## Problems

This first chapter has dealt principally with definitions, and with some discussion of the characteristics and capabilities of turbomachinery and gas turbines. Answering questions on definitions does not engender a love for the subject matter. Accordingly, the following questions probe background knowledge. Few readers will have more than a few of the data asked for in the first question. Its purpose is to stimulate a survey of the engineering-society papers in the library, and perhaps the advertisements in some of the engineering magazines. Some of the other questions ask for opinions. Again, the purpose is to stimulate thought and perhaps some reading. There are not necessarily "correct" answers to these questions. August committees of eminent scientists and engineers have been frequently totally wrong when they have tried to forecast the future.

**1.1.** Complete as much of table P1.1 as possible, from your own knowledge or from library study. In general, every entry will be for a different machine, although in some cases there will be relationships between two figures. For instance, the highest-power steam turbine may not operate at the highest pressure used for steam turbines but may well have the largest low-pressure flow volume. Use numbered references to footnotes to identify your sources.

**Table P1.1.**

| Give the maximum known value of | Steam turbine in generating station | Boiler-feed pump in generating station | Gas expander in gas-turbine engine | Compressor in gas-turbine engine | Axial compressor, any duty per single casing |
|---|---|---|---|---|---|
| Power (MW) | 1500 (1750?)(a) | 50 (a) | 340(b) | 200 | 200 |
| Pressure (MPa) | 25 (a) | 33 | 3.5 | 4.0 | 4.0 |
| Temperature (deg C) | 565 (a) | 40 | 1550(c) | 845 | 845 |
| Pressure ratio (max/min) | 900 | 1,000 | 75(b) | 75(b) | 75(b) |
| Temperature ratio (max/min) | 2.7 | — | 7.0 | 3.6 | 3.6 |
| Number of stages | 32 | 8 | 11 | 24(d) | 81(g) |
| Low-pressure flow volume ($m^3/s$) | 30,000 | 1.4 | 800 | 410 | 7650(f) |
| Mass flow (kg/s) | 1400 | 1400 | 500 | 500 | 7700(f) |
| Efficiency (percent, which?) | 90 polytropic | 90 hydraulic | 92 polytropic | 93? polytropic (d) | 93 polytropic |

| Give the maximum known value of | Centrifugal compressor for any duty, per casing | Water pump for pumped-storage system | Pelton water turbine (high-head impulse) | Francis water turbine (medium-head inflow) | Kaplan water turbine (low-head axial-flow) |
|---|---|---|---|---|---|
| Power (MW) | 39 | 250 | 1400 (h) | 1000 (j) | 170 |
| Pressure (MPa) | 50 | 10 | 18 (1800 m) | 7.3 (734 m) | 0.75 (75 m) |
| Temperature (deg C) | 350 | — | — | — | — |
| Pressure ratio (max/min) | 500 | 100 | 180 | 73 | 7.5 |
| Temperature ratio (max/min) | 2.0 | — | — | — | — |
| Number of stages | 8 | 2 | 1 | 1 | 1 |
| Low-pressure flow volume ($m^3/s$) | 75 | 2.5 | 17 | 100 | 200 |
| Mass flow (kg/s) | 410 | 25,000 | 17,000 | 100,000 | 200,000 |
| Efficiency (percent, which?) | 87 (polytropic, t-s) | 92 (hydraulic) | 90 (hydraulic) | 93 (hydraulic) | 94 (hydraulic) |

**Problem 1.1, notes for table**

a. The largest steam-turbine generating units are at least 1500 MW, possibly 1750 MW. Until the energy "crises" of the 1970s, unit sizes of steam turbines were steadily increasing. The sharply increased energy price reduced demand, and many units on order were canceled. In the mid-1980s combined cycles became popular (gas turbines supplying the exhaust heat to steam generators feeding steam turbines), and these have become preferred over "straight" steam-turbine power plants. Large combined-cycle units are producing over 400 MW in the late 1990s, with efficiencies approaching 60 percent (see chapter 3).

b. The highest compressor pressure ratio I know of is 75:1, in the Brown-Boveri L-GT 10/13 used in an compressed-air storage plant. The air mass flow is 410 kg/s, giving a low-pressure flow volume of about 400 cu m/s. It is an axial-radial compressor of 25 stages. The turbine-expander exhaust volume at 400° C or above would be approximately 760 cu m/s; the turbine has eleven stages. The highest pressure ratio for a gas-turbine engine is probably 40.5 for the GE-36.

c. The highest turbine-inlet temperature for an operating (rather than a research) engine is about 1825 K, possibly higher, for military jets. This gives a temperature ratio with the compressor-inlet temperature, when operating at altitude, approaching 7:1.

d. The highest compressor efficiency, polytropic total-to-static to the diffuser outlet, a low-blade-speed 24-stage axial compressor of 4:1 pressure ratio for the BTH gas turbine in the Shell tanker "Auris", was stated to be almost 0.94 by the designer, C. L. G. Worn. However, in published records I have not been able to find confirmation of an efficiency higher than 0.91. I believe that modifications were made after these publications were produced.

e. Axial-flow turbines should be capable of reaching levels of efficiency at least equal to those of axial compressors of the same size and pressure ratio. However, I cannot quote cases to verify this assumption.

f. Some of the largest gas-moving turbomachines are for research wind tunnels. The large-scale wind tunnel at Moffet Field, NASA-Ames Research Center with a 24.4m by 36.6m section has six single-stage axial fans each of 12.2-m diameter, each driven by a 17-MW electric motor at 180 RPM.

g. Parsons designed and built some axial-flow compressors with as many as 81 stages (see the historical chapter)

h. The highest rating for a Pelton turbine is 1400 MW, a Sulzer-Escher-Wyss unit for Colombia.

j. The highest head used for a Francis turbine is 734 m. These are Sulzer 180-MW units for the Hausling power station in Austria. The highest power rating of a Francis turbine is 1000 MW

For comparison of sizes, the world's biggest Diesel engine is the Sulzer 12RTA84, 42 MW, twelve-cylinder two-stroke running at 95 RPM, weighing 1750 tonnes. The smallest Diesel engines are for model aircraft, and give outputs of under 100 W.

Another comparison outside the scope of the book is the largest controllable-pitch propeller, with a power rating of 20.5 MW (Sulzer).

**Problem 1.2 Gas-turbine engines have not reached the power-output levels of the largest steam turbines. Why?**

Gas turbines are increasing in output, but the largest (at under 300 MW) is still small compared with the largest steam turbines at over 1500 MW. Gas turbines may reach 1500 MW, especially in combined-cycle form. However, the trend at the end of the 1990s is towards more-distributed power rather than fewer very large generating stations. Two reasons for this trend are the result of gas-turbine characteristics. One is that high efficiencies can be produced by relatively small gas turbines, whereas only the largest steam plants can incorporate all the devices and processes needed to attain high efficiencies. A second reason is that gas turbines require far fewer supervisory personnel than do steam turbines: gas turbines can even run unattended for long periods. The large quantities of natural gas currently available, and the consequent low prices, have greatly helped the conversion of much electrical generation to gas-turbine or combined-cycle systems.

**Problem 1.3 Estimate the design power output of the smallest gas-turbine engine produced in the last decade. Why aren't smaller engines made?**

There are very small model-aircraft jet engines made, but these are not, perhaps, in the spirit of the question. Small shaft-power gas turbines are in the 20-30-kW range (Solar T-206, 21 kW, or Capstone, a recuperated engine with rotating parts from turbochargers, at 24 kW). The component and overall efficiencies worsen as engines are made smaller, because of increased relative tip clearances, of lower Reynolds numbers, of increased relative roughness, and of the impracticality of providing blade cooling for very small blades. At some power level it is more attractive or more cost-effective to use piston engines even for applications that might seem to be suited for gas turbines.

**Problem 1.4 Give your opinion of the two most-promising new applications for gas-turbine engines in the next twenty years, and give reasons for your opinion.**

Crystal balls are unreliable. I believe that gas-turbine engines have sufficient advantages over Diesel engines for trucks and buses that they are likely to be used in these applications. Nowadays, many, perhaps most, transitions of this scope are driven by government regulations or taxes, and these could produce a significant incentive. The same is true to a lesser extent for private automobiles, the engines of which have been dominated by the requirements of regulation for twenty-five years.

**Problem 1.5 Why is the maximum temperature of steam turbines so much lower than the current turbine-inlet temperature of gas-turbine engines?**

Steam-turbine maximum temperatures are limited at present by the corrosive nature of high-temperature steam on superheater tubes. The limit is presently about 566° C, and there is no immediate prospect that I know of (given the increasing prices of high-chromium-cobalt-nickel steels) for this "limit" to be exceeded. The efficiency of steam plants has been decreasing in recent years because of the energy requirements imposed by environmental-pollution limits. Improved methods of removing sulfur should reduce energy costs and allow the thermal efficiency to rise slightly again, but there seems little prospect of steam-plant efficiencies reaching 50 percent while remaining economically competitive.

**Problem 1.6 What do you think are the two principal problems preventing gas-turbine engines from having a much wider application?**

Up to close to the present time, gas-turbine engines have poorer design-point and much poorer off-design-point efficiencies than Diesel engines, while usually costing more per kilowatt of design power. The situation is changing: simple-cycle engines can have thermal efficiencies of 40%, similar to that of large Diesels, and regenerative engines can have a considerably higher efficiency. If ceramic regenerators and ceramic turbines are developed to be reliable low-cost components, two substantial blocks to the greater use of gas turbines would be removed.

**Problem 1.7 Do you think that gas-turbine engines will be used in outboard motor boats by 2010? Why, or why not?**

It is most unlikely. Although the higher power levels used in outboard "motors" (strictly they are not "motors" but "engines") are in the range where gas-turbine engines can be competitive (particularly where lightness and compactness are important, as in this application) the salt-spray environment near the air intake in seagoing boats is hostile to turbine-engine survival. An inboard location where the air intake can be situated as remote from spray as possible is much more favorable.

**Problem 1.8 For which of the applications in the list below do you think that the gas-turbine engine, as a prime mover, would be:**
**a. suitable now, and, if so, how would it be used, or in what form?**
**b. suitable after certain developments have been successfully completed, and if so, which?**
**c. Unsuitable, and if so, why?**
(The list is not repeated here).
When ceramics are developed to enable reliable high-temperature regenerators and turbines to be incorporated, gas turbines should be suitable for highway trucks, city buses, long-distance interurban buses, and automobiles. The automobile application is the least likely of these because of the huge changeover costs, but much, pro and con, depend on governmental regulation.
Governmental regulation also seems likely to play an increasing role in the pollution from motorcycles, snowmobiles, and lawn mowers. The uncontrolled level of emissions is very high. Gas-turbine engines are possible for all three applications, although they would suffer from the effects of small size (as do piston engines) and any applications would be near the limit of what would be possible. They would be likely to be low-pressure-ratio regenerative cycles. The exploitation of geothermal energy and sea-water thermal gradient with depth are unlikely to use Brayton cycles because the temperature differences are too small to give good measurable efficiencies. Solar energy, where mirrors are used to concentrate the radiation on to a target, and nuclear energy from high-temperature reactions are suitable applications for gas-turbine engines.

**Problem 1.9 Discuss any present applications of, and future prospects for, vapor-cycle engines using fluids other than water.**
Vapor-cycle engines have been frequently proposed as "bottoming" (heat-rejection) cycles for other heat engines (in the way that steam cycles act as bottoming cycles for gas-turbine engines in combined-cycle plants.) ThermoElectron of Waltham MA built and sold vapor-cycle engines for the exhaust systems of Diesel trucks. (These lost their economic worth when price of fuel dropped after the so-called "energy crises" of the 1970s and 1980s.) A major proposal was the Ocean Thermal Energy Cycle (OTEC) in which a fluid, probably ammonia, would be boiled by the warm surface waters of the Gulf of Mexico (for example), the vapor would be expanded through a large single-stage axial turbine, and the exhaust vapor would be condensed by heat exchange with deeper cooler water. This cycle also fell victim to low energy prices.