Micro-Jet Test Facility for Aerospace Propulsion Engineering Education*

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This paper describes the methodology that has been developed and implemented at the School of Aeronautics (ETSIA) of the Universidad Politecnica de Madrid (UPM) to familiarize aerospace engineering students with the operation of real complex jet engine systems. This methodology has a two-pronged approach: students carry out preparatory work by using, first, a gas turbine performance prediction numerical code; then they validate their assumptions and results on an experimental test rig. When looking at the educational aspects, we have taken care that, apart from being sufficiently robust and flexible, the experimental set-up is similar to real jet engine rigs, so the students are not constrained to exploring a much too limited parametric space. Also, because a facility like this is usually subject to extensive and somewhat rugged use, we have focused on a low cost design.

Keywords: micro-jet engine test facility; aerospace propulsion

INTRODUCTION

AEROSPACE ENGINEERING EDUCATION in Europe is undergoing a significant change for two reasons: (1) the aerospace industry, which used to be a mostly national concern, is now consolidating at the continental level, and (2) a common frame of engineering education is developing under the so-called Bologna initiative. In this context, many different approaches are being tested to fulfil the objective of producing well trained professionals who will be able to generate significant added value when they join companies that compete at a global level. Furthermore, the problem of educating engineers for an increasingly competitive market is not only of European concern, as in the article by Joshi [1]. It this paper, the author argued for the need to evolve the aerospace engineering education system and proposed a series of approaches. In particular, he stressed the need to adopt a concurrent engineering approach, if only because industry is ranking acquisition and life cycle costs at the same level as they rank technical performance. On the educational side, Joshi [1] proposes that students obtain a more comprehensive view of the practical aspects of engineering systems, which include manufacturing, performance prediction, the understanding of support systems and, last but not least, business plans.

Jet propulsion is an essential topic in aerospace engineering. Its study addresses the design, diagnostics, and selection of power plants for a large number of different platforms, both civil and military. At this point, two competing aspects should be considered: (1) a comprehensive understanding of these systems is based on acquiring theoretical, computational and experimental test knowledge, and (2) the cost of a jet engine experimental facility is too high for many public universities, not to mention the environmental aspects associated with the fact that some of these institutions, like ours, are located in downtown areas. So, if we want to retain an approach that combines the advantages of theoretical, computational and experimental knowledge [2] in the frame of a concurrent engineering point of view, a micro-jet engine would be one way to proceed.

These types of small engines are not new, although they have been used in other contexts; in particular, a very interesting example has been reported by Santeler and Wagner [3] who presented a study on a home built gas turbine engine. Also of interest are the articles published by Ross [4], Rodgers [5], Akbari and Muller [6] and Tesson et al. [7]. In particular, these papers deal with the operation and research of small engines and they show that this technology is both robust and affordable, so it could be adapted for engineering education purposes. In our case, the test rig that we set up allows the students to obtain both the on-design and off-design characteristics of the jet engine, as well as a series of relevant performance parameters such as: exhaust gas emissions, noise measurement, transient behaviour, and starting and acceleration times. The students of ETSIA can also characterise the engine cycle, so they can correlate it with theoretical and numerical simulation models. That is, we believe that this hands-on approach really helps familiarise the student, at an affordable cost, with a type of a complex aerospace engineering system that, otherwise, they would only encounter in books.

The paper is organised as follows: first the experimental test bench is described. Then, the educational goals that we pursue and the type of activities that the students perform are detailed.

EXPERIMENTAL TEST BENCH

At the core of the experimental facility is the mini jet engine Olympus HP, see Fig. 1, manufactured by AMT Netherlands. It is a single shaft jet engine, with a centrifugal compressor, a unique single stage axial flow turbine, an annular combustion chamber, a bellmouth inlet, and a fixed convergent nozzle. The working cycle is the Brayton cycle. The Olympus engine was released in 1995 for large model aeroplanes and special applications, such as target and surveillance drones, providing excellent performance and a high power-to-weight ratio. The engine runs on liquid fuel, either kerosene or Jet A-1, and needs no separate oil reservoir as the hybrid bearings are lubricated by a small percentage of oil added to the fuel, which has proved to yield maximum reliability and robustness. The engine uses a fully automatic microprocessor based Electronic Control Unit (ECU) with pre-programmed software. It offers several innovative features, including assisted start-up and shut-down programmes, data display, retrieval and storage facilities, with a basic telemetry software (exit gas temperature EGT, engine speed and engine condition) and a fail-safe system. The main engine characteristics are given in Table 1.

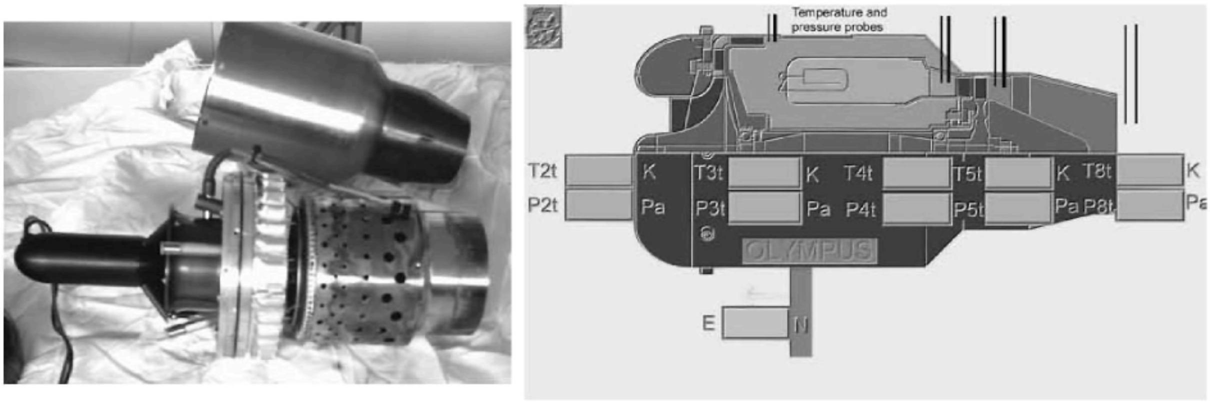
Fig. 1. View of the Olympus jet engine.

To gather the data needed for appropriate performance assessment, the following parameters need to be measured: fuel flow, air flow, thrust, total pressures and total temperatures at all engine stations, inlet conditions, test cell temperature and pressure, barometric pressure, and ambient humidity. Accordingly, we disassembled the engine and inserted total pressure and total temperature probes, as shown in Figs 2(a) and 2(b). The signal from the thermocouples is then driven to signal conditioners, while the pneumatic signal from the pressure probes goes to individual dedicated pressure transducers. Because the flow is not uniform at the engine stations, a complete assessment of the flow field would require the use of pressure taps and thermocouples located at different positions on the circumference. However, we have not inserted these because it would lead to a blockage of flow in the duct (the passage height in the compressor exit being 5.2 mm) and generate interference effects [8] that would degrade engine performance. That is, only one pressure and one temperature probe were installed at each station, except for at the combustion chamber exit, where two opposing thermocouples were placed. This setting of the probes led to an engine thrust loss of about 10% of its nominal value. Fuel flow rate is determined by using a fuel flow measurement system that consists of a turbine flow meter connected to a digital frequency counter and signal conditioner. Engine thrust is measured by means of a standard load cell attached to a pedestal supported by the test cell floor, see Fig. 3. The engine speed measurement system is made up of a magnetic pickup placed in front of compressor blades, which creates a pulse when

Table 1. Characteristics of the Olympus HP engine

Engine	Olympus HP (Electric start-up)	Olympus HP (Air start-up)
Diameter	130 mm	130 mm
Length	374 mm	267 mm
Weight	2.850 kg	2.475 kg
Thrust (STP*)	230 N (108 000 rpm)	190 N (108 000 rpm)
Maximum rpm. (N_{MAX})	112 000 rpm	112 000
Iddle rpm	36 000 rpm	36 000 rpm
Thrust (Iddle rpm)	8 N	—
Pressure ratio (N_{MAX})	4 : 1	4:1
Exhaust gas temperature (EGT)	973 K	973 K
Maximum EGT	1023 K	1023 K
Mass flow (STP, 108000 rpm)	0.45 kg/s	0.4 kg/s
Fuel flow (STP, 108,000 rpm)	0.64 kg/min.	0.4 kg/min
Fuel type	JET A1 – Kerosene	JET A1 – Kerosene
Oil	Aeroshell 500	Aeroshell 500

* STP : ISO sea level standard day (T_0 = 288 K, P_0 = 101 325 Pa)



(a) (b)

Fig. 2. View of the disassembled engine (a) and location of probes (b).

the compressor blade crosses in front of it. The use of a conventional calibrated nozzle to measure engine airflow posed some difficulties because of the engine size, so we decided to measure the flow indirectly from total pressure and temperature measurements in the engine nozzle exit after performing a calibration exercise. Finally, the data acquisition system allowed the students to store engine run data in a portable memory device so that they could use it for their homework.

Finally, it is to be mentioned that the cost of the full facility is €44 000 or about US$59 400. The annual maintenance costs are €1000 (US$1350). This cost seems to be competitive as we have already been awarded a contract to set up a similar facility at Universidad Politecnica de Valencia (UPV) in Spain.

STUDENT ACTIVITIES AND ASSESSMENT

The main objective of the experimental work carried out by the students is the evaluation of system performance and its comparison with the theoretical results. This comparison is carried out on two levels: (1) by using simple textbook analytical models and (2) by running commercial numerical simulation codes, like Gasturb or GSP, that are also used for industrial applications in the gas turbine industry. Regarding the simple engineering models, a summary of the equations used is given in Table 2 for the sake of completeness. The nomenclature that we use in this table is standard in the gas turbine field [9]. The interested reader could find a good review of these models in the books of Oates [10] and Kerrebrock [11]. As for the commercial codes, we find that our experimental facility provides a natural environment (and opportunity) for introducing the student into the practice of using tools that are the day-to-day workhorse of the gas turbine industry. In particular, we organize the students' work as a series of consecutive steps as follows:

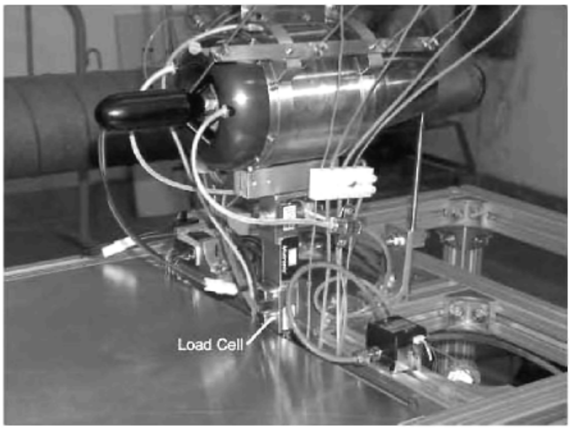


Fig. 3. General picture of the educational experimental set-up.

- Use of the automatic data acquisition system to measure pressure and temperatures at each station engine, thrust, fuel flow, and engine speed at several different engine speeds at steady state.
- Data averaging and editing. Once the data acquisition has been carried out, an averaging is performed. These parameters are then used in the performance calculations.
- Data validation and uncertainty analysis. That is: assessment of the acceptability of the measured data.
- Estimation of values of the actual efficiencies of the compressor, the combustion chamber and the turbine at on-design from experimental measurements of pressure and temperature at each engine station.
- Determination of theoretical values of engine thrust and SFC by a simple model and commercial computer codes at on-design. Comparison with the experimental results.
- Determination of the theoretical operating line on a compressor map. Comparison with experimental results.
- Study of the influence of engine speed on thrust, specific fuel consumption, air–fuel ratio, compressor pressure ratio, and engine pressure ratio. Comparison with experimental results, and

results obtained by using analytical simple models and commercial computer codes. Use of different approaches and assessment of the possible error sources.
- Comparison of the thrust specific fuel consumption of this engine with the thrust specific fuel consumption of large jet engines.

In the near future, we are also planning to maximize the benefits that we get from this facility by addressing the following additional aspects:

- Engine noise measurement carried out by placing the microphone at several positions around the engine. Study of the frequency spectra and discrimination by engine component and regimes.
- Measurement of emission level of the main pollutants as a function of the engine operating regime. Comparison with theoretical results obtained from semi-empirical correlations and commercial computer codes.

Regarding the practical methodology, the students first compare performance parameters for different inlet conditions and perform the required corrections to achieve common reference conditions using the International Standard Atmosphere (ISA) nomenclature: $\theta = T_{amb}(K)/288,15$, $\delta = P_{amb}(kPa)/101,355$. Corrections are then applied to engine thrust, mass airflow rate, fuel flow rate and specific fuel consumption to obtain the well known corrected values (*): $T^* = T/\delta$, $W^* = W\theta^{1/2}/\delta$, $c^* = c/(\theta^{1/2}\delta)$, and $c_E^* = c_E/\theta^{1/2}$. To obtain consistent engine performance results, actual maps of the different components, compressor, turbine, intake, nozzle, and combustion chamber, are needed. Since we only have the compressor map supplied by the engine manufacturer, the students work out the remaining maps for themselves using the simple theoretical models, the numerical simulation results and the experimental measurements. A sample of the results that the students obtain is presented in Figs 4(a)–(c). The

Table 2. Summary of the analytical expressions used by the students in their work.

Inlet

$$T_{2t} = T_0\left(1 + \frac{\gamma_c - 1}{2} M_0^2\right)$$

$$P_{2t} = \pi_{02} P_0\left(1 + \frac{\gamma_c - 1}{2} M_0^2\right)^{\frac{\gamma_c}{\gamma_c - 1}}$$

Compressor

$$P_{3t} = \pi_{23} P_{2t}$$

$$\eta_{23} = \frac{\pi_{23}^{\frac{\gamma_c - 1}{\gamma_c}} - 1}{\frac{T_{3t}}{T_{2t}} - 1}$$

Combustion

$$P_{4t} = \pi_{34} P_{3t}$$

$$\eta_q W_f L = (W_a + W_f)\,\bar{c}_p(T_{4t} - T_{3t})$$

Turbine

$$(W_a + W_f) c_{Pe}(T_{4t} - T_{5t}) = W_a c_{Pc}(T_{3t} - T_{2t})$$

$$\eta_{45} = \frac{1 - \frac{T_{5t}}{T_{4t}}}{1 - \left(\frac{P_{5t}}{P_{4t}}\right)^{\frac{\gamma_e - 1}{\gamma_e}}}$$

Nozzle

$$P_{8t} = P_{5t}$$

$$\frac{P_{5t}}{P_0} \le \left(\frac{\gamma_e + 1}{2}\right)^{\frac{\gamma_e}{\gamma_e - 1}} \Rightarrow P_8 = P_0$$

$$V_8 = \sqrt{2 c_{Pe} T_{5t}\left(1 - \left(\frac{P_0}{P_{5t}}\right)^{\frac{\gamma_e - 1}{\gamma_e}}\right)}$$

$$\frac{P_{5t}}{P_0} > \left(\frac{\gamma_e + 1}{2}\right)^{\frac{\gamma_e}{\gamma_e - 1}} \Rightarrow M_8 = 1 \quad P_8 = \left(\frac{2}{\gamma_e + 1}\right)^{\frac{\gamma_e}{\gamma_e - 1}} P_{5t}$$

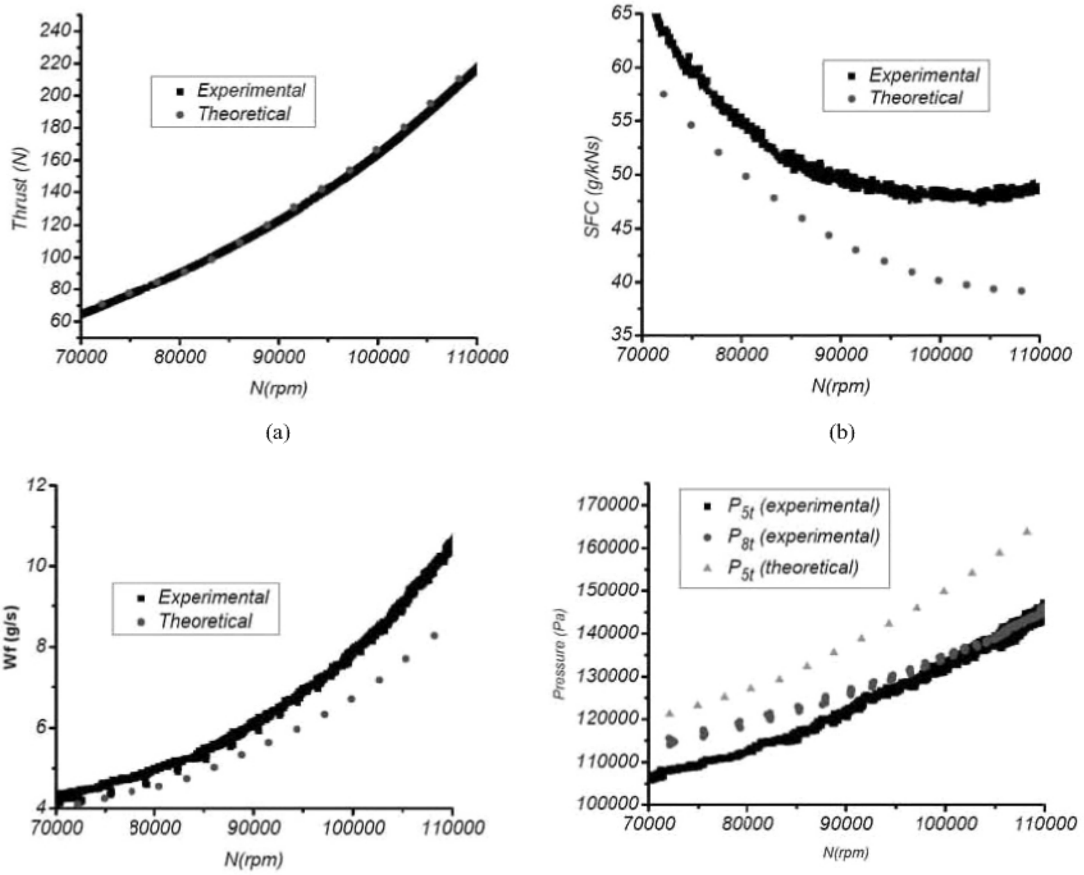
$$V_8 = \sqrt{\gamma_e R T_8} = \sqrt{\gamma_e R \frac{2}{\gamma_e + 1} T_{5t}}$$

Engine Thrust

$$F = W_8 V_8 - W_0 V_0 + A_8 (P_8 - P_0)$$

Specific fuel consumption

$$SFC = \frac{W_f}{F}$$



(a) (b)

(c) (d)

Fig. 4. Sample of results obtained by the students: engine thrust (a), specific fuel consumption (b), fuel flow rate (c), and pressure at different stations (d).

observed discrepancies are reasonable for the current educational setting, and are caused by the used of the students' generated performance maps and the flow non-homogeneity at measurement stations.

On the practical side, the students work in teams of five, and operate the facility by themselves (under the supervision of a Professor and a Technical Staff). They are then expected to deliver a written technical note discussing all the theoretical, numerical and experimental aspects relating to their work. These students are in the first semester of their fifth academic year (equivalent to a Master's degree) and perform this study under the technical discipline of a second air-breathing engines course.

This project has now been running for three years in a row and our impression is that the students do really benefit from experiencing first-hand the dynamics of real jet engine operation and they appreciate the hands-on approach to the job. Currently, we conduct a single enquiry on the whole discipline of 'Aero-engines' at the end of the term, so the assessment of the students is global and does not reflect their specific opinion about the project. In this sense, from the educational point of view, it would be a good idea to perform 'entry' and 'exit' interviews on the project and we expect to start implement this on the next course.

CONCLUSIONS

We have developed an experimental facility for aerospace engineering education purposes that familiarises students with an industry-like environment. The facility is low cost, flexible and robust, and provides an educational environment where students can: (1) test the theoretical background, (2) start tinkering with industrial software tools, and (3) have the opportunity to familiarise themselves with a full gas jet engine system (albeit on a small spatial scale) without the fear of causing havoc if their experiments go wrong . We also believe that this is of educational value in the present context, which is characterized by the engineering view that industry currently holds. Finally, it is to be said that this approach, because of its cost efficiency, could be of interest to universities in emerging countries where funding for educational purposes might be scarce.

NOMENCLATURE

A	area
c_P	pressure constant specific heat
F	uninstalled thrust
L	lower heating value of fuel
M	Mach number
P	pressure
R	gas constant
T	temperature
V	velocity
W	mass flow rate

Greek symbols

γ	specific heat ratio
η	adiabatic efficiency
η_q	combustor efficiency
π	pressure ratio
ρ	density

Subscripts

a	air
c	properties at compression phase
e	properties at expansion phase
f	fuel
number	engine station
t	total/stagnation values of properties

REFERENCES

1. D. S. Joshi, Viewpoint: Aerospace education for 2000 and beyond, *International Journal of Engineering Education*, **13**(2), 1997, pp. 138–142.
2. L. G. Kraige and D. Morris, Recent curriculum changes in engineering science and mechanics at Virginia Polytechnic Institute and State University, *Journal of Engineering Education*, **16**(5), 2000, p. 436–440.
3. A. Santeler and T. Wagner, Analytical and experimental investigation of a home-built gas turbine engine, *41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, Tucson, Arizona, July 10–13, 2005.
4. H. Ross, Aircraft homebuilding in Europe: the German scene, *AIAA International Air and Space Symposium and Exposition: The Next 100 Years*, Dayton, Ohio, July 14–17, 2003.
5. C. Rodgers, Turbofan design options for mini UAV's, *AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, 37th, Salt Lake City, UT, July 8–11, 2001.
6. P. Akbari and N. Muller, Performance investigation of small gas turbine engines topped with wave rotors, *39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, Huntsville, AL, July 20–23, 2003.
7. V. Tesson, M. Doty and D. McLaughlin, experimental investigation of jet noise and core noise using a small gas turbine engine, *8th AIAA/CEAS Aeroacoustics Conference and Exhibit*, Breckenridge, Colorado, June 17–19, 2002.
8. M. Piankoand and F. Wazelt, *Suitable Averaging Techniques in Non-uniform Internal Flows*, AGARD Advisory Report No. 182, (1983).
9. *Gas Turbine Engine Performance Station Identification and Nomenclature*, Aerospace Recommended Practice (ARP) 755A, SAE, Warrendale PA, (1974).
10. G. C. Oates, *Aerothermodynamics of Gas Turbine and Rocket Propulsion*, AIAA Education Series, American Institute of Aeronautics and Astronautics, Reston, (1997).
11. J. L. Kerrebrock, *Aircraft Engines and Gas Turbines*, MIT Press, Cambridge, MA, (1992).

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