

6.1.5 GAS TURBINES

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THERMODYNAMIC PRINCIPLE AND CLASSIFICATIONS

The gas turbine is an internal combustion engine differing in many respects from the standard reciprocating model. In the first place, the process by which a gas turbine operates involves steady flow; hence pistons and cylinders are eliminated. Secondly, each part of the thermodynamic cycle is carried out in a separate apparatus. The basic process involves compression of air in a compressor, introduction of the compressed air and fuel into the combustion chamber(s), and finally expansion of the gaseous combustion products in a power turbine. Figure 1 illustrates a simple gas turbine.

The Brayton, or Joule, Cycle Figure 2 shows an ideal Brayton, or Joule, cycle illustrated in PV and TS diagrams. This cycle is commonly used in the analysis of gas turbines.

The inlet air is compressed isentropically from point 1 to point 2, heat is added at an assumed constant pressure from point 2 to point 3, the air is then expanded isentropically in the power turbine from point 3 to point 4, and finally heat is rejected at an assumed constant pressure from point 4 to point 1. From Figure 2, the compressor work is $h_2 - h_1$, the turbine work is $h_3 - h_4$, and the difference is the net work output. The heat input is $h_3 - h_2$. One can then derive an expression for thermal efficiency as follows:

$$\eta = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2}$$

In reality, the cycle is irreversible and the efficiency of the compression, combustion, and expansion must be taken into account. However, an examination of the thermal efficiency equation shows the need of high compressor and turbine efficiencies in order to produce an acceptable amount of work output. The importance of h_3 is also readily apparent.

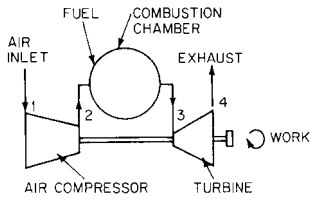


FIGURE 1 Components of simple gas turbine

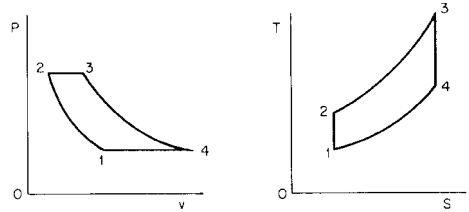


FIGURE 2 PV and TS diagrams for an ideal Brayton, or Joule, cycle

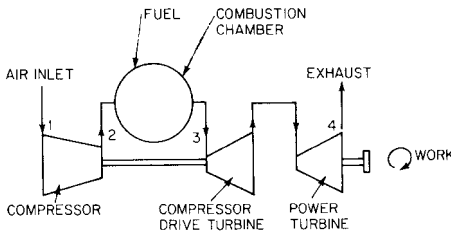


FIGURE 3 Components of a split-shaft gas turbine

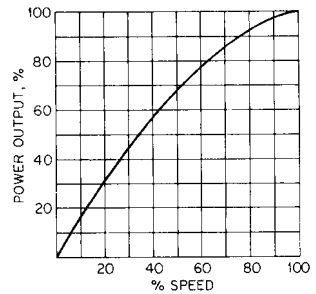


FIGURE 4 Typical curve of power output versus shaft speed for a split-shaft gas turbine

In noting that h_3 is directly proportional to temperature, one can appreciate why continuous emphasis is being placed on the development of materials and techniques that permit higher combustion temperatures and correspondingly higher turbine inlet temperatures.

Classifications In an *open-cycle* gas turbine, the inlet air mixes directly with the combustion products and is exhausted to the atmosphere after passing through the power turbine. The *closed-cycle* gas turbine uses a heat exchanger to transfer heat to the working fluid, which is continuously recirculated in a closed loop. A *combined cycle* uses the principles of both the open and closed cycles. In current practice, the combined cycle uses an open cycle to provide shaft work while the heat from the exhaust is partially recovered in a waste-heat boiler. The heat recovered then proceeds through a standard steam power cycle until heat is rejected to the most readily available low-temperature reservoir.

Of the above configurations, the open-cycle gas turbine is most extensively used today for driving centrifugal pumps. This is probably due to the important consideration of minimum capital investment for each power output.

Two distinct types of open-cycle gas turbines have evolved: the *single-shaft* and *split-shaft* versions. The single-shaft gas turbine was developed primarily for the electric power industry and uses a compressor and a power turbine integrated on a common shaft. As the unit is used continuously at a single rotational speed, the compressor and power turbine efficiency can be optimized.

The split-shaft gas turbine was developed primarily for mechanical drive applications where output power and speed might be expected to vary. Figure 3 illustrates such a turbine. A typical curve of power output versus shaft speed is illustrated in Figure 4.

Split-shaft gas turbines are available in *conventional* and *aircraft-derivative* versions. The conventional gas turbine evolved from steam turbine technology and is illustrated in

Figure 5. Figure 6 shows a modified jet engine used as a source of hot gas to a power turbine. Note that the jet engine combines the compression, combustion, and power turbine necessary to drive the compressor.

RATINGS

In the evolution of the gas turbine as a prime mover, various organizations have put forth standard conditions of inlet temperature and elevation to allow direct comparison of various gas turbines.

Four common standards exist:

ISO (International Standards Organization): sea level and 59°F (15°C)

NEMA (National Electrical Manufacturers Association): 1000 ft (304.8 m) above sea level and 80°F (27°C)

CIMAC (Congres International des Machines a Combustion): sea level and 59°F (15°C)

Site: actual elevation and design temperature at installation site

With the evolution of higher combustion temperatures and with the greater need for power over relatively short daily periods, new ratings have developed: emergency (maximum intermittent), peaking (intermittent), and base load. These classifications are based on the number of hours per unit of time that a gas turbine is operated and are related to the material used in the power turbine blading. A common standard is to use materials suitable for 100,000 h of continuous operation. Higher temperatures are permitted, but at the sacrifice of the life of the material and an increase in maintenance costs.

In a pump-driving application, the cycle of operations should be considered in specifying a gas turbine driver. A typical curve of gas turbine output as a function of inlet temperature (Figure 7) clearly indicates the necessity of specifying an accurate design temperature. Figure 8 is a typical correction curve for altitude.

FUELS

A wide range of fuels, from natural gas to the bunker oils, may be burned in simple-cycle gas turbines. In most cases, units can operate on gas or liquid fuels, and some turbines have automatic switchover capability while under load.

Although it would appear advantageous to choose the cheapest fuel available, there may be disadvantages in such a choice: impurities such as vanadium, sulfur, and sodium definitely result in high-temperature corrosion; solid impurities and a high ash content will lead to erosion problems. One is therefore often faced with a trade-off between the cost of treating a fuel and the higher original cost.

With ever-increasing firing temperatures, research is continuing in the field of high-temperature corrosion with or without accompanying erosion problems. Present approaches to the problem include the use of inhibitors in the fuel as well as coatings for power turbine blades. Another solution that has been used on some crude oil pipelines is the topping unit. This is a small still that removes a specific fraction of the crude oil for burning as gas turbine fuel. It is good practice to include a detailed fuel analysis as part of any request for bids.

ENVIRONMENTAL CONSIDERATIONS

Legislation at both the federal and state levels has been concerned with the protection of our environment. An engineer must now consider the effects of the project on the environment.

Noise Any piece of dynamic mechanical equipment will emit airborne sounds that, depending on frequency and level, may be classified as noise.

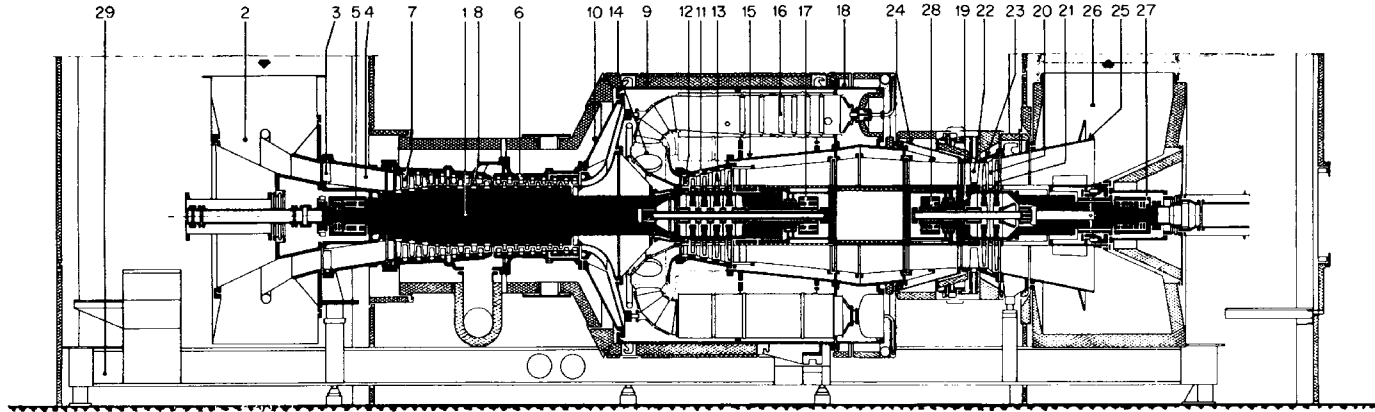


FIGURE 5 Gas turbine cross section: (1) gas generator turbine rotor, (2) inlet air casing, (3) compressor inlet guide vanes, (4) conical inlet casing with bearing support, (5) compressor radial-axial bearing, (6) compressor stator, (7) compressor stator blades, (8) compressor rotor blades, (9) combustion chamber main casing, (10) intermediate conical casing with diffuser, (11) gas generator turbine stator blade carrier, (12) gas generator turbine stator blades, (13) gas generator turbine rotor blades, (14) hot gas casing, (15) intermediate casing, (16) nine incorporated combustion chambers, (17) compressor radial bearing, (18) central casing, (19) power turbine rotor, (20) power turbine stator blades, (21) power turbine rotor blades, (22) power turbine adjustable rotor blades, (23) power turbine stator blade carrier, (24) conical intermediate piece, (25) outlet diffuser, (26) outlet casing, (27) power turbine radial-axial bearing, (28) power turbine radial bearing, (29) metallic foundation (Turbodyne)

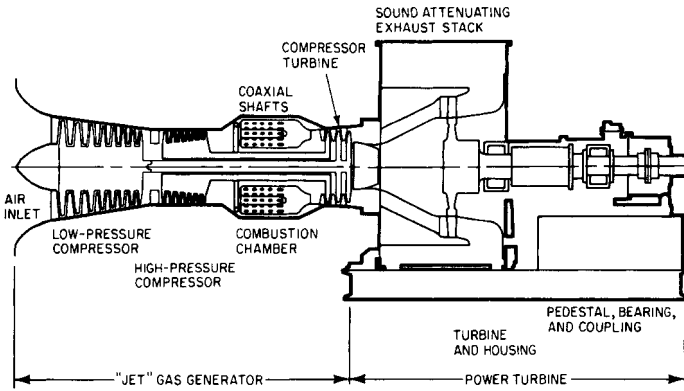


FIGURE 6 Cross section of aircraft-derivative gas turbine driver (Turbodyne)

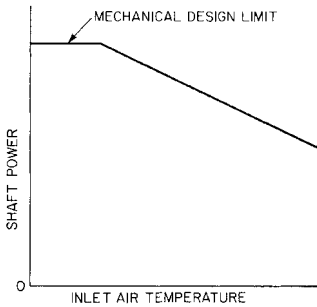


FIGURE 7 Typical curve of gas turbine output versus inlet temperature

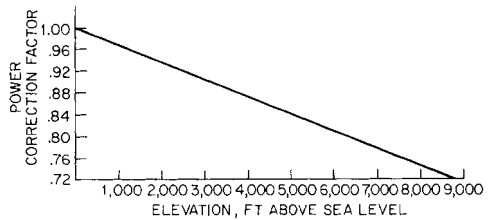


FIGURE 8 Typical curve of gas turbine power correction versus altitude (ft \times 0.3048 = m)

The primary sources of noise in the gas turbine are the turbine inlet and exhaust and the accessories and support systems, such as fin fan lubrication oil coolers, auxiliary air blowers and fans, starting devices, and auxiliary lubrication oil pumps. It is common practice for manufacturers to provide inlet and exhaust silencers as well as some form of acoustic treatment for auxiliaries.

In considering the degree of acoustic treatment necessary for each installation, the practicing engineer must consider the following parameters:

1. Federal law (Walsh-Healy Act) limiting the time a worker may spend in a noisy environment
2. Local codes and their interpretation
3. Plant location and existing noise level at site
4. Site topography, including any noise-reflective surfaces
5. Applicable ASME standards and other relevant standards

Emissions The federal air quality acts require each state to develop a plan for achieving satisfactory air quality. Specifically, goals have been put forth to limit suspended particulate temperature matter and oxides of sulfur and nitrogen. Therefore,

the engineer must investigate existing regulations during the planning stage of a pump installation.

In general, gas turbines have low particulate emissions. The amount of sulfur oxides exhausted to the atmosphere is in direct proportion to the content of sulfur in the fuel, and current practice calls for elimination at the source. The formation of oxides of nitrogen is a direct result of combustion. Manufacturers are currently committing a considerable amount of resources to the investigation and solution of this problem.

GAS TURBINE SUPPORT SYSTEMS

Starting Systems A form of mechanical cranking is necessary to bring a gas turbine up to its self-sustaining speed. The amount of energy necessary will depend on each manufacturer's design. Available systems include electric motors, diesel engines, and gas-expander turbines.

Lubrication The gas turbine manufacturer normally provides a combined pump-turbine lubrication oil system. A main lubrication oil pump of sufficient capacity for the combined system is necessary, in addition to a standby pump in the event of failure of the main pump. A reservoir sized for a retention time of at least four minutes is usually specified. Filtration to 10- μ m particle size should be adequate for most gas turbines and pumps.

Lubrication oil can be cooled by various means, the selection of which depends upon local conditions. The simplest and cheapest method uses a shell-and-tube heat exchanger with water as the cooling medium. In arid regions, a fin fan cooler with direct air-to-water cooling is commonly used.

Inlet Air Filtration The degree of inlet air filtration needed is primarily a function of the size and number of particles in the atmosphere surrounding the installation. In most cases, a simple tortuous-path precipitator will suffice. For dirtier atmospheres or in arid regions where sandstorms occur, inertial separators followed by a rolling-media filter should be considered.

Any filtration will result in a loss in performance because of the pressure drop across the inlet filter. Conservative design practice calls for a face velocity of 500 ft/min (150 m/min) for a rolling-media filter and 1700 ft/min (520 m/min) for a tortuous-path precipitator.

Control Most manufacturers offer control packages which provide proper sequencing for automatic start-up, operation, and shutdown. During automatic start-up, the sequencer receives signals from various transmitters to ensure that auxiliaries are functioning properly and, with the aid of timers, brings the unit on line through a planned sequence of events.

Key operating parameters—for example, output speed, gas turbine compressor speed, turbine inlet temperature, lubrication oil temperature and pressure—are continually monitored during normal operation. Signals from a pump discharge-pressure transmitter can be fed into a speed and fuel controller to cause the unit to respond to changes in speed and output.

As with start-up, normal and emergency shutdowns are accomplished through the sequencer. Most standard control packages are easily adaptable to remote control by means of cable or microwave.

APPLICATION TO PUMPS

Gas turbines are available to drive centrifugal pumps in a wide range of speeds and sizes, from 40 hp (30 kW) to over 20,000 hp (15,000 kW). It is not practical to list here all the avail-

able units because they are too numerous and are continually being upgraded and added to. A listing can be found in *Sawyer's Gas Turbine Catalog*, which is published annually.

Pipeline Service Crude oil pipeline service has seen a tremendous growth in the use of gas turbine drivers since the mid-1950s, and this trend will continue as crude oil production becomes more and more remote from its markets. The advantages of the gas turbine for this application are as follows:

1. Installed cost is usually lower than that of a corresponding reciprocating engine.
2. Variable-speed operation allows maintenance of a specific discharge pressure under a wide range of operating conditions, thus achieving maximum flexibility.
3. Normal gas turbine control system is easily adapted to unattended operation and remote control.
4. Operating experience has proved the gas turbine to have a high degree of reliability.
5. Gas turbines can be packaged into modules for ease of transportation and erection.

Water Flooding An important aspect of oil production is the use of secondary recovery methods to increase the output of crude oil reservoirs whose pressure does not allow the crude to flow freely to the surface. Flooding the reservoir with high-pressure water has been a primary technique for years. The development of high-pressure centrifugal pumps has allowed increased water flow into oil fields.

As most oil production is located in remote areas, the packaged gas turbine driver has become increasingly popular. Figure 9 shows a typical 3300-bhp (2460-brake kW) split-shaft gas-turbine-driven centrifugal water flood pump package. A cutaway view of a typical 1100-hhp (820-brake kW) gas turbine is shown in Figure 10; note the reduction gearing at the exhaust end for direct driving of a pump. Supporting systems, such as starter, lubrication oil pumps, governor, and fuel oil pumps, are driven off the accessory pods located at the air inlet end. Offshore platform installations require drivers with a minimum vibration as well as small, unbalanced inertial forces. The gas turbine fits both of these descriptions very well.

Cargo Loading Another interesting application of this prime mover is in the field of cargo loading, where units are currently in operation charging tankers with crude oil. Selection of a gas turbine pumping unit with critical speeds above the normal operating range allows great flexibility of operation, particularly during final topping operations.

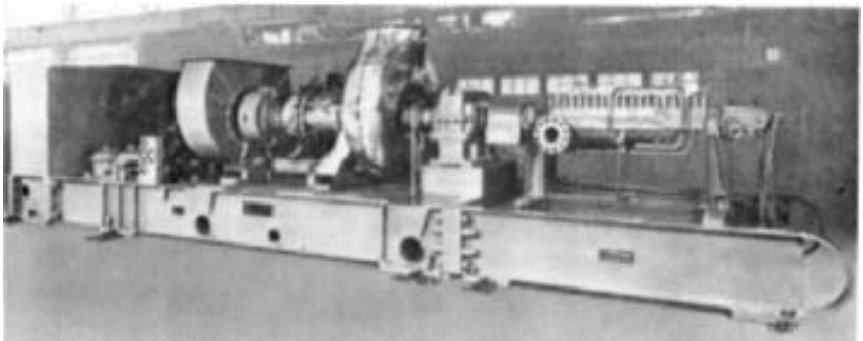


FIGURE 9 A 3300-bhp (2460-bkW) gas turbine-driven waterflood package (Solar Division of International Harvester)

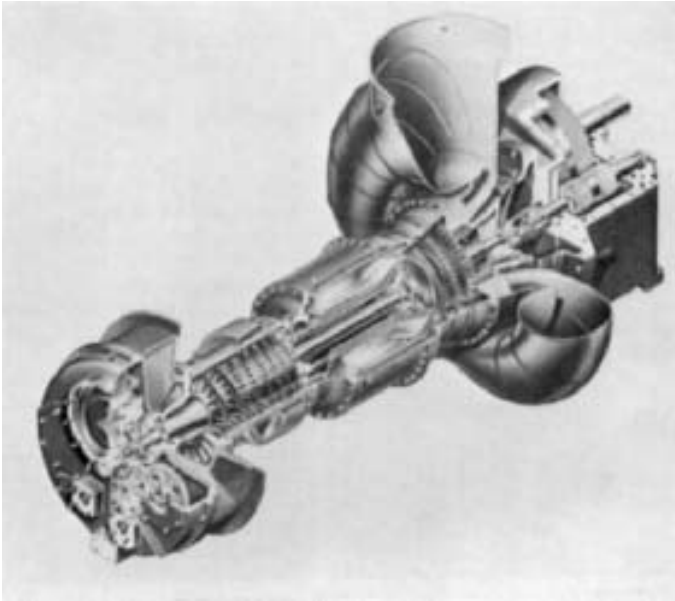


FIGURE 10 Cutaway view of 1100-bbp (820-bkW) split-shaft gas turbine driver (Solar Division of International Harvester)

Application Considerations The application of gas turbine drivers can vary from a simple driver for one pump operating at constant flow and discharge pressure to a multiplicity of units operating at variable speed on a pipeline. For the purposes of this discussion, it is assumed that the pumping system has been analyzed, a pump selection has been made, and all possible operating conditions have been analyzed so brake horsepower (brake kilowatt) and speed requirements are known.

The brake horsepower (brake kilowatt) output of the gas turbine must equal or exceed that required by the pump. This output can be determined by the use of specific performance curves similar to Figure 7 as corrected for elevation (Figure 8). Gear losses as necessary are added to the brake horsepower (brake kilowatt) required by the pump. Intermediate brake horsepower (brake kilowatt) and speed requirements should then be checked against a gas turbine output versus speed curve (Figure 4).

A torsional analysis of the combined unit is made (usually by the gas turbine manufacturer) to ensure the absence of any critical speeds in the operating range. Table 1 is a typical data sheet recommended for use when purchasing a gas turbine to drive a centrifugal pump.

TABLE 1 Typical data sheet for gas turbine driven centrifugal pump

Information from purchaser	Information from manufacturer		
Pumping requirements	Pumping requirements		
Service _____	Service _____		
Liquid _____	Liquid _____		
Pumping temp. _____	Pumping temp. _____		
Capacity (total) normal/max _____ / _____	Capacity (total) normal/max _____ / _____		
No. pumps operating _____	No. pumps operating _____		
Specific gravity at pump temp. _____	Specific gravity at pump temp. _____		
Viscosity at pumping temp. _____	Viscosity at pumping temp. _____		
Total head _____	Total head _____		
NPSH available _____	NPSH available _____		
Pump type, materials, and accessories	Bhp (brake W)		
	required	normal	max
	Speed, rpm	normal	max
	Efficiency	normal	max
Site conditions	Pump type, materials, and accessories		
Elevation, ft (m) _____	Gas turbine excluding gear		
Range of site ambient temperature	Design	Max	Min
	Dry bulb		
	Wet bulb		
Design, °F (°C) _____			
Maximum, °F (°C) _____			
Minimum, °F (°C) _____			
Atmospheric air	Total utility consumption		
Dust below 10 μm , ppm _____	Cooling water, gpm (l/s) _____		
10 μm and above, ppm _____	Electric power, kW ac/dc _____		
Corrosive constituents:	Steam, lb/h (kg/h) _____		
Sulfur, ammonia, ammonium salts,	Compressed air, standard		
salt or seacoast, other _____	ft ³ /min (m ³ /min) _____		
Noise specifications	Shipping data		
City, state, federal, other _____		Turbine	Aux.
		items	
Emission specifications	Shipping wt, tons (kg) _____		
City, state, federal, other _____	Max erection wt, tons (kg) _____		
	Max maint. wt, tons (kg) _____		
Utilities available at site	Length, ft-in (m) _____		
Steam: Pressure, lb/in ²	Width, ft-in (m) _____		
(kPa) gage _____	Height, ft-in (m) _____		
Temp., °F (°C) _____			
Quantity, lb/h (kg/h) _____			
Electricity			
V	Phase	Cycles	
ac _____	_____	_____	
dc _____	_____	_____	
Cooling water			
Source _____ quality _____			
Supply temp. _____ min _____ max			
Supply press, lb/in ²			
(kPa) gage _____			
Max return, °F (°C) _____			

TABLE 1 Continued.

Information from purchaser	Information from manufacturer	
Fuel Gas _____ liquid _____	Accessories included (as required by purchaser)	
Analysis attached	Inlet air filter	___yes ___no
Accessory items required (see list in right-hand column)	Inlet air silencer	___ ___
	Exhaust silencer	___ ___
	Exhaust duct	___ ___
	Starting equipment	___ ___
	Load gear (if required)	___ ___
	Driven pump	___ ___
	Coupling	___ ___
	Fire protection system	___ ___
	Equipment enclosure	___ ___
	Baseplate or soleplates	___ ___
	Combined turbine-pump	___ ___
	Lub. oil system	___ ___
	Main lube pump	___ ___
	Auxiliary lub. pump	___ ___
	Lub. reservoir	___ ___
	Lub. filter	___ ___
	Lub. oil cooler	___ ___
Unit control panel	___ ___	
Auxiliary motor	___ ___	
Control center	___ ___	

Source. Adapted from API Standard 616.

FURTHER READING

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