Operating Experience with the Turbine Technologies SR-30 Turbojet Engine Test System

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Abstract

The experience gained from the operation of a commercially available turbojet engine laboratory system is described. This system, the Turbine Technologies, Ltd. Mini-Lab^{TM}, is suitable for use in undergraduate mechanical and aeronautical engineering laboratories. Key turbojet engine performance parameters can be computed from the data measured during test runs. The use of this system provides an excellent opportunity for students to apply the principles of thermodynamics.

The Mini-Lab^{TM} was acquired by the Mechanical Engineering Department of Loyola Marymount University (LMU) during the fall semester of 1999. It was checked out and interested faculty members were trained in the use of the system. The system was installed in the Thermal Sciences Laboratory at LMU and approved for operation by the university's Environmental Health and Safety Officer. The installation included providing the necessary utilities, building a baffled intake manifold for sound suppression and building a double-walled exhaust manifold for exhaust gas expulsion, thermal protection and sound suppression.

The Mini-Lab^{TM} includes the SR-30 turbojet engine, the auxiliary subsystems required for the operation of the engine, controls, a safety enclosure, the instrumentation needed to acquire the experimental data and the data acquisition interface. The engine consists of a conical diffuser, a centrifugal compressor, a reverse flow annular combustor, an axial flow turbine and a converging conical exhaust nozzle. The system has been used in LMU's senior mechanical engineering laboratory for the past two years and for demonstrations during open house type events. Engine speed, various pressures and temperatures, fuel flowrate and thrust are measured. Using these measured data, thermodynamic relationships, and property data, the following performance parameters can be determined: compressor, turbine and exhaust nozzle adiabatic efficiencies; fuel-air ratio; air mass flowrate; engine thermal efficiency; specific thrust; and thrust specific fuel consumption. In addition, the thrust can be computed from exhaust nozzle data and compared with the measured thrust.

Overall, the operational experience and test results have been very good. There are some exceptions to the test results that are most likely related to measurement errors. The most notable exceptions are the values of the turbine and nozzle isentropic efficiencies (computed from the measured data) which are too large (sometimes exceeding 100%). A second exception is the value of the thrust computed from the measured data, which does not agree with the measured value of the thrust. The use of unshielded thermocouples is one source of measurement error that would affect both of these results. The method of measuring thrust is a second (possible) source of error.

Background

In 1999, Loyola Marymount University (LMU) made the decision to add a turbojet engine to its undergraduate mechanical engineering laboratory. A laboratory turbojet engine system is a desirable addition to an undergraduate mechanical or aeronautical engineering laboratory for three reasons. First, experimental studies using such a system are an excellent opportunity to apply thermodynamics principles. Second, EAC/ABET likes to see students experimentally studying thermodynamic systems. Third, the turbojet engine is an important contemporary product. Gas turbine engines provide the propulsion for the majority of commercial and military aircraft. Variations of aircraft gas turbine engines include turboprop, turbojet and fan jet engines. Conceptually, the turbojet engine is the simplest of these three propulsion systems and, thus, was selected for inclusion in LMU's undergraduate Thermal Sciences Laboratory. After reviewing commercially available products that were suitable for LMU's application, a Turbine Technologies, LTD (TTL) Model 2000DX Mini-Lab^{TM} system (Reference 1) was acquired. This system is shown in Figure 1 (with safety shield tilted up and back). The heart of this system is the TTL Model SR-30 turbojet engine, Figure 2. The specifications for this system are described in Reference 1 and the system is described in Reference 2.

Figure 1. The TTL Mini-Lab^{TM} Test System

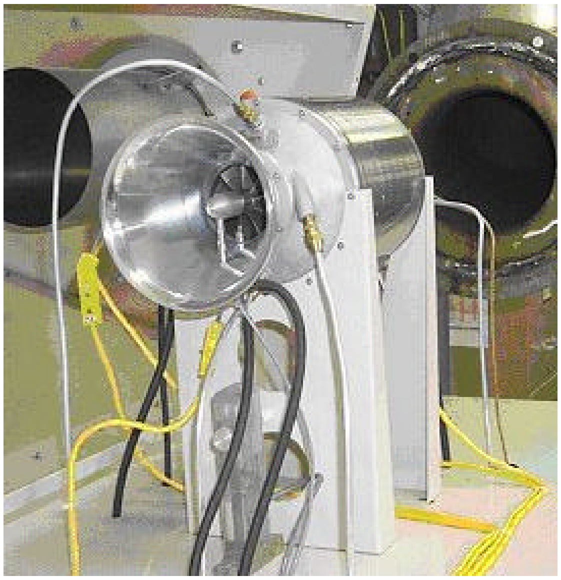

Figure 2. The TTL SR-30 Turbojet Engine

Installation

The Mini-Lab^{TM} system is advertised as a "turnkey" system and training for personnel who may be working with it is included with its purchase. The system includes the auxiliary subsystems required for the operation of the SR-30 engine. These include fuel, lubrication and ignition subsystems. It requires 110 v, 60 Hz AC electrical power and a source of 100 psig compressed air (for starting the engine). However, it is not suitable for indoor operation as delivered because of the noise and exhaust gases. The noise level can be reduced by adding an acoustical intake manifold and a dual pipe insulated exhaust. The exhaust system directs the exhaust gases out of the laboratory building. Mr. Michael Vocaturo of Princeton University provided valuable suggestions for designing both an intake manifold and an exhaust system (Reference 3). His suggestions were based on their design and operating experience.


Figure 3. Acoustical Intake Manifold


Figure 4. Mini-Lab™ with Intake and Exhaust System

The intake manifold is a reverse flow, folded wave guide chamber approximately 6 ft. high, 4 ft. wide and 2 ft. deep. It is fabricated of high density particle board. The inside surfaces are lined with fiberglas, covered by canvas, for sound absorption (Figure 3). The intake air enters the manifold through an 8 inch by 18 inch rectangular opening, flows downward through the right chamber, flows into the left chamber, reverses direction and exits through a 13 inch diameter opening, flowing into the Mini-Lab™ system (Figure 4). The exhaust system consists of concentric 8 and 12 inch diameter stainless steel ducts with a high temperature mineral wool insulation between ducts (see Figure 4). A section of 8 inch duct extends into the test chamber to capture the exhaust jet and to entrain cooler air into the exhaust duct. This design absorbs sound and provides some thermal protection. The installed Mini-Lab™ system is shown in Figure 5. The SR-30 turbojet engine is enclosed in a steel and polycarbonate cabinet to provide protection to the operators in the event of a mechanical failure. This enclosure transmits sound. The noise level in the laboratory room where the system is installed is 100 dBA when the engine is operating at top speed. The corresponding OSHA Action Limit is 1.15 hours. Typical test programs can be completed in about 0.5 hours. Nevertheless, students conducting or observing tests are required to wear ear plugs. The installed engine was approved for student use by the university's environmental health and safety officer.


Figure 5. Jet Engine Installation Ready for Testing

The SR-30 Engine, Its Instrumentation and Operation

The SR-30 turbojet engine, Figure 6, produces a maximum thrust of approximately 130 N (about 30 lbf). Referring to Figure 6, air enters the diffuser of the engine from the left and the products of combustion exit the nozzle of the engine to the right. From the diffuser, the air flows into the centrifugal flow compressor where a typical pressure ratio is about 3.5:1. The high-pressure air enters the reverse-flow annular combustor where the products of combustion leave the combustor at temperatures in the range of 600-800 ^{o}C (1100-1500 ^{o}F). The products of combustion enter the single stage axial flow turbine where a typical pressure ratio is 1:2.3. From the turbine, the gases flow through the converging conical nozzle exiting the engine with a typical computed exhaust velocity of 450 m/s (about 1475 ft./sec.) and a Mach number of about 0.8.

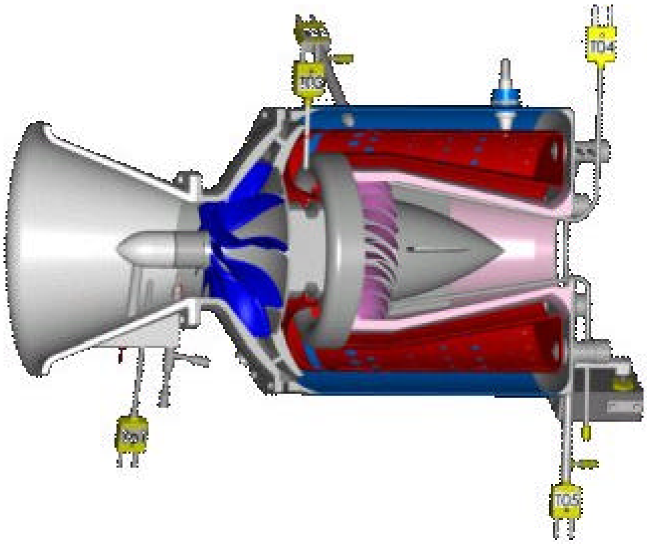

Figure 6. Drawing of the SR-30 Turbojet Engine, Reference 1.

The instrumentation provided with the SR-30 engine includes temperature and pressure sensors at the following locations: compressor inlet, combustor inlet, turbine inlet, exhaust nozzle inlet and exhaust nozzle exit. The temperature sensors are Type-K thermocouples and the pressure sensors are piezoresitive pressure transducers. The engine speed sensor is a 2-pole generator driven by the engine. Fuel mass flowrate is determined using a pressure transducer system that monitors the fuel injector return flow pressure. Engine thrust is measured using a strain gage type load cell. The load cell measures the force about halfway up the front engine support and is visible in Figure 2. Calibration factors are provided for each of the sensors (Reference 4). The data acquisition interface is located on the side of the cabinet. In addition, there are digital meters on the Mini-Lab^{TM} console that indicate exhaust gas temperature, engine speed and thrust and analog meters that indicate oil pressure, combustor pressure, fuel pressure and compressed air pressure. A computer data acquisition system is available from TTL for collecting and processing the data. However, in order to give the students a better understanding of what is involved in data processing, the data generated by the LMU system is collected using instruments that measure sensor output directly (except for the thermocouples). The output of the pressure transducers, load cell and fuel flow system are fed through a switching box to a Kiethley Model 175A Autoranging Digital Multimeter. The output of the thermocouples was measured using an Omega Model DP25-TC Digital Thermocouple Controller.

The operating procedure is described in Reference 4. The following is an overview of that procedure. Prior to the test, the fuel, lubricating and compressed air systems must be checked to insure they are functioning properly and adequately supplied for the tests planned. The engine operates satisfactorily using a variety of fuels (e.g., various grades of jet engine fuel, kerosene and diesel fuel). Various switches are turned on in sequence to power up the instrumentation and auxiliary systems and initial meter readings are checked. The ignitor is switched on and its functioning verified. The throttle is pushed into the wide-open position. The compressed air is turned on, rotating the turbine. When the rotational speed of the engine reaches a specified value (5000 rpm for the initial start and 7000 rpm for subsequent starts), the fuel pump is turned on and ignition occurs. The engine speed increases rapidly and the throttle is pulled back to idle the engine at about 50,000 rpm. The compressed air supply and ignitor are shut down and initial instrument values are checked. The system is now ready for conducting tests. The emergency shutdown procedure is to switch off the fuel pump.

Experimental Results Obtainable

The most obvious choice of controlled (i.e., independent) variable when conducting tests with this engine system is the engine speed. The properties that can be measured with the system instrumentation are listed in Table 1. These measured properties can be presented graphically as a function of engine speed. The temperatures and the pressures, except for the compressor inlet pressure, are stagnation values (Reference 4). The compressor inlet pressure is the difference between the stagnation and static pressures at that location. In addition, the turbojet engine component and system performance parameters listed in Table 2 can be computed using thermodynamic relationships and appropriate thermodynamic properties. The required relationships can be found in most engineering thermodynamics textbooks (for example Reference 5). The needed thermodynamic properties for air and the products of combustion of jet engine fuel burning with air at various mixture ratios can be found in Reference 6, Appendix D. A sample of typical results, taken from Reference 7, are shown in Figures 7 and 8. As indicated in these figures, the thrust of the engine varies almost linearly with engine speed and the compressor adiabatic efficiency is essentially constant at about 60%. A complete set of engine performance parameters for one run (reference 7) is shown in Table 3. These results are typical of the tests that have been conducted at LMU.

Table 1. Measured Properties
Engine Speed
Compressor Inlet Pitot-Static Pressure
Combustor Inlet Pressure
Turbine Inlet Pressure
Nozzle Inlet Pressure
Nozzle Exit Pressure
Compressor Inlet Temperature
Combustor Inlet Temperature
Turbine Inlet Temperature
Nozzle Inlet Temperature
Nozzle Exit Temperature
Thrust
Fuel Mass Flow Rate

Table 2. Computed Performance Parameters
Compressor Adiabatic Efficiency
Turbine Adiabatic Efficiency
Combustor Fuel-Air Ratio (computed assuming that the combustor is adiabatic)
Air Mass Flowrate
Nozzle Exit Velocity
Nozzle Efficiency
Engine Thermal Efficiency
Thrust Specific Fuel Consumption
Specific Thrust
Thrust (computed independently of the measured thrust from measured and computed properties)

Discussion

Three of the results shown in Table 3 are obviously incorrect. They are the turbine adiabatic efficiency, the nozzle adiabatic efficiency and the thrust computed from measured data. It appears that these problems are caused by temperature measurement errors. The

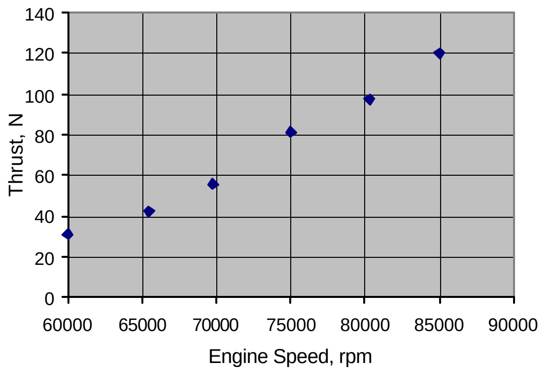

Figure 7. Measured Thrust as a Function of Engine Speed for the SR-30 Engine

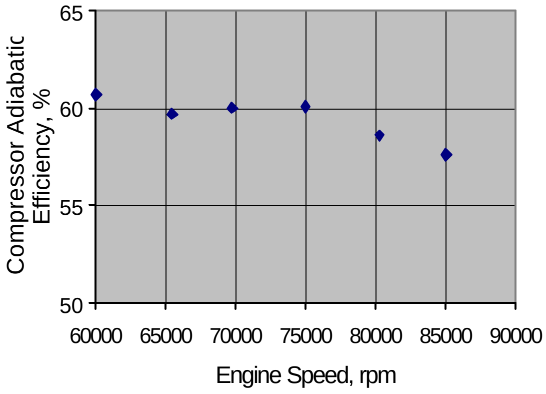

Figure 8. Compressor Adiabatic Efficiency vs. Engine Speed

Table 3. Computed Performance Parameters (Reference 7)	
Engine Speed, rpm	85040
Compressor Adiabatic Efficiency, %	57.6
Turbine Adiabatic Efficiency, %	111
Combustor Fuel-Air Ratio	0.016
Air Mass Flowrate, kg/s	0.296
Nozzle Exit velocity, m/s	463
Nozzle Efficiency, %	211
Engine thermal Efficiency, %	15.9
Thrust Specific Fuel Consumption, (kg fuel/s)/N	3.95×10^{-5}
Specific Thrust, N/(kg air/s)	405
Thrust Computed from Measured Data, N	139
Thrust, N	120

thermocouple probe inserted into the exhaust gas stream is sheathed and bulky (about 5 mm in diameter) and "sees" cold surfaces in more than 50% of its view. This probe can be seen in Figure 6 (the probe marked T_{05} in the lower right-hand corner). Thus, the indicated temperature is significantly lower than the true exhaust gas temperature. This results in a computed exhaust gas velocity that is too large, explaining a nozzle efficiency greater than 100% and a thrust, computed using this value of the velocity, that is larger than the measured thrust. The incorrect turbine efficiency can be explained in a similar fashion. The thrust measurement is subject to an error due to mechanical hysteresis because of the manner in which it is taken (measuring a force on the engine support structure). A further measurement problem is the probe used to measure the pitot-static pressure difference at compressor inlet. It appears that the probe is either improperly designed or improperly oriented in the air stream at that location.

Conclusions

The overall performance of the TTL Mini-Lab^{TM} turbojet engine system has been very satisfactory. The experimentally determined values of the thrust specific fuel consumption and the specific thrust for the SR-30 shown in Table 3 compare favorably with published results, 2.83×10^{-5} (kg fuel/s)/N and 490 N/(kg air/s) respectively, for the J69-T-25, a small (thrust of

4560 N) military turbojet engine (Reference 6, Appendix B). The use of this engine has complemented the classroom instruction in LMU's Thermodynamics and Propulsion courses.

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