zero. ATREX has the highest thrust with 20 ~ 30 % lower Isp than PCTJ. Structural weight ratio of the vehicle except for the engine system (engine, fuel and tank) is shown in Fig.3, which shows the payload capability. All of the PCTJ systems exceed 40%, which is the lower limitation to be feasible for the TSTO first stage.

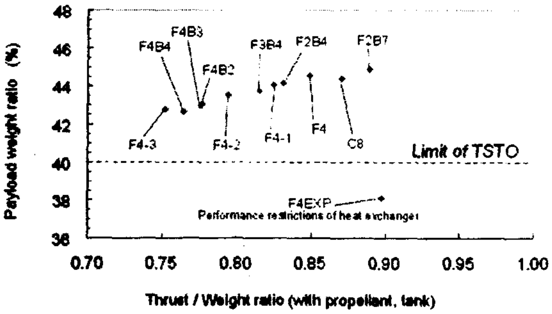


Fig.3 Payload Capability of TSTO

The optimization of air-breathing engine system for space plane is more complicated than the rocket engine system because of the cross coupling among the propulsion performance, the airframe aerodynamic characteristics and the trajectory including its return way. A joint optimization between the engine throttling and the selection of the trajectory has been performed under the accelerating conditions. This study will be extended to treat the unsteady problem including the thermal management.

System Firing Test

We have conducted the system firing tests using the subscale engine under the sea-level-static condition in order to verify the engine system and to develop the components such as a tip turbine, heat exchangers etc. Recently, the development of the precooler has been one of the most essential objectives. The precooler system is the most distinctive feature of the ATREX is to extend its flight envelope and to improve its performance. A shell-and-tube type precooler is installed in front of the fan of the engine. When the precooler is operated under the lower Mach number at low altitude (below 5km) to improve the engine performance much more, the severe frost formation problem 'icing' on the precooler tube surface becomes obvious. A countermeasure against the icing was tested in the last test in 2003. A principle of the methanol effect for the defrosting is referred in Ref.[2].

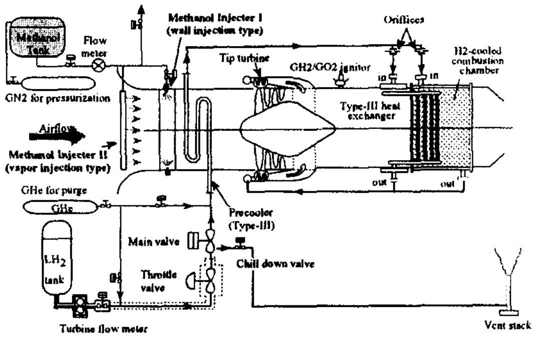


Fig.4 Flow diagram of the ATREX firing test

A flow diagram of the ATREX engine test is shown in Fig. 4. The ATREX-500 engine (Fig.5) was used whose overall length of the engine is about 4.5 m and fan inlet diameter is 0.3 m. The liquid hydrogen supplied from the pressurized storage tank is regenelatively heated by the precooler and heat exchangers. Methanol is supplied from a tank, which is pressurized by nitrogen gas. Several types of injectors were tested shown in Table 3. The main difference among the injectors is the average particle diameter of the injected methanol. A fundamental test shows that the atomization or vaporization of the methanol is effective to prevent the surplus methanol from freezing on the precooler tubes. Pneumatic spray type injectors and vapor injectors were used in the last test, which make about 10 micrometer of the averaged methanol particle diameter, while it is about 100 micrometer by the colliding type injector. Liquid methanol is atomized and accelerated by the compressed air in the injector like an atomizer. Methanol and pneumatic air are injected into the main airflow from 40 injector blocks arranged in the outer ring. Gaseous methanol, which is heated and vaporized by a heat exchanger, is supplied from the vapor injector located in front of the engine bell mouth. The injector has thirty-seven holes of 5 mm of diameter. Temperature of the supplied methanol gas is about 350 K.

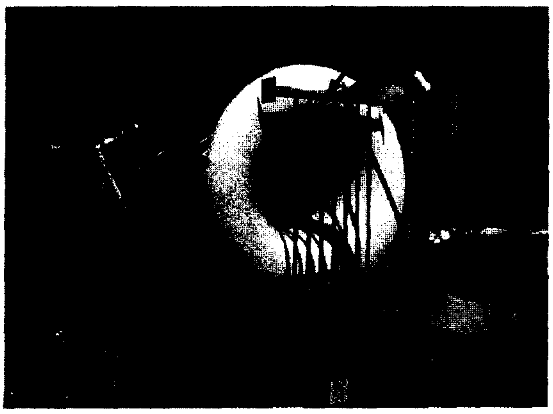


Fig.5 ATREX-500 Engine

Table 3 Methanol Injectors

Nozzle Type	Parallel	Colliding	Splay	Vapor
Average Particle Diameter, mm	400	100	10	-
Year	2001	2002	2003	2003

Test results are summarized in Table 4 including no methanol injection case. The methanol effectiveness is evaluated by the total pressure loss of the airflow due to passing through the precooler. Figure 6 shows transition of the pressure drop coefficient, which is defined by the difference between pressures measured before and behind of the precooler divided by the dynamic pressure of the airflow before the precooler. The transverse axis is the cumulative water vapor breathed into the engine.

Table 4 Summary of the Test Result

Test Number	ATREX10-2	ATREX12-1	ATREX13-4	ATREX14-2	ATREX14-4
Date	1998.9.17	2001.8.31	2002.9.29	2003.8.1	2003.8.6
Duration, sec	60	75	90	70	80
Atmospheric Temperature, K	294	302	295	301	302
Absolute Humidity, g/kg-air	13.0	12.4	11.6	12.9	13.7
Style of Methanol Injection	not injected	parallel	colliding	spray	gaseous
Methanol Mass, kg/s	-	0.428	0.132	0.0798	0.0538
Fan Rotating Speed, rpm	17,700	17,300	17,600	16,900	16,900
Thrust, N	2,940	2,860	3,360	2,770	2,700
Specific Impulse, N sec/kg	10,700	10,200	13,500	15,700	15,200
Hydrogen Mass, kg/s	0.274	0.292	0.249	0.176	0.178
Air-flow Mass,kg/s	5.05	6.21	6.64	6.58	6.79
Fan Inlet Temperature, K	206	203	195	200	195
Pressure Loss Coefficient	177.0	101.6	57.7	43.5	55.8
Heat Transfer Rate of P/C, kW (Hydrogen Side)	820	1,027	931	696	704
Heat Transfer Rate of P/C, kW (Air Side)	444	617	660	665	680

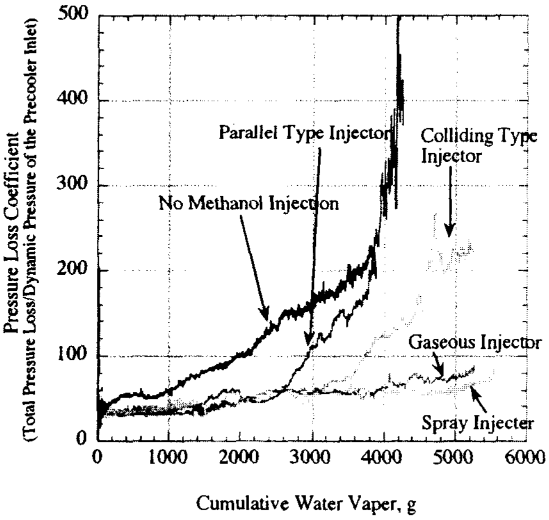


Fig.6 Transition of Pressure Loss Coefficient

This result shows that the methanol injection is effective to compensate the pressure drop by the icing and atomization or vaporization of the injected methanol is effective. Methanol injection could not eliminate the frost formation completely, however, more than 80% of the pressure drop could be compensated. Figure 7 shows video pictures of the outermost tubes in case of no methanol injection and the gaseous methanol injection. Frost formed on the outermost side completely disappears by the methanol injection. On the other hand, frost formed on the innermost tubes, which is lowest temperature parts, is not conspicuously changed.

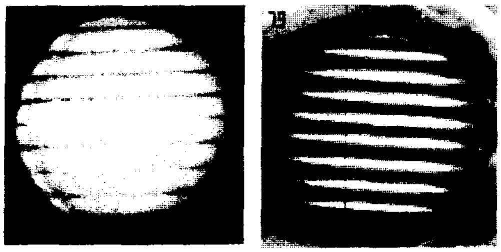


Fig.7 Frost Formation on the Precooler
(Left: no methanol, right: with methanol)

Application studies of C/C composites

Employment of heat resisting and lightweight composite materials is one of the most important issues to actualize hypersonic turbojets. Feasibility studies have been carried out aiming at the application of carbon/carbon (C/C) composites to the inlet, a turbine disk, heat exchangers, and a plug nozzle for the ATREX engine [3]. In order to withstand high temperature environment, attempts were made to utilize three-dimensionally reinforced C/C composites. The most serious problem encountered in the application of C/Cs to the turbine disk is the loss of fragments of the composite located near the outer periphery due to strong centrifugal force, which resulted in severe vibration due to rotational imbalance. The heat exchangers and plug nozzle have complex shapes in order to obtain large heat exchanging areas. The principal effort in these applications has been placed on finding structures requiring low joining strength and developing materials with low gas leakage and anti-oxidization.

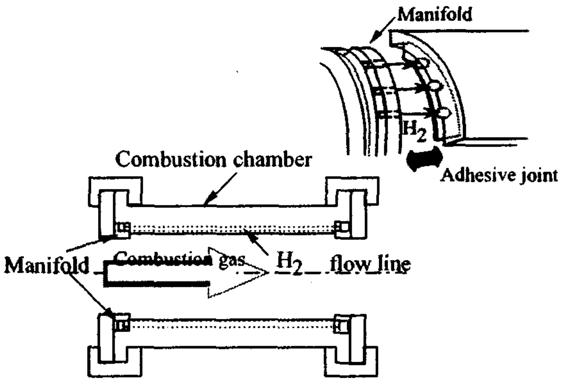


Fig. 8 Wall Type Heat Exchanger

Recently, we manufacture a wall type heat exchanger and a plug nozzle. The primary difficulty in these applications is how to form 3D-C/Cs into the complex shapes of the heat exchanger. The hydrogen gas within the ducts of the heat exchangers possesses a maximum pressure of 4 MPa, whereas the pressure of the combustion chamber is lower than 1 MPa. On the other hand, temperature of the wall would be 1300 K by regenelatively cooling. The heat exchanger formed in the wall of the combustion chamber (Fig.8) is composed of a cylinder containing many duct holes and manifolds. The manifolds are mounted at the inlet and outlet portions of the combustion chamber. They distribute the fuel hydrogen to the ducts of the heat exchanger, and gather and send it to the turbine. 90 copper tubes with an outer diameter of 5 mm are inserted to form the ducts for the hydrogen flow. Copper tubes are used because copper does not chemically react with carbon. Next, the copper tubes are chemically dissolved with nitric acid. Si is infiltrated into the 3D-C/C in order to reduce the gas leakage. Finally, a SiC coating and vitreous over-coat is to be applied on the surfaces of the chamber to prevent oxidation of the 3D-C/C. The glass over-coat evaporates easily, so that the over-coating should be treated periodically after a pre-determined operation time.

Figure 9 schematically shows the plug nozzle for the ATREX engine. This nozzle is connected to the combustion chamber at the cowl, whose plug is supported by two struts. The combustion gas flows through the space between the plug and the cowl and mobile skirt. The movement of the skirt makes an optimum outlet gap, which varies with flight speed and altitude. The temperature of the sharp end of the mobile skirt is estimated to be higher than 2200K due to high temperature gas flow. This region is cooled by gas flow supplied by the 45 holes of 3 mm in diameter. The cowl and the mobile skirt were fabricated using 3D-C/Cs. The holes for the ejection of cooling gas are formed using the Cu resolving technique employed in the wall-type heat exchanger. Near net shape 3D-preforms of the struts are difficult to weave. Consequently, the struts are determined to be divided into simple elements, which can be formed with 2-dimensional in-plane reinforcement by, for example, the filament winding process. All the elements thus formed are then arranged into the final shape as shown in Fig.10. Finally, thin CFRP rods are pierced in order to join the elements and to reinforce them in the thickness direction.

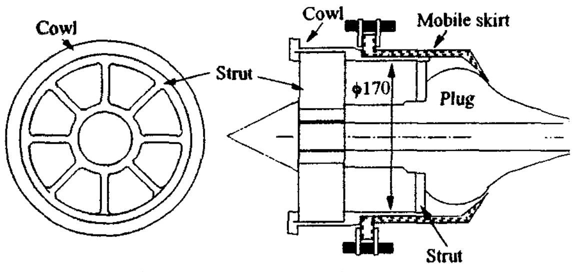


Fig.9 Schematic Drawing of the Plug Nozzle.

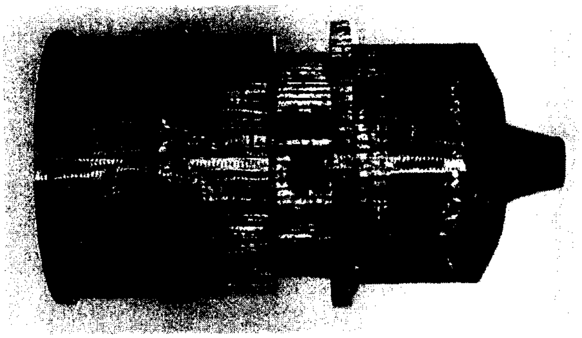


Fig.10 Chamber and Plug Nozzle Made of C/C

Basic studies

Wind tunnel test of the air inlet

An axisymmetric air inlet has been studied for the ATREX engine, which must be operated under the wide velocity range. We devised a new type air inlet called "Multi-Row-Disk (MRD) Inlet" to improve the off-design performance. The conventional inlet (left side of Fig.11) has a variable system by translating its spike (centerbody) forward and backward. Its off-design performance deteriorates because it cannot control total pressure ratio (TPR) governed by the throat area of inlet and mass capture ratio governed by the incidence position of the oblique shock from spike tip into the cowl independently. The spike of the MRD inlet (right side of Fig.11) is composed of a tip cone and several disks, which are arranged in axial direction and form cavities on the spike surface. It can adjust its throat area and total length independently to the flight speed by changing spaces between the tip cone and some disks.

Two kinds of wind tunnel tests were conducted to investigate the characteristics of the MRD inlet. First, the influence of cavities generated between disks on the boundary layer was investigated. The result shows the change of the pressure distribution is negligible if the cavity depth (D) is larger than the cavity length (L), which is called "deep cavity". Second, the performance of the MRD inlet model was investigated. Figure 12 shows a typical Schlieren image. The result shows that the MRD inlet improves TPR by 10% with the same MCR compared with a conventional inlet at Mach 3.5. The drive mechanism for changing the shape will be designed as well as getting the more detailed performance.

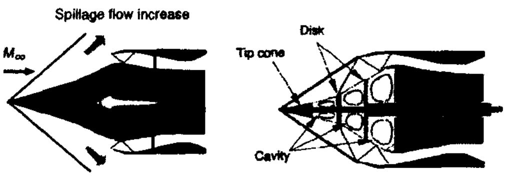


Fig.11 Conventional Axisymmetric Inlet (Left) and MRD Inlet (Right)

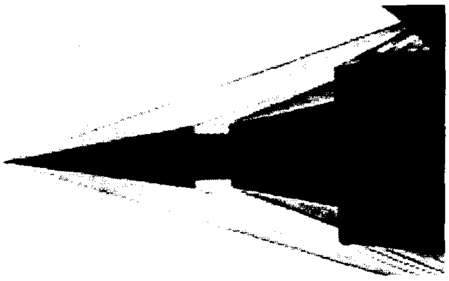


Fig.12 Schlieren Image of the Flow Field around MRD Inlet

Study of the plug nozzle

The plug nozzle for the ATREX should be worked under wide ranges of compression ratio and of mass flow rate. A wind tunnel test to research the off-design date of the plug nozzle was conducted for comparing with the CFD analysis shown in Fig.13. Both results on the thrust show good agreement quantitatively. The nozzle shows good performance in case of the design flow rate and the smaller flow rate. When the flow rate is twice of the design rate under the high expansion ratio, the thrust efficiency decreased about 5 % due to the shock wave in the internal expansion region. This shock wave causes the temperature rise on the plug surface.

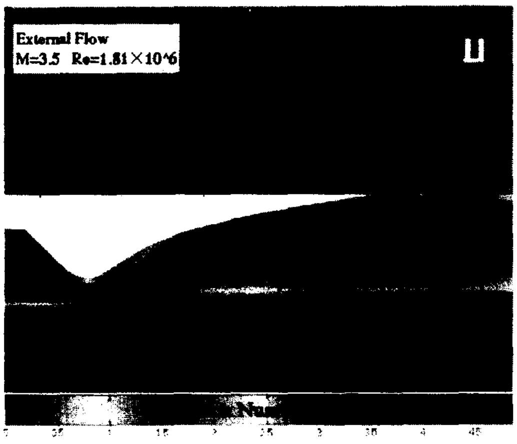


Fig.13 Flow Field of the Plug Nozzle

Basic research of icing on the precooler

We have conducted the fundamental researches of the icing on the precooler tube. Up to now, some key technologies have been devised such as the LOX injection method, the methanol injection method including the effect of its particle diameter, etc. A CFD program code applying for the precooler with water vapor condensation is under development to grasp the detailed feature of the icing. The ATREX precooler, which is a cryogenic heat exchanger, has a distinctive feature as follows. It has a very wide temperature range of the cooling surface from near the boiling point of LH2 to near the room temperature at sea-level-static as well as having a wide range of air temperature. Therefore solid or liquid particles called "mist" are generated in the airflow. The mist generation reduces the quantity of the water vapor included in the airflow and makes the prediction of the icing phenomenon difficult. The Navier-Stokes equations adding the conservation equations of vapor density, mist density and number of the mist particle. The boundary layer flow on the flat plate and around a cylinder (Fig.14) was analyzed. The result on the flat plate agrees qualitatively with the experimental data and grasps the phenomenon that the frost formation rate decreases drastically when the wall temperature is below 170 K.

An experiment of the frost formation on the flat plate (Fig.15) was conducted to grasp the phenomenon plainly and to use for a comparison with the CFD analysis. Cooling cupper plates of both sides having 10 mm interval make the air flow passage, which height and length are 100 mm and 500 mm respectively. These plates are cooled from the rear side by LN2. Gaseous nitrogen including the water vapor and methanol vapor is used as the main flow. The frost weight along the flow direction is measured at 5 points by scratching them after each test. A weight ratio of the methanol in the frost is also measured. When the plate temperature is relatively high (Tw = 240 K), the frost formation rate of the pure water agrees well with the analytical value based on the turbulent mass transfer equation. In the lower temperature case (Tw = 120 K), the frost formation rate is less than the analytical value due to the mist generation. When the main flow includes the water and methanol vapor, the frost formation rate is less than the analytical value of pure water vapor or that of pure methanol vapor. A weight ratio of the methanol in the frost is close to that in the main flow in every test.

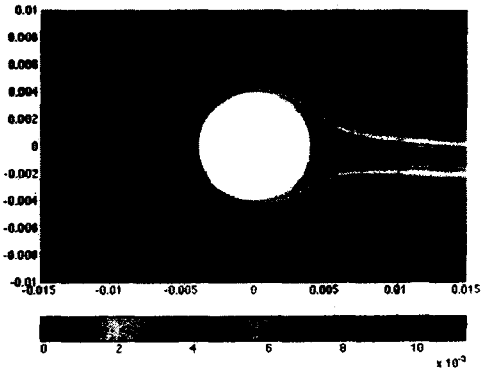


Fig.14 Mist Concentration around the Cylinder

Conclusion

Development studies of the ATREX engine in JAXA were shown here. It is not easy to develop the space plane engine because a large amount of manpower and cost is required. However, we believe it is important to research the key technologies step by step and to demonstrate the engine by a flight test [4] as soon as possible.

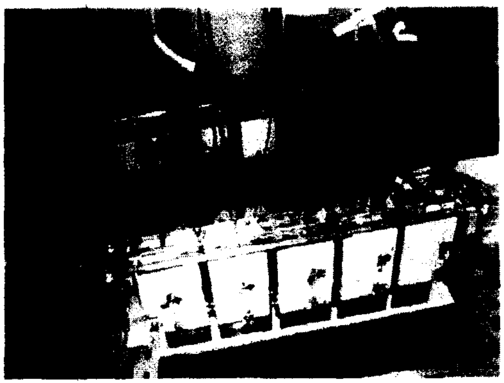


Fig.15 Test Apparatus of the Frost Formation Test

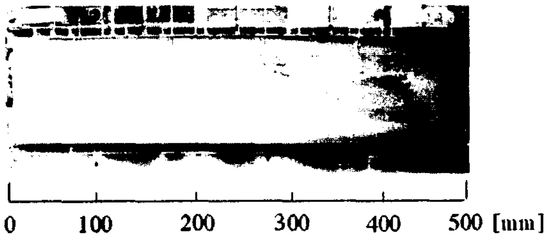


Fig.16 Frost Formation on the Cupper Surface

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