An Applications Oriented Gas Turbine Laboratory Experience

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Abstract

The gas turbine industry is experiencing growth in many sectors, particularly in the area of power generation. An important part of teaching a gas turbine course is exposing students to the practical applications of the gas turbine. This laboratory enabled students to view the application of gas turbines in the area of propulsion. A Pratt and Whitney PT6A-20 turboprop was run at a local airfield and engine parameters typical of cockpit instrumentation were taken. The students, in teams of two, then modeled the system in the software of choice (EES, MathCAD, Matlab, EXCEL, PARA and PERF) in an attempt to match the manufacturer's specifications. This applications laboratory required students to research the parameters necessary to model this engine that were not part of the data set provided by the manufacturer. The research and modeling encompassed areas such as technology level, efficiencies, fuel consumption, and performance. The end result was a two-page report containing the students' calculations comparing the performance of the engine with the manufacturer's specifications. Supporting graphs and figures were included as appendices. The same type laboratory could be adapted for co-generation gas turbines. Over 121 colleges and universities have co-generation facilities on campus and that presents a unique opportunity for the students to observe the operation of a land gas turbine used for power generation. A 5 MW TB5000 manufactured by Ruston (Alstom) Gas Engines is available on the Baylor University campus and is highlighted as an example. Potential problems encountered with using the Baylor University gas turbine are discussed which include lack of appropriate engine instrumentation.

Introduction

The introduction of laboratory experiences into the undergraduate curriculum is paramount to the successful completion of an engineering degree. Much emphasis is being placed by ABET EC2000[1] on topics such as the students having an ability to design and conduct experiments, as well as analyze and interpret data, however, within budget constraints, purchasing commercial equipment for many types of practical laboratories is prohibitive due to cost. Space requirements at universities are also at a premium so leaving the equipment set-up year round is often not an option. At Baylor University, the mechanical engineering laboratory space available for use by undergraduates is very limited. The single fluids/thermal laboratory must serve as classroom, laboratory, and storeroom for any experimental apparatus. Much of the equipment is used for demonstration purposes only once or twice each year. Due to cost and space limitations, the addition of desirable labs involving large-scale hardware is restricted. The possibility exists for virtual laboratories or computer exercises to fill some of this void. However, students need exposure to actual "hands-on" experiments with hardware to solidify much of what is learned in the classroom. There is no substitute for practical experience.

One such area that would be of tremendous benefit to any thermal-fluids program would be the addition of a gas turbine laboratory. A gas turbine would be of use in several courses throughout the mechanical engineering curriculum at Baylor University. In thermodynamics, the basics of the first and second law are discussed and an introduction to the Brayton cycle is accomplished. The students learn about the individual components, such as the compressor, combustor, and turbine, and link these components in a cycle at the end of the course. All engineering majors at Baylor University take this course and they could accomplish a gas turbine laboratory at this point in the curriculum. In the follow-on advanced thermodynamics course, mechanical engineering students learn more about the Brayton cycle and what modifications would improve the cycle efficiency. They also learn more about applications of the cycle and do a preliminary design project for power generation using a gas turbine. In fluid mechanics, a four-lesson block on turbomachinery introduces students to velocity triangles and pumping characteristics. No longer are compressors and turbines black boxes, but machines that either extract energy or add energy to the flow. Lastly, a senior elective course looks at the gas turbine engine as a propulsion system. The course has students design an engine cycle for an aircraft application. This includes choosing the appropriate cycle compressor pressure ratio, fan pressure ratio, and bypass ratio. After selecting these design choices the student then looks at the engine cycle off-design performance. As part of the course, several lessons on rotating machinery, combustors, and inlets/nozzles are included. Two lessons are planned for each topic, including one lesson showing pictures of the history of the component with current technology and future trends. The additional lesson develops the design methodology and shows design considerations for the components. After studying these topics it would be a natural extension of the class to look at the performance of an actual gas turbine engine.

Several options exist to give the students a laboratory experience with gas turbines. The simplest option, and perhaps the most costly, would be the purchase of a commercial gas turbine test system. These can be purchased from companies such as Turbine Technologies, LTD[2], Armfield, Inc.[3], and G. Cussons, LTD[4]. Prices range from $30,000 to well over $100,000. Looking at the capabilities, these machines are very versatile and offer the greatest opportunities for students to learn about gas turbines in a laboratory setting. Most engine test systems commercially offered have the capability to perform basic cycle analysis in addition to detailed experiments on component performance. The test systems also have the capability of being integrated with computers for control of the experiment/engine and for data acquisition. However, the cost is prohibitive for most universities. At best, these high dollar items must be budgeted several years in advance and integrating their use into the curriculum during the appropriate courses to the maximum extent possible is absolutely necessary to justify their cost.

Another option would be to design and build a test system similar to the commercial systems. Many such suitable engines exist, which are currently being used in R/C model aircraft applications. Mathioudakis et al.[5] outline the development of such a small engine test cell that was accomplished with student help. While the design process itself is beneficial, the cost is still high and the time involved with the development cycle can be long.

Other options explored by this author involve facilities that are available in the community or on campus. As part of the gas turbine propulsion course, the class visited a local airport and was able to run a turboprop engine. Another possibility for exposure to gas turbine engine operation is the co-generation plant located on the Baylor University campus. This paper will explore the use of these two facilities to augment Brayton cycle instruction in the classroom.

Aircraft Gas Turbine Engine Experiment

As part of the elective course in gas turbine propulsion, two lessons on turboprops are given as a precursor to the turboprop laboratory. At this point in the course the students have studied cycle analysis, component performance, and engine cycle off design performance. Students understand performance parameters and what figures of merit are used to characterize gas turbine operation. They understand things like efficiency, specific fuel consumption and specific thrust. The turboprop lessons introduce them to turboprop operation including work coefficient. The first class lecture develops the equations of performance to include the core and power turbine work coefficient. Since the course is a propulsions system design course, propeller efficiency is also discussed. The second lecture looks specifically at the engine to be tested. The engine is a Pratt and Whitney PT6A-20 turboprop with the specifications given in Table 1[6]. A cross-section diagram of the engine gas path is discussed as well as prominent features of the engine (see Figure 1). The students were to run the engine, collect typical cockpit data, and then model the performance of the engine for comparison to the manufacturer's data. The requirement was to write a maximum two-page report and include supporting graphs and figures as appendices.

Baylor is fortunate to have this particular engine available through its Department of Aviation Sciences. The department is focused on the development and qualification of alternative fuels. As part of their program, they have a PT6A-20 mounted on a truck bed (Figure 2). The engine runs regular aviation fuel in addition to fuels such as ethanol and other bio-fuels. The airfield is approximately 10 minutes from campus and is easily accessed by the students. Extra time must be allocated for this exercise above the normal class time. The students were given one class for compensation but the overall laboratory takes approximately two hours including transit time. Upon arrival, the students were given a tour of the engine and facilities. The students looked closely at the propeller connected to the power turbine as shown in Figure 3. Other components, such as the inlet, starter-generator, compressor, etc., were also identified by the students. Eventually the engine technician explained the starting procedure for the engine prior to initiating the sequence. The control panel was equipped with all the standard engine instruments found in any cockpit (see Figure 4). Table 2 displays the data taken for the laboratory. The engine was run at five different power settings and allowed to stabilize prior to taking data. This data formed the basis for the comparison with the manufacturer data and the theoretical engine simulation.

While not every university has a Department of Aviation Science, there are two other possibilities to accomplish the same desired result. The first would be a local community college or aviation maintenance school. Co-located at the same airfield with Baylor University's Department of Aviation Science is the Texas State Technical College (TSTC) which also possesses a PT6A-20 engine on a test stand. Figure 5 shows this test stand. It is used for their students to become familiar with running an engine and contains all cockpit controls as shown in Figure 6. All the same cockpit data can be taken with this engine also. An added bonus with visiting the TSTC campus is the cut-away engines (Figure 7 and 8) and the spare parts available for viewing (Figure 9). Possibilities are being discussed which will enable Baylor students to participate with TSTC students during their PT6-A engine teardown classes. This would allow Baylor students to see the inner workings of the engine which would be an invaluable experience. It would also give the students an appreciation for the work of the aviation maintenance technician.

If either of these two opportunities is not available, it is possible to talk with a local Fixed Base Operator (FBO) or Airfield Manager to run an engine that is mounted on an aircraft. Again, all the same data should be available through the cockpit instruments.

The students' assignment from the lab was to model the engine performance in the software of their choice. Students preferred to use the software provided with their textbook, as it was the software used for their cycle design project. The textbook, Elements of Gas Turbine Propulsion[7], comes with cycle analysis software, PARA and PERF. Not much is known about the PT6A engine efficiencies. This required the students to do research to find reasonable values for the software. Examples of the student input and output are in Figures 10 and 11. Some problems were encountered finding parameters, such as efficiencies, and the calculated output did not match closely the manufacturer's data or the experimental results. The exercise was valuable as the students learned to do a sensitivity analysis for the various input parameters to decide which parameter might be in error and by how much.

Co-Generation Gas Turbines

Another alternative to the aviation gas turbine is the co-generation plants. Baylor University is one of over 121 colleges and universities across the United States that has such facilities on campus[8]. Baylor's co-generation plant is located in the center of the campus and generates approximately 4.1 MW of electrical power 24 hours a day for seven days a week. See Figure 12 and 13 for pictures of the facility. The gas turbine is a 5 MW TB5000 manufactured by Ruston (Alstom) Gas Engines installed in 1989. It uses exhaust gases to heat water and also includes a mister for the inlet to increase performance during the hot Texas summers. The thermodynamics and freshman orientation classes have been visiting the facility as a field trip. The purpose of these trips is to expose the students to power generation as an illustration of the cycles discussed in class. Of all the colleges and universities listed with co-generation facilities, only one has made academic use of their facility. The University of Florida has a laboratory/control room simulator with "read only" computer output[9]. At Baylor University, not enough parameters are being monitored by the facility to enable calculations of performance. The energy complex at Baylor University is only concerned with electrical power output and not with efficiency. More work could be done to look at the possibility of instrumenting the engine to take engine health parameters. Discussions are in progress to explore possibilities. Any data would be taken from existing monitoring screens as shown in Figure 14.

Conclusion

In an effort to increase the "hands-on" aspects of education, several alternatives to purchasing commercial gas turbine demonstrators are presented. Using an aviation gas turbine on a test stand is optimum, however, facilities at either a local community college, aviation maintenance school, or at a fixed base operator at the local airfield will provide a suitable alternative. The students learned by watching the start cycle and actual engine operation. The data taken exposes the students to the typical instrumentation and units used in aviation. The attempt by the students to model the engine performance was somewhat open ended which led to student frustration. Searching databases for manufacturer's data and efficiencies was good exercise for students to make them aware of the data available in the literature. Since the databases are incomplete for the students' purposes, they had to estimate other parameters and then perform a sensitivity analysis to determine which parameters had the biggest impact on the performance. Eventually, the students were able to reasonably model engine operation successfully but were not able to bring closure with the manufacturer's data. This provided some additional frustration to the students but they gained valuable experience nonetheless. Most enjoyed the opportunity to get out of the classroom and see a practical application of the knowledge gained in the classroom.

As an alternative to the turboprop laboratory, co-generation facilities exist at numerous colleges and universities. These facilities are under utilized and could be developed for academic purposes.

References

1. http://www.abet.org/
2. www.turbinetechnologies.com
3. www.armfield.co.uk
4. Compuserve: 100536.365

5. Mathioudakis, K., and Argyopoulos, P., 2003, "Design and Development of a Small Jet Engine Test Cell," Paper number GT2003-38315, Submitted for presentation at the ASME IGTI Turbo Expo 2003, June 16-19, 2003, Atlanta, GA.
6. PT6A-20 Technical Manual, Pratt and Whitney.
7. Mattingly, J., 1996, Elements of Gas Turbine Propulsion, McGraw-Hill Book Company, New York
8. http://www.energy.rochester.edu/us/list.htm
9. http://gatorpwr.che.ufl.edu/cogen/

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Ken Van Treuren is an Associate Professor in the Department of Engineering at Baylor University. He received his B. S. in Aeronautical Engineering from the USAF Academy and his M. S. in Engineering from Princeton University. He completed his DPhil in Engineering Sciences at the University of Oxford, UK. At Baylor he teaches courses in laboratory techniques, fluid mechanics, energy systems, propulsion, and freshman engineering.

Table 1 Manufacturer's Data[6]

	ESHP	SHP	Prop RPM	Jet Thrust (lbs)	Fuel Consumption (lb/ESHP/hr)	Fuel Consumption (lb/hr)
Take-off	579	550	2200	72	0.649	376
Max Cont.	579	550	2200	72	0.649	376
Max Climb	566	538	2200	70	0.653	370
Max Cruise	550	495	2200	68	.067	369

Table 2 Typical PT6A-20 engine data Fall 2002

Turb Inlet (^{o}R)	1410	1437	1482	1590	1626
Torque (ft-lb_f)	100	290	500	850	950
RPM (%)	51	70	80	90	93
Fuel Flow (lb/hr)	1325	1250	2200	2950	3250
Power (ft-lb/s)	11750	4676	92153	176243	20353
Power (hp)	18	89	160	241	327

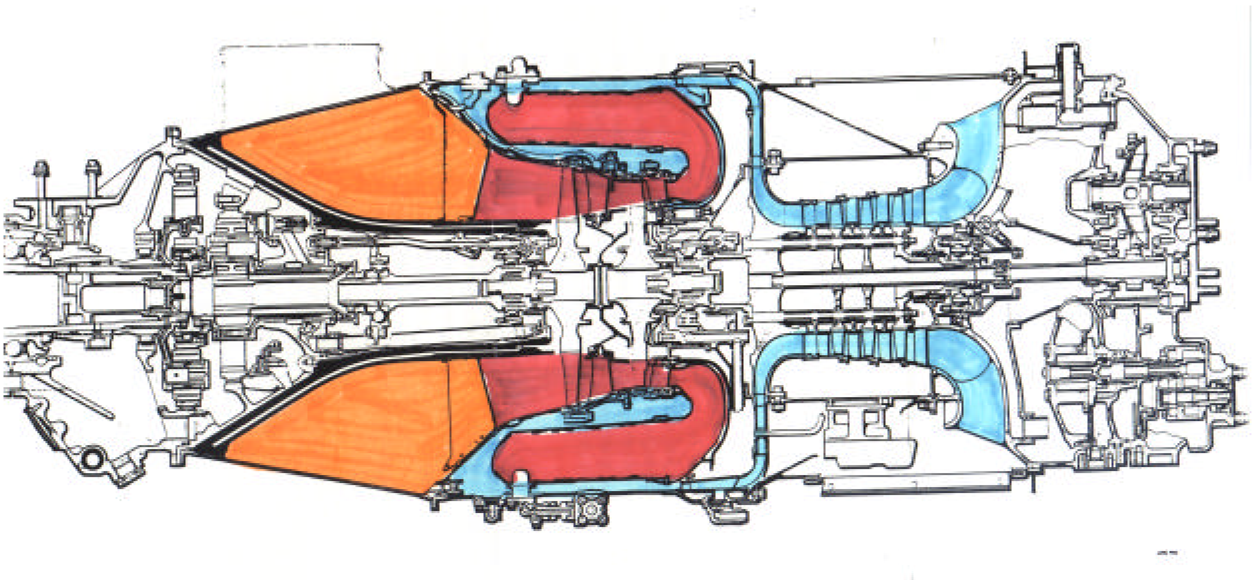


Figure 1 PT6A-20 Cross-Section Diagram[6]

Figure 2 Baylor University PT6A-20 Gas turbine

Figure 3 Students examining the engine

Figure 4 Control panel operation

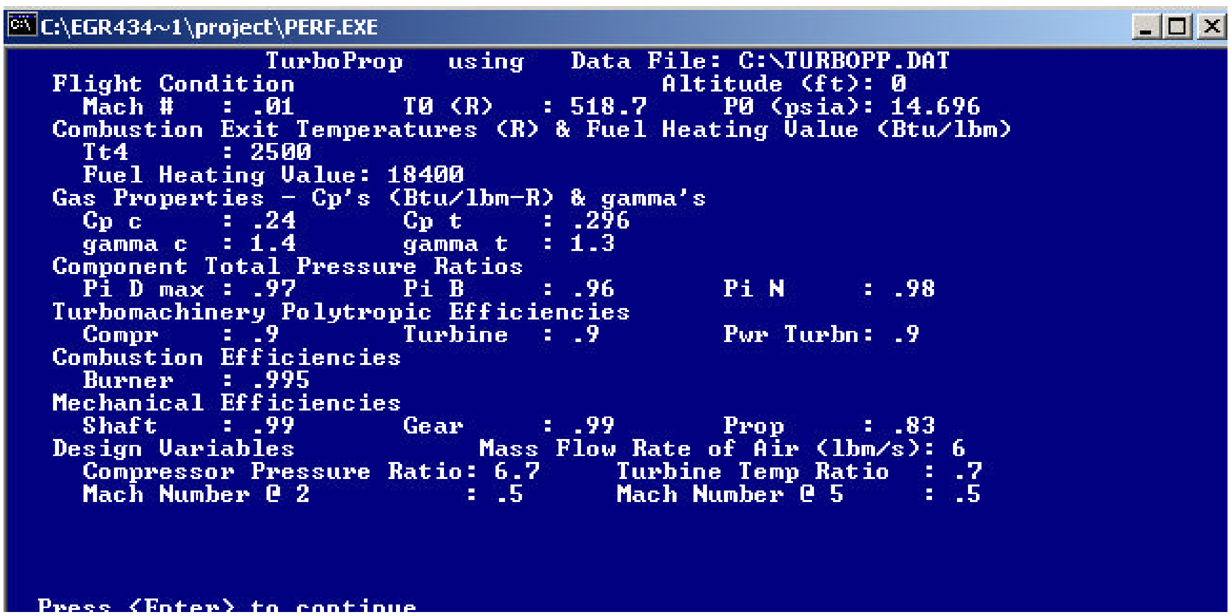
Figure 5 Turboprop at Texas State Technical College

Figure 6 Control Panel for Texas State Technical College

Figure 7 Early turbojet engine

Figure 8 PT6-A cutaway engine

Figure 9 Miscellaneous engine parts



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C:\EGR434~1\project\PERF.EXE
                 TurboProp   using   Data File: C:\TURBOPP.DAT
 Flight Condition                        Altitude (ft): 0
   Mach #    : .01        T0 (R)    : 518.7     P0 (psia): 14.696
 Combustion Exit Temperatures (R) & Fuel Heating Value (Btu/lbm)
   Tt4       : 2500
   Fuel Heating Value: 18400
 Gas Properties - Cp's (Btu/lbm-R) & gamma's
   Cp c      : .24        Cp t      : .296
   gamma c   : 1.4        gamma t   : 1.3
 Component Total Pressure Ratios
   Pi D max : .97         Pi B      : .96       Pi N      : .98
 Turbomachinery Polytropic Efficiencies
   Compr     : .9         Turbine   : .9        Pwr Turbn: .9
 Combustion Efficiencies
   Burner    : .995
 Mechanical Efficiencies
   Shaft     : .99        Gear      : .99       Prop      : .83
 Design Variables              Mass Flow Rate of Air (lbm/s): 6
   Compressor Pressure Ratio: 6.7     Turbine Temp Ratio   : .7
   Mach Number @ 2           : .5     Mach Number @ 5      : .5


 Press <Enter> to continue
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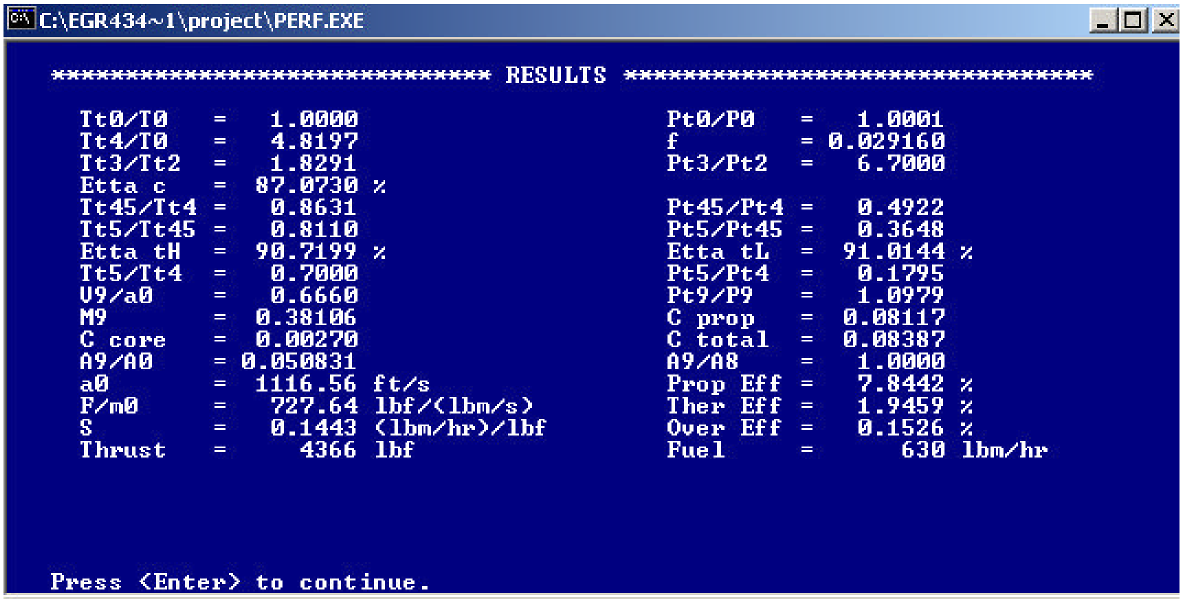
Figure 10 Input data for PERF Program


C:\EGR434~1\project\PERF.EXE

```
******************************* RESULTS *********************************

  Tt0/T0    =   1.0000                     Pt0/P0    =   1.0001
  Tt4/T0    =   4.8197                     f         = 0.029160
  Tt3/Tt2   =   1.8291                     Pt3/Pt2   =   6.7000
  Etta c    =  87.0730 %
  Tt45/Tt4  =   0.8631                     Pt45/Pt4  =   0.4922
  Tt5/Tt45  =   0.8110                     Pt5/Pt45  =   0.3648
  Etta tH   =  90.7199 %                   Etta tL   =  91.0144 %
  Tt5/Tt4   =   0.7000                     Pt5/Pt4   =   0.1795
  V9/a0     =   0.6660                     Pt9/P9    =   1.0979
  M9        =  0.38106                     C prop    =  0.08117
  C core    =  0.00270                     C total   =  0.08387
  A9/A0     = 0.050831                     A9/A8     =   1.0000
  a0        =  1116.56 ft/s                Prop Eff  =   7.8442 %
  F/m0      =   727.64 lbf/(lbm/s)         Ther Eff  =   1.9459 %
  S         =   0.1443 (lbm/hr)/lbf        Over Eff  =   0.1526 %
  Thrust    =     4366 lbf                 Fuel      =      630 lbm/hr



Press <Enter> to continue.
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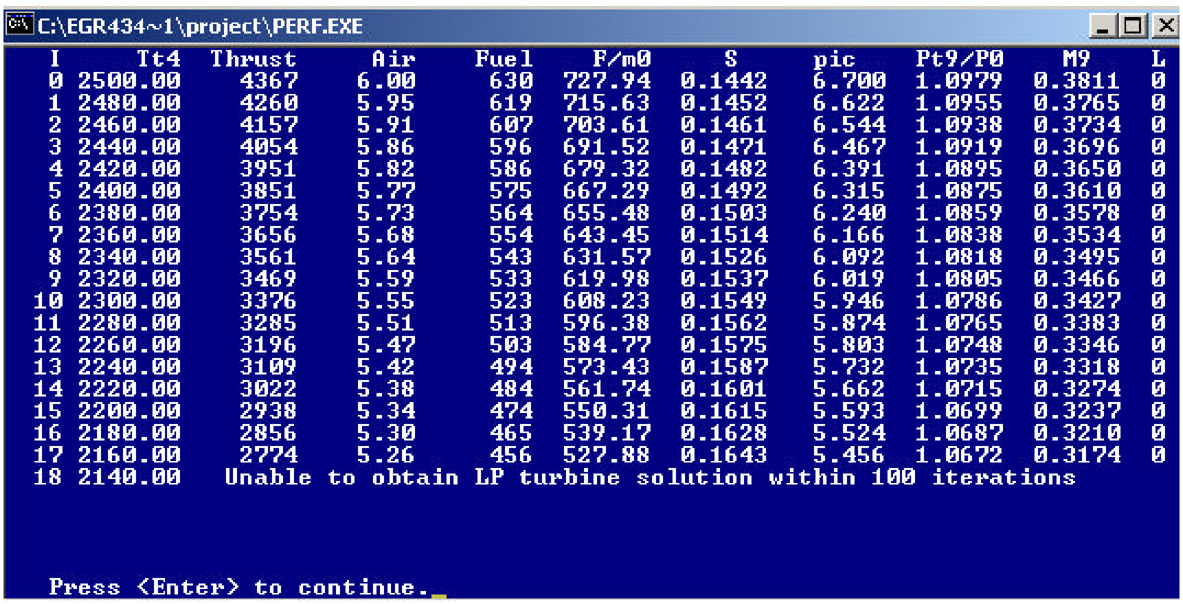
C:\EGR434~1\project\PERF.EXE

I	Tt4	Thrust	Air	Fuel	F/m0	S	pic	Pt9/P0	M9	L
0	2500.00	4367	6.00	630	727.94	0.1442	6.700	1.0979	0.3811	0
1	2480.00	4260	5.95	619	715.63	0.1452	6.622	1.0955	0.3765	0
2	2460.00	4157	5.91	607	703.61	0.1461	6.544	1.0938	0.3734	0
3	2440.00	4054	5.86	596	691.52	0.1471	6.467	1.0919	0.3696	0
4	2420.00	3951	5.82	586	679.32	0.1482	6.391	1.0895	0.3650	0
5	2400.00	3851	5.77	575	667.29	0.1492	6.315	1.0875	0.3610	0
6	2380.00	3754	5.73	564	655.48	0.1503	6.240	1.0859	0.3578	0
7	2360.00	3656	5.68	554	643.45	0.1514	6.166	1.0838	0.3534	0
8	2340.00	3561	5.64	543	631.57	0.1526	6.092	1.0818	0.3495	0
9	2320.00	3469	5.59	533	619.98	0.1537	6.019	1.0805	0.3466	0
10	2300.00	3376	5.55	523	608.23	0.1549	5.946	1.0786	0.3427	0
11	2280.00	3285	5.51	513	596.38	0.1562	5.874	1.0765	0.3383	0
12	2260.00	3196	5.47	503	584.77	0.1575	5.803	1.0748	0.3346	0
13	2240.00	3109	5.42	494	573.43	0.1587	5.732	1.0735	0.3318	0
14	2220.00	3022	5.38	484	561.74	0.1601	5.662	1.0715	0.3274	0
15	2200.00	2938	5.34	474	550.31	0.1615	5.593	1.0699	0.3237	0
16	2180.00	2856	5.30	465	539.17	0.1628	5.524	1.0687	0.3210	0
17	2160.00	2774	5.26	456	527.88	0.1643	5.456	1.0672	0.3174	0
18	2140.00	Unable to obtain LP turbine solution within 100 iterations								

Press <Enter> to continue.

Figure 11 PERF Results

Figure 12 Co-generation power facility

Figure 13 Close-up of the gas turbine and generator housing

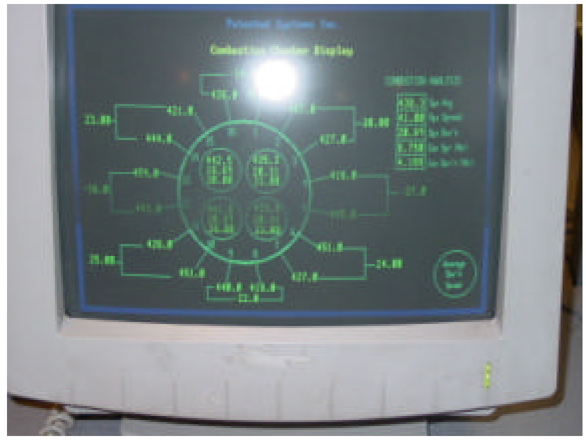

Figure 14 Close up of the control computer screen