Laboratory Experience with a Model Jet Turbine

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Abstract

This paper describes the experience gained from the operation of a JetCat model turbojet engine as part of an undergraduate mechanical engineering program. The engine was remotely controlled from a laptop using Jettronic for Windows software for the serial interface. Engine speed, fuel consumption, and exhaust gas temperature were measured using the software and the thrust was determined from a digital force gauge and compared with calculations based on different readings. Students designed the turbine mount and a safety enclosure for the engine. The use of this engine has been a low cost alternative to other commercially available turbojet laboratory systems.

Introduction

It is now 65 years since the first successful flight using a jet turbine in the Heinkel He 178 aircraft[1]. Since then, modern turbo-jets have been developed to a high level of sophistication. During the last 15 years, model aircraft builders have also developed fully functional scale versions of jet turbines[2-4]. In recent years the Turbine Technologies SR-30 turbojet engines have been used in mechanical engineering laboratories[5-7]. Another available laboratory system is the Powertek axial flow gas turbine engine. Our choice was to purchase a lower cost model aircraft engine kit that included all the necessary auxiliary equipment.

In this study, a turbojet laboratory system was set up in the undergraduate manufacturing course, and used for labs and demonstration purposes in fluid mechanics and applied thermodynamics[8]. The laboratory set up consists of a JetCat P-70 model jet engine and subsystems required for operation. The turbojet engine with a weight of only 1.2 kg and a diameter of 94 mm produces a maximum thrust of around 70 N at 120,000 rpm. The idle rpm is 35,000. The instrumentation provided with the engine includes a temperature sensor at the exhaust exit and a speed sensor. Furthermore, an electronic control unit (ECU) simplifies start up and assures safe operation by maintaining turbine rpm within certain limits. A support unit (GSU) was connected to the ECU for monitoring parameters such as temperature, rpm, and fuel pump voltage. By using a RS-232 serial

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interface and Windows software, the ECU was linked to a laptop computer for download of operational data. The software also allowed the user to start and stop the turbine and to set desired rpm, see figure 1.

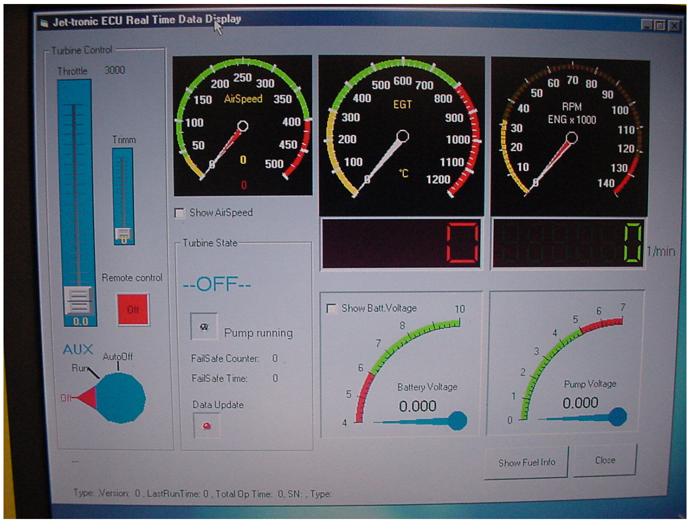

Fig. 1. Jettronic for Windows software used to control the jet turbine

Engine thrust was measured using Transducer Techniques HFG-45 digital force gauge, see figure 2. The engine could operate using deodorized kerosene, 1-K kerosene or Jet-A1 fuel. The fuel was mixed with 5 % Aeroshell 500 turbine oil and Coleman Powermax fuel was used as starting gas during initial startup driven by an electric motor positioned at the intake of the turbine.

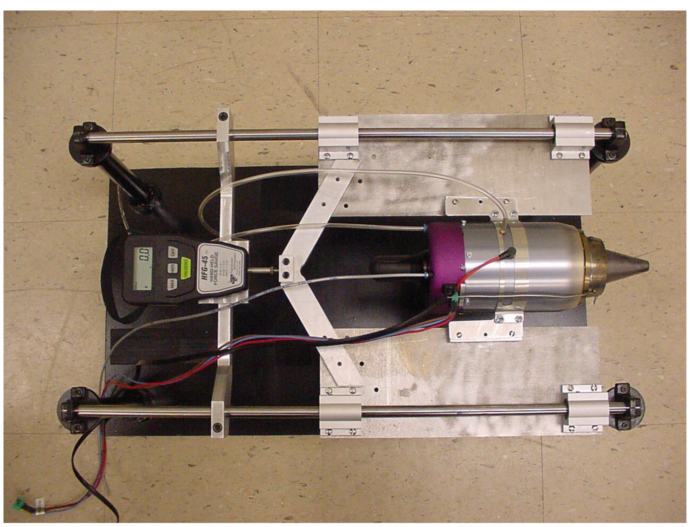

Fig. 2. Test stand including engine and digital force gauge

Students designed and fabricated the basic engine mount based on four linear bearings for movement. The entire mount was screwed to a removable plate attached to a cart. A

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safety system was installed by enclosing the engine with polycarbonate. Two fans were added at the top to blow along the polycarbonate in order to ensure that it would not be overheated, see figure 3.

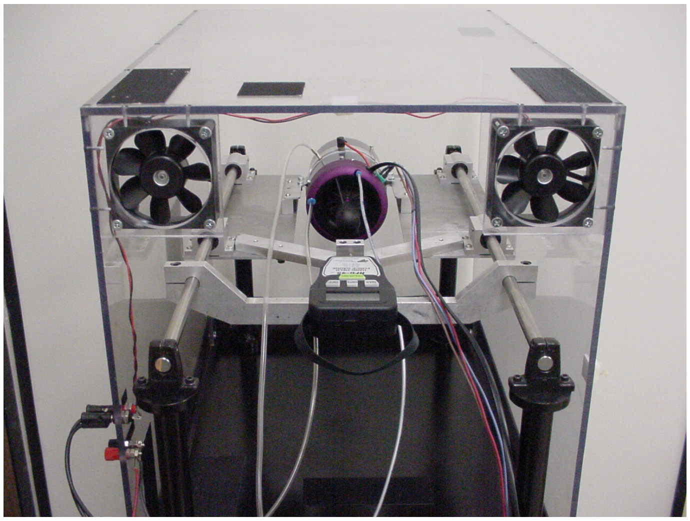

Fig. 3. Engine test stand showing polycarbonate enclosure and cooling fans.

Theory

The properties that can be measured and calculated using this system are listed in Table 1. The thrust measured by the force gauge was compared with theoretical results based on the turbine's outlet triangle and the mean peripheral speed *u* related to the mean diameter of the turbine wheel $d_m = 0.0553m$ and the rotational speed *n*.

$$u = \pi n d_m \tag{1}$$

Measured Properties	***Calculated Properties***
Rotational Speed *n (*120,000 rpm*)*	Compressor Pressure Ratio p_c / p_a (2.43)
Turbine Exit Temperature T_{exit} (620 °C)	Turbine Exit Temperature T_{exit} (789 °C)
Thrust *F (*71.3 N*)*	Thrust *F* (71.4 N)
Fuel Flow Rate $\dot{V}_{fuel}$ (270 ml/min)	Fuel Flow Rate $\dot{V}_{fuel}$ (320 ml/min)
Compressor Inlet Temperature T_{inlet} (20 °C)	Compressor Temperature Ratio T_c / T_{inlet} (1.29)

Table 1. A list of measured and calculated properties. The given values were determined at full power.

The outlet speed U_{exit} is perpendicular to *u,* and parallel to the rotational axis. The outlet angle α of the turbine blades was measured to be approximately 41°. The outlet speed can then be determined from the relation

$$U_{exit} = u \tan \alpha \tag{2}$$

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The mass flow rate through the engine can be determined by

$$\dot{m} = \rho_{exit} U_{exit} A_{exit} \tag{3}$$

where the cross sectional area of the outlet

$$A_{exit} = \frac{\pi\left(d_{o,exit}^2 - d_{i,exit}^2\right)}{4} \tag{4}$$

is based on the outer $d_{o,exit} = 0.0667\,m$ and inner $d_{i,exit} = 0.0439\,m$ diameters of the turbine wheel. The density depends on the nozzle gas exit temperature T_{exit} and atmospheric pressure p_a as determined from the ideal gas relation

$$\rho_{exit} = \frac{p_a}{RT_{exit}} \tag{5}$$

where *R* is the gas constant. The thrust can finally be determined from

$$F = \dot{m} U_{exit} = \rho_{exit} A_{exit} \pi^2 n^2 d_m^2 \tan^2 \alpha \tag{6}$$

where we have neglected the inlet air velocity and assumed a high air-fuel mass ratio. The compressor stage pressure ratio can be calculated from the shaft power $\dot{W}_s$ and the mass flow rate $\dot{m}$

$$\frac{p_c}{p_a} = \left(\frac{\eta_c \dot{W}_s}{\dot{m} c_p T_{inlet}} + 1\right)^{\frac{\gamma}{\gamma-1}} \tag{7}$$

where γ is the ratio of specific heats, η_c is the compressor efficiency, c_p is the specific heat of air at constant pressure and T_{inlet} is the inlet air temperature. Since the shaft power of the turbine wheel can be expressed as

$$\dot{W}_s = \dot{m} u^2 \tag{8}$$

we get the following relation for the pressure ratio over the compressor

$$\frac{p_c}{p_a} = \left(\frac{\eta_c \pi^2 n^2 d_m^2}{c_p T_{inlet}} + 1\right)^{\frac{\gamma}{\gamma-1}} \tag{9}$$

and the corresponding temperature ratio over the compressor is

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$$\frac{T_c}{T_{inlet}} = \left(\frac{p_c}{p_a}\right)^{\frac{\gamma-1}{\gamma}} \tag{10}$$

The temperature at the turbine exit can approximately be determined from the given pressure ratio, the input power at the turbine stage and the turbine efficiency η_t

$$T_{exit} = \frac{\pi^2 n^2 d_m^2 \left(1 + \frac{\tan^2 \alpha}{2}\right)}{\eta_t c_p \left(1 - \left(\frac{p_c}{p_a}\right)^{\frac{1-\gamma}{\gamma}}\right)} \tag{11}$$

The fuel consumption can be calculated under the assumption that the thermal energy is used to heat the working medium. The thermal output $\dot{Q}$ is determined from

$$\dot{Q} = c_p \dot{m} \Delta T \tag{12}$$

where $\Delta T = T_{exit} - T_{inlet}$ is the temperature difference between inlet and outlet as measured by the thermocouple in figure 4. The fuel consumption is

$$\dot{V}_{fuel} = \frac{\dot{Q}}{\rho_{fuel} h_{fuel}} = \frac{c_p \rho_{exit} \pi n d_m A_{exit} \Delta T \tan \alpha}{\rho_{fuel} h_{fuel}} \tag{13}$$

where ρ_{fuel} is fuel density and h_{fuel} is the heating value of the fuel.

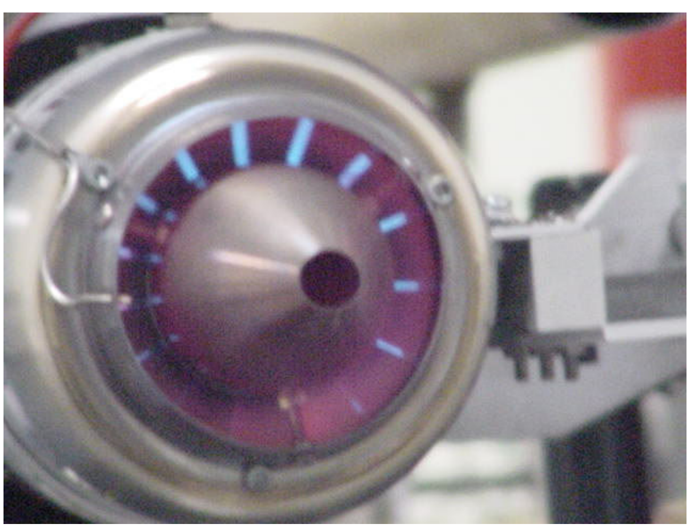

Fig. 4. Jet turbine shown running at 78,000 rpm.

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Laboratory Teaching

Prior to the laboratory, the students have to read the laboratory manual, understand the derivations of the relevant equations and take a quiz on the material covered in the laboratory.

During the lab, students can read fuel consumption directly on the GSU unit or on the computer screen but they also have to determine fuel consumption by weighing the fuel tank before and after a test run at a certain rpm. Thereby, students determine fuel consumption in several different ways including the use of equation 13.

From the force gauge, the students measure the thrust in pounds and apply unit conversions to SI units. The engine is also attached to a spring with a known spring constant giving an alternative means of determining the thrust produced by the engine by measuring displacement of the spring.

The inlet airflow rate was measured using an Extech 451212 vane anemometer adapter mounted in a Plexiglas cylinder that can be attached to the turbine, see figure 5. In this way the students are able to check if the assumptions made in the derivation of equation 6 are reasonable. Furthermore, as an alternative way of measuring the inlet airflow rate a Prandtl tube with a semi-spherical nose can be used to measure the dynamic pressure as the difference between the total pressure at the nose and static pressure further downstream along the Prandtl tube. The students are thereby introduced to two common methods of measuring airflow speed in experimental fluid dynamics. The pressure ratio over the compressor is measured using a Scanivalve model PDCR23 differential pressure transducer.

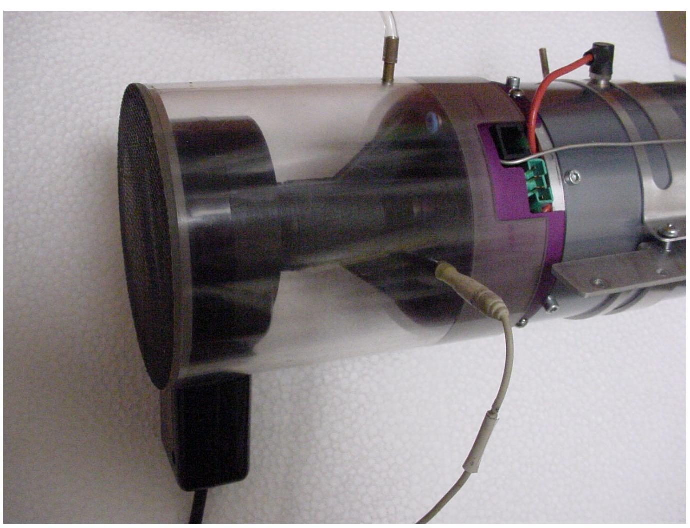

Fig. 5. Vane anemometer attached to the jet turbine inlet

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The students also have to take digital photographs of the test stand and short movies of the running engine using a Sony MVC-FD90 camera. The photographs are included in their lab reports.

Further improvements of this laboratory set-up will include using LabView software to acquire the signals from the force gauge, the pressure transducers and the inlet temperature sensor. Moreover, the temperature after the compressor stage will be measured together with the temperature before the turbine stage. This will enable the students to perform continuous sampling of a wider range of properties.

Conclusions

This paper has shown a model jet turbine project done by undergraduate students in mechanical engineering. It was initiated as a project in manufacturing processes where the students designed the engine mount and a safety enclosure. The turbine was used in a fluid mechanics laboratory where the students applied their knowledge gained from the thermodynamics course. The measured and calculated thrusts were in good agreement while the engine exit temperatures and fuel flow rates were lower in the measurements.

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