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Development of a Small Jet Engine Test System for University Education

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ABSTRACT

For an effective understanding of the characteristics of gas-turbine engines and of jet engines, a project is made to develop a small jet engine test system by university students. A commercial turbo-charger for automotive use is employed and a combustor and nozzles are designed to match it. Auxiliary components such as fuel or lubricant or cooling water supplies are also selected for operation. Diagnosis system to monitor the operating conditions is designed. Most of these components are mass production parts for automobiles that meet the educational requirement of low-cost and heavy-duty. The first firing was achieved in the first year of the project. By improving components performance and matching, the engine achieved the maximum thrust of 42 N at an engine speed of 170,000 rpm and efficiency of 8 % at 160,000 rpm, finally.

INTRODUCTION

Education of university student in aerospace engineering often has difficulty in teaching the characteristics of gas turbines and jet engines. The lectures often deal with those engines, while most of experiments on thermodynamics and gas cycles are done with reciprocating engines. The difficulty arises because jet engines are not commonly used in their daily life and they are not able to think in reality. The most effective and most required way for students to understand the characteristics is to experience its operation.

Beside the educational effects, conventional ready-made test systems are very expensive and hard to put into educational program. A project to develop a small and inexpensive jet engine for educational purpose is started on this viewpoint.

PROJECT OVERVIEW

The project started in FY2001 and ended in FY2002. In each year, two undergraduate students contributed for the development. By the studies necessary for the development, they completed their bachelor thesis.

The first year is consumed for understanding the characteristics of automotive turbo-charger and for designing and testing components. Performance design and first firing was the goal. Our primary requirement being building a cost effective test system, selecting commercial products are one important task. Apart from the conventional way to develop jet engines, we started from selecting a suitable turbo-charger. The design flow is described in Fig. 1.

The second year is spent on the improvement of the performance and handling of the system. From the starting sequence of the engine to an accurate measurement of thrust, minor modifications and improvements have been made.

Since combustor and nozzle are not available in the market, this had to be designed newly.

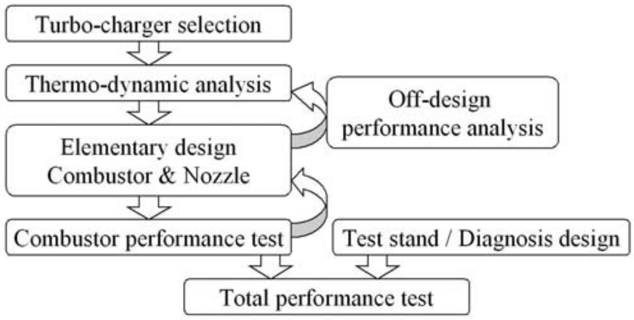

Fig. 1 Design flow

SYSTEM OVERVIEW

A turbo-charger for automotive use is chosen for the basis. The specifications are shown the table below.

Table 1 Turbo-charger specifications (Type: RHB5 by IHI)

	Compressor	Turbine
Type	Radial	Radial
Inlet diameter mm	36	52
Outlet diameter mm	52.5	49
Temperature max. K	-	>1073
Efficiency max. %	74	77

Other auxiliary elements are selected to fit the system from commercial market. The only one-off parts are the combustor and the nozzle. Undergraduate students designed a can-type combustor and convergent nozzles. This way of development yields design restriction, while it allows significant amount of cost reduction. Turbine inlet temperature is limited to be less than 1100 K and pressure ratio is at most 2.5. The matching of turbine and compressor is designed for the use of automotive engines and very poor for the gas turbine use. That is, the designed turbine inlet pressure is higher than compressor exit. As a result, excess mass flow rate is required to keep compressor exit pressure high for the present use. With this restriction, the challenge to build a jet engine of maximum possible performance was done.

For the purpose to simplify fuel supply system, we took propane as a fuel. The planned thrust was 35 N at an engine speed of

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175,000 rpm operating with A/F of 69, airflow rate of 0.135 kg/s with pressure ratio of 2.5. Table 2 summarizes the design maximum and idle conditions.

Table 2 Designed operating conditions

	Max Thrust (175,000 rpm)		Idle (80000 rpm)	
	T [K]	P [kPa]	T [K]	P [kPa]
Comp. in	293	96	293	96
Comp. out	427	240	328	125
Turbine in	1073	228	1073	118
Turbine out	958	121	1043	101
Air Flow	0.135 [kg/s]		0.037 [kg/s]	
A/F	69 [-]		60 [-]	
Thrust	36 [N]		-	
Pres. Ratio	2.5 [-]		1.3 [-]	

For the thrust measurement, four fine steel wires as is shown in Fig. 2 hang the engine. All wires from sensors and hoses for water and oil supply are hung from the ceiling so that they are free to swing. The engine is free to move in the axial direction and pushes the load cell when it generates thrust.

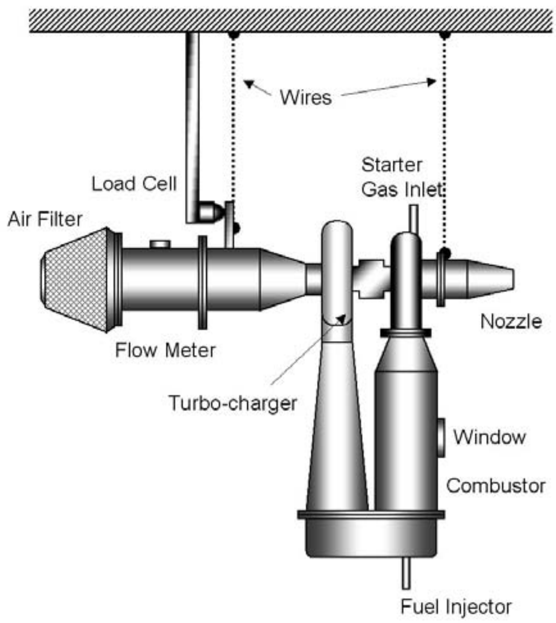


Fig. 2 Schematic of jet engine test system

Since the turbo-charger is for automotive use, a quantity of auxiliary parts are available from so-called "tune-up shops". The air filter, the flow meter, spark plug and hoses are from these shops. These parts has high durability and inexpensive.

Inlet and outlet pressures and temperatures of compressor, combustor and turbine are monitored to control within each component's capacity. The temperature measurement is done by K and J type thermocouples. Pressure sensors are semi-conductor type (COPAL PG-30-102R/103R) that are designed for factory production lines. A magnetic detector coupled with a digital counter detects the engine speed. A piezoelectric sensor monitors vibration.

The engine is started with a compressed nitrogen or air that is issued into the turbine. After it is accelerated up to 30,000 rpm, that is the maximum speed achievable by the starting air, fuel is injected. Ignition is done by a spark plug with coaxial electrode (NGK BUR9EQP) that is commonly used for rotary SI engines and is resistant to high heat flux.

For the performance test, we varied the fuel flow rate and the nozzle. The convergent nozzle can change area ratio so as to control the exit velocity and turbine outlet pressure. To realize a better compressor- turbine matching, and hence, to allow a reduced flow rate with high pressure ratio, the nozzle must control the resistance. The fuel flow rate and the area ratio of conversion nozzle are the only two parameters that vary the operating conditions of the jet engine

COMBUSTOR

The student designed combustor is can-type combined with a diffuser. The photo of the combustor is shown in Fig. 3. The designed combustor has a swirler with 45-degree vanes for flame stabilization. The air is divided to 15:35:30:20 for primary and secondary combustion, dilution and cooling respectively. This value is defined by testing the blow-out limit. Since the primary air flow rate is important for flame stabilization, a snout is attached upstream of the swirler. By adjusting the diameter of the snout, the air ratio is optimized. The flow velocity of the primary section is set to 5 m/s and the mean flow velocity is 13 m/s in the combustor. The total pressure drop should be less than 5 %. To reduce cost, the most of the parts are made of stainless steel.

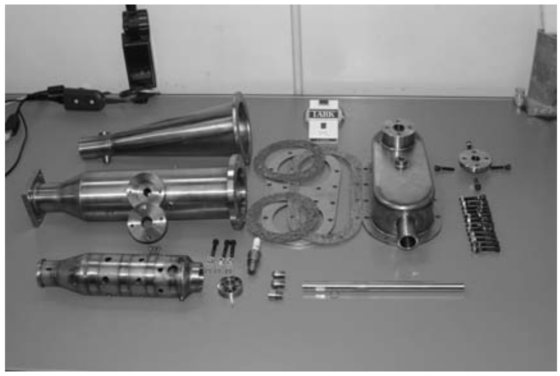


Fig. 3 Combustor Elements (disassembled)

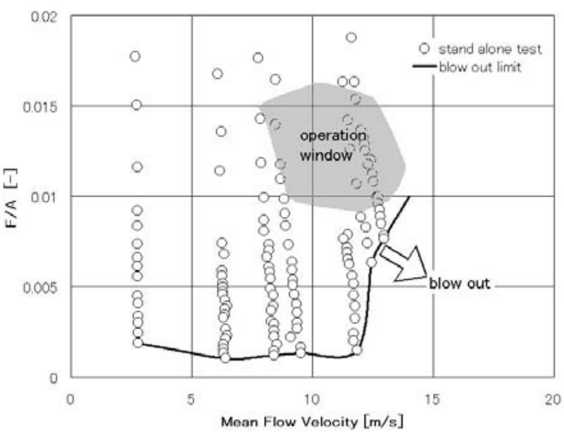


Fig. 4 Blow-out limit of the combustor

To confirm the performance of the combustor, stand-alone test is conducted. Air is supplied with a blower. The end of the combustor is opened to atmosphere. Thus only the characteristics under atmospheric pressure are obtained. Figure 4 shows the blow-out limit of the combustor under the condition. The circular dots express the tested conditions under which combustion is stable. The upper boundary of the dots is due to the temperature limit of the combustor that is about 1100 K. The lower boundary expresses fuel-lean limit of the flame holding. As is seen, the flame stability is sufficient up to the design flow velocity of 13 m/s. Below the mean flow velocity of 12 m/s, the blow-out limit is extremely low that indicates diffusive combustion is dominant. For the higher velocity cases the limit switches to F/A of about 0.007 (i.e. 140 in A/F). Somewhat premixed flame seems to dominates the flame holding. This test confirmed the stable operation of the jet engine. The operation condition for the case of total performance test is marked as “operation window”. It is within the flame holding region. There should be some margins for higher pressures.

Figure 5 shows the temperature uniformity of the combustor outlet. Since the part of the cooling air meet the hot gas at the very vicinity of the combustor outlet, the outer boundary shows quite reduced temperature. In the middle part shows rather flat temperature distribution that is favorable.

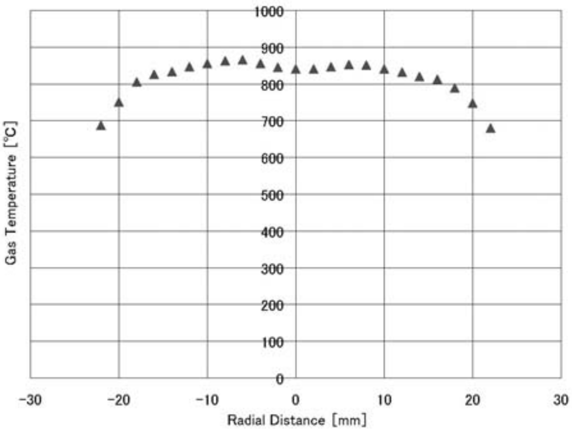


Fig. 5 Temperature uniformity at the combustor outlet

atmospheric pressure, mean flow velocity = 12 m/s

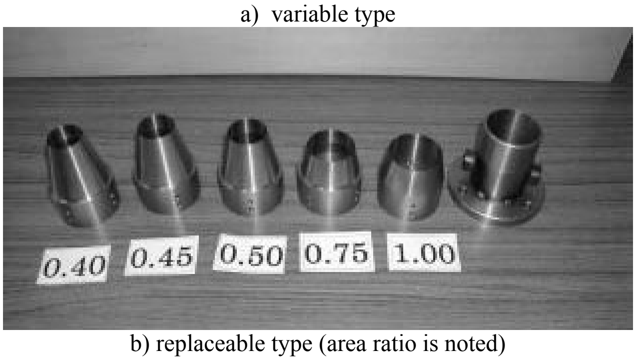
During these test, the total pressure drop is examined at the same time and found to be less than 5 % for the entire flow velocity range tested.

From these components test, the design of the combustor is confirmed to be appropriate and completed. The construction of the total system proceeded.

NOZZLE

Nozzle is the only component that controls the matching of compressor and turbine here.

a) variable type



b) replaceable type (area ratio is noted)

Fig. 6 Nozzles

To vary the area ratio of the inlet and outlet of nozzle, two types are tested. One is cone type variable nozzle and the other is replaceable nozzle. Variable type can change area ratio arbitrary. The replaceable type is not free of choice in terms of area ratio. This has advantage of simplicity and high efficiency due to the relatively smaller surface area.

After testing these nozzles, we decided to choose the replaceable type for integration of the system. Since the total pressure drop of the variable type is relatively high, we skipped to adopt this.

TOTAL PERFORMANCE TEST

Since there occurred combustion oscillation at about 60,000 rpm to 80,000 rpm, we had to pass quickly the region after the engine is lit at 30,000 rpm. This yielded change in idle speed. The new idle speed is set to 100,000 rpm.

The measured compressor operating conditions for five different area ratios of the nozzle are shown in Fig. 7. The compressor characteristics curves are shown at the same time. The two limits are shown. The vibration limit does not allow the run at the design condition and the designed maximum thrust was not obtained. On the other hand, we could search for a better operating condition by choosing appropriate area ratio of the nozzle.

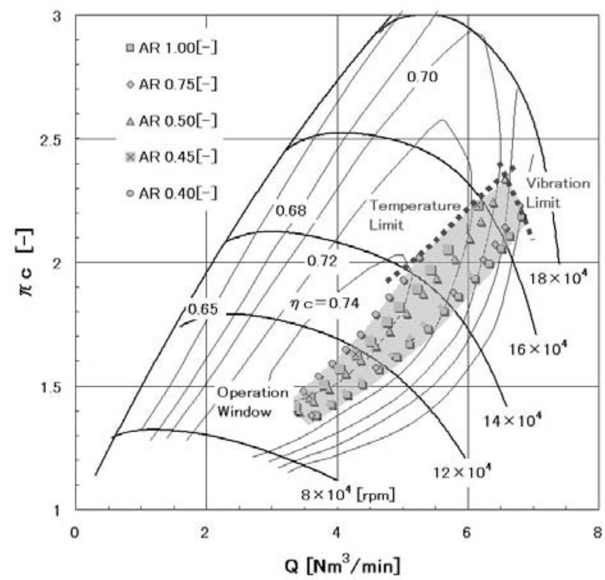


Fig. 7 Compressor operation window

By choosing smaller nozzle exit, the curve tends to lay left-upper side. This is because nozzles of low area ratio requires high pressure ratio. Thus turbine outlet pressure must become high. This yields high compressor pressure ratio. By keeping engine speed constant, the higher pressure ratio result in lower flow rate. From the viewpoint of compressor efficiency, the lower area ratio seems to be favorable in the region. Only this requires high temperature at turbine inlet. In most cases, the lower area ratio case hits the temperature limit.

Figure 8 shows the thrust of different nozzles and engine speeds. In spite of the reduced flow rate, high turbine outlet pressure of small nozzles achieves higher thrust. In the present range, a smaller nozzle seems to realize a better thrust. Only temperature limit yields the lower maximum thrust for the nozzles of 0.4 and 0.45 in the area ratio. The maximum thrust obtained is higher than the designed value. The area ratio at design point is 0.6. This value was the planned minimum for starting and idling the engine. Reducing this to 0.5 and reducing engine speed slightly realized the better performance. The reduction in the area ratio was possible simply by modifying start-up sequence and idle speed.

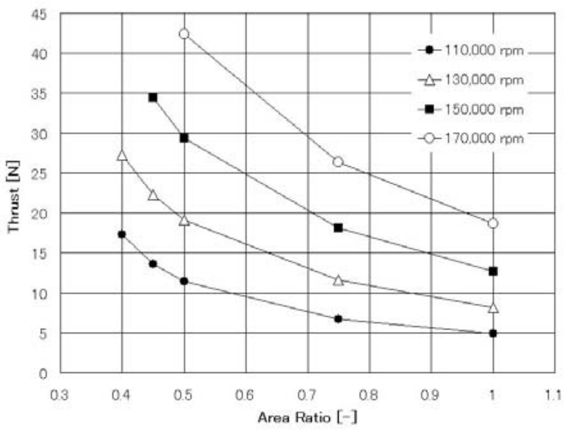
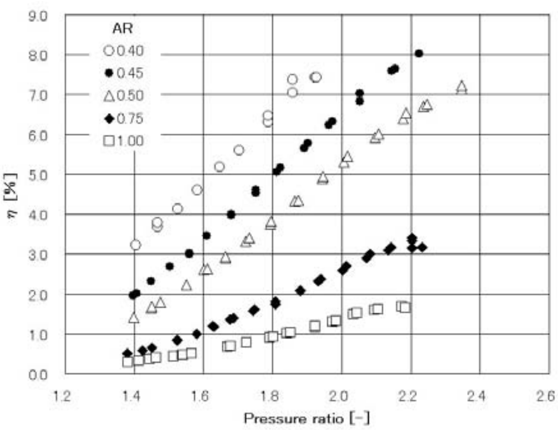


Fig. 8 Thrust dependence on nozzle area ratio

Figure 9 shows thermal efficiency estimated from the measured thrust ‘F’, mass flow rate of exhaust gas ‘$\dot{m}$’ and from fuel consumption rate ‘$\dot{m}_f$’, using the following equation.

$$\eta = \frac{F^2 / 2\dot{m}}{\dot{m}_f LHV}$$

As theory tells, increasing pressure or temperature ratio yields higher efficiency for such low values of ratios. The best efficiency lies above 8 percent, which is extremely high for jet engines build in this manner.



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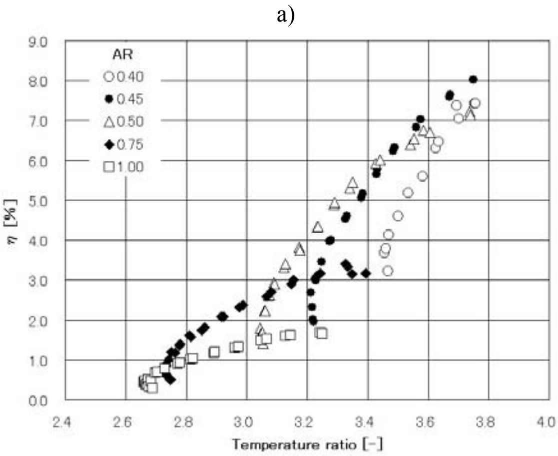

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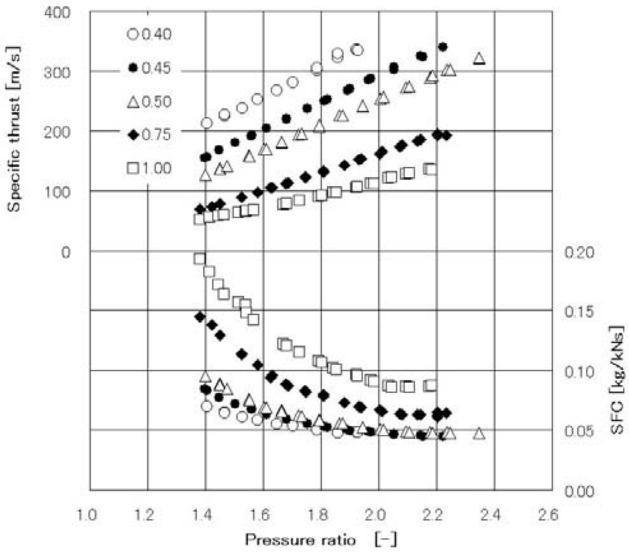
Fig. 9 Thermal efficiency estimated from thrust

Specific thrust and specific fuel consumption rate are plotted against pressure/temperature ratio in Fig. 10. As the efficiency plots, general trend is that a higher ratio gives a higher performance.



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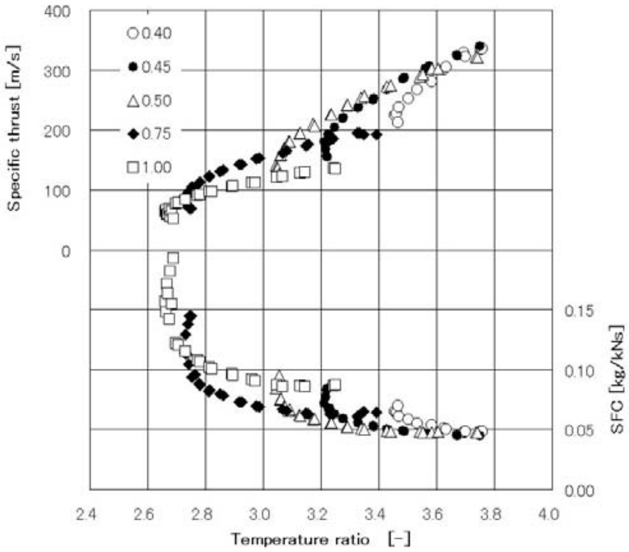

b)

Fig. 10 Specific thrust and fuel consumption rate

CONCLUSIONS

The two yeas educational project achieved an optimized performance of a student designed small jet engine. The basis for future student experiments has been completed.

As well as the performance of the engine, we must notice that the educational effects are significant. All the students got very deep understandings on the basic characteristics of jet engines through this project.

Acknowledgement

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