Prime Movers

Dong Zhang and Xiangqiang Kong

Contents

D. Zhang (✉)
School of Energy and Power Engineering, Lanzhou University of Technology, Lanzhou, China
e-mail: zhdlgn@126.com

X. Kong
Department of Thermal Energy and Power Engineering, College of Mechanical and Electronic Engineering, Shandong University of Science and Technology, Qingdao, China
e-mail: kxqiangly@126.com

R. Wang, X. Zhai (eds.), *Handbook of Energy Systems in Green Buildings*,
https://doi.org/10.1007/978-3-662-49120-1_37

Abstract

This chapter provides an introduction to the prime movers and power equipment used in combined cooling, heating, and power (CCHP) systems, including steam turbines, gas turbines, internal combustion engines, Stirling engines, and fuel cells. The power subsystems are the driving source of the power supply system; they are used to generate electricity or provide mechanical power directly. The chapter includes a discussion of the types and important performance parameters of steam engines and gas turbines; the characteristics and basic types of gas-steam combined-cycle systems; the working principles of internal combustion engines; the basic profiles of diesel, gasoline, and gas internal combustion engines; the working principles, characteristics, and main applications of Stirling engines; the working principles, type, development, and research status of fuel cells; and applications in CCHP systems. Through the information in this chapter, we hope to provide readers with a full understanding of the power equipment used in CCHP systems.

Keywords

Prime movers · Power equipment · Working principles · Performance parameters

Boilers and Steam Turbines

Steam turbines have a long history of providing electric power around the world by converting the energy of steam into electricity or work. Currently, the main working fluid of a steam turbine comes from a boiler, which converts the chemical energy of fuel to heat energy. This chemical energy is converted into heat energy through the chemical reaction of burning.

Boilers

The boiler is composed of two parts: the boiler itself and auxiliary equipment. The core equipment for steam production includes the furnace, boiler barrel, burner, water wall superheater, economizer, air heater, boiler structure, and brickwork, also known as the “boiler proper.” The most important parts of the boiler proper are the furnace and boiler barrel.

The furnace (also known as the combustion chamber) provides the space for fuel combustion. In a grate furnace, the solid fuel is placed on the grate for grate firing. In a suspension firing boiler, the solid fuel, gas, or liquid is sprayed on the furnace. A fluidized bed furnace uses air to lift the granulated coal with a fluidized state. A cyclone furnace is a columnar furnace that use air currents to rotate the coal with strong deflagration.

Similarly, there are three methods of combustion in a boiler: grate firing, suspension firing, and fluidized-bed combustion. The combustion equipment differs depending on the type. Grate firing is used to burn solid material, which includes a combined grate incinerator, travelling grate stoker, and vibrating stoker. Suspension firing uses a coal boiler, oil fired boiler, gas boiler, or other boiler. Suspension firing is used to burn solid fuel, liquid fuel, gas fuel, bubbling fluidized beds, or circulating fluidized beds in fluidized-bed combustion, which is used to burn granular solid fuel. The combustion methods of a spreader feeder-fired travelling grate stoker are grate firing and suspension firing, which are both types of mixed combustion.

In a grate firing boiler, the solid fuel is burned on the grate with a certain thickness. It is used for burning high-quality coal with high volatility and low ash content. The fuel for a chamber combustion furnace or cyclone furnace is in powder, mist, or gas form with air sprayed over the furnace. With a proper air flow rate, the fuel combustion in the fluidized bed can be carried out in the fluidized state. Inferior coal types are suitable for use with these two kinds of boilers, especially modern circulating fluidized bed boilers. The solid particles are collected from the outlet of the furnace, which are then returned to furnace combustion to improve the combustion efficiency. This method will burn not only inferior coal, but also a wide variety of other coals. It can also be carried out in furnace desulfurization to achieve clean combustion, reducing emissions of SO_2 and NO_x.

The characteristics of the various types of boilers are shown in Table 1. When choosing a boiler, one should consider the advantages and disadvantages of various combustion modes, coal quality, combustion efficiency, and the operating technical requirements of coal mines. For example, a traveling grate boiler should be selected when the boiler needs to operate at 65 t/h or less. If the boiler should be operating at greater than 65 t/h, a circulating fluidized bed boiler should be selected.

The workflow of boiler includes the water vapor system flow, combustion, and air and flue gas system flow. In the water vapor system, water flows through the water supply pipe and enters the coal economizer after the water supply is heated to a certain temperature in the heater. The water in the water wall tube absorbs radiation heat to form a steam-water mixture, which goes through the rising pipe to the boiler drum. Water and steam are separated by a steam-water separator. Saturated steam is separated from the upper stream to the boiler superheater, where it continues to absorb heat to become superheated steam of a certain temperature. (At present, the maximum temperature of a 300–600 MW unit is approximately 540 °C). Afterward, the saturated steam is transferred to the steam turbine. In combustion and smoke systems, the blower feeds the air into the air preheater to a certain temperature. Pulverized coal is processed to a certain size in the pulverizer. A portion of the hot air from the air preheater carries the pulverized coal through the burner into the furnace. Combustion of the pulverized coal and air mixture from the burner combusts with the rest of the hot air in the furnace, releasing much heat. After combustion, the

Table 1 The characteristics of various boilers

Types	pulverized coal furnace	grate boiler	spreader stoker	furnace in fluid bed	circulating fluidized bed boiler	cyclone furnace
Chemical incomplete combustion loss (%)	0	<2	<1	≈0	≈0	0
Mechanical incomplete combustion loss (%)	2–4	5–15	6–12	5–30	2–4	≈0
Thermal efficiency of boiler (%)	More than 85	70–82	70–82	65–72	More than 85	More than 85
Rated evaporation (t/h)	≥35	≤35	≤35	≤35	≥35	≥75
Applicable coal type	Anthracite, bituminous coal, lean coal and lignite	II, III anthracite, II, III soft coal, meagre coal	III anthracite, II,III soft coal, meagre coal, bagasse	Stone coal, lignite coal gangue	Anthracite, soft coal, meagre coal, lignite coal	Soft coal, anthracite, meagre coal
Load variation adaptability	Can work stably when the rated evaporation is 70%	Can work stably at 50% of rated evaporation, load changes slowly	Variation range of evaporation is extensive, load changes rapidly	Variation range of evaporation is extensive, load changes quickly	Variation range of evaporation is larger, load changes rapidly	Load adjustment range is small, cannot quickly start and stop

Small and medium sized cogeneration engineering design manual 2006

fumes sequentially flow through the combustion chamber, slag bundle, superheater, economizer, and air preheater. Then, the fly ash is removed with the dust removal device and finally sent to the chimney by the draft fan.

According to their main steam parameters, boiler steam turbine units can be classified as low pressure, secondary medium pressure, medium pressure, sub-high pressure, high pressure, ultra-high pressure, subcritical, supercritical, or ultra-supercritical units. The main steam pressures and steam temperatures of these boiler classifications are as follows: low-pressure boiler, 2.45 MPa and 400 °C; medium-pressure boiler, 3.83 MPa and 450 °C; sub-high pressure boiler, 5.29–6.27 MPa and 450–485 °C; high-pressure boiler, 9.8 MPa and 540–555 °C; subcritical boiler, 16.66 MPa and 540–570 °C; supercritical boiler, >22.05 MPa and 540–560 °C; and ultrasupercritical boiler, 25–31 MPa and 580–610 °C. Table 2 shows the technical parameters of boilers in China. Table 3 shows the parameters of small- and medium-sized power plant boilers in China.

Table 2 Main capacity and parameters of boilers in China

Parameters			
Steam pressure, MPa(g)	Steam (°C)	Feed temperature (°C)	Capacity (t/h)
0.588	Saturation	20	0.1 / 0.2 / 0.4 / 0.7 / 1 / 1.5 / 2 / 3
0.784	Saturation	20	0.1 / 0.2 / 0.4 / 0.7 / 1 / 1.5 / 2 / 3 / 4
1.27	Saturation / 250 / 300 / 350	50 / (101)	1.5 / 2 / 3 / 4 / 6.5 / 10 / 15 / 20
(1.568)	350 / 375	100	6.5 / 10 / 15 / 20
2.45	400 / 420	100	6.5 / 10 / 15 / 20
3.83	450	172	35 / 65 / 75 / (120) / 130 / (240)
9.8	510 540	215	230 220 / 410
13.72	540 / 540 555 / 555	240	670 400
16.66	555 / 555 540 / 540	320	1000 1980

Table 3 Boiler parameters of medium and small thermal power plants

boiler rating (t/h)	steam pressure (MPa)	superheated steam temperature (°C)	feed temperature (°C)
6 / (6.5) / 10 / 20	1.25	350	105
6 / (6.5) / 10 / 20	2.45	400	105
35 / 65 / (76) / 120 / (130)	3.82	450	105 / 150 / 170
35 / 65 / (76)	5.29	485	105 / 150
220 / 310 / 410	9.81	540	210

Steam Turbines

A steam turbine is a rotary prime mover that transforms steam energy into mechanical energy using turbine machinery. The main body of a steam turbine consists of two parts: stators and rotors. The stator is composed of cylinders, diaphragms, static cascades, admission/exhaust parts, gland steam seal, bearings, and bearing block. The rotor consists of the shaft, impellers, rotor blades (or drum rotors with blades and integral rotors) and couplings. In a steam turbine, static blades and subsequent cascades, as well as their related parts, make up the basic unit that transforms steam thermal energy into mechanical energy. This is considered to be the turbine stage; steam turbines are classified as single stage or multistage. A turbine is equipped with an adjusting safety system, oil system, and various auxiliary systems to guarantee safe and effective work.

Steam (at a certain pressure and temperature) comes from the boiler and continuously flows through the flow paths, which are composed of an injector (static cascade) and rotor cascade. Steam gains speed through its expansion in the injectors and moves into the crooked paths that are installed in the rotor cascades. A force is generated in this way to drive the rotors. The rotation of the rotors will power various driven devices, such as pumps, compressors, propellers, and generators, with external work by the shaft. The injector transforms steam thermal energy into kinetic energy, whereas the rotor cascade transforms steam kinetic energy into mechanical energy. A series of fixed nozzles and cooperating rotor cascades are the basic units of a steam turbine. Steam converts energy in a steam turbine in various ways depending on the working principles of the turbine, such as impulse and reaction types.

When the high-speed airflow passes through rotor cascade, impulsive force will be generated in the rotor cascade by energy transformation, driving the rotor cascade and creating mechanical energy. According to the momentum theorem, the magnitude of mechanical energy is determined by the mass flow rate of the working steam and the speed transformation. In other words, a larger mass flow rate creates a larger speed transformation, thus generating a greater force. Airflow in the rotor blade channel does not accelerate expansion, due to the limited channel shape of the rotor blades. The vapor stream is forced to change direction and thus can generate a centrifugal force that acts on the blades, which is considered to be dynamic power. The micromechanical work of the steam in the steam turbine is equal to the steam flow into and out of the channel (its kinetic energy variation); this level is called the impulse stage.

Steam continues to expand and accelerate in the rotor blade paths while the airway changes the flow direction. When the accelerated steam flows out of the paths, it produces a reaction force that acts on the rotor blade in the opposite direction of steam flow. This force is similar to the high-speed gas that flows from a rocket's tail, giving the rocket a reaction that is opposite to the direction of steam flow. This is called the reaction force, whereas the reactionary stage occurs with the anti-power force acts. In the modern turbine stage, dynamic and anti-power forces often act simultaneously, under the effects of the combination of the two forces: the moving blade rotates and produces mechanical work. The effects of the two forces are different, with the dynamic power capability being larger while the anti-power flow efficiency is higher.

An impulse steam turbine has an impulse stage, with the steam mainly expanding in the nozzle (vanes). Only a small amount expands in the moving vanes. The reaction turbine is mainly composed of a reaction-type stage. Steam expands in both the nozzle (stator blade) and the moving blade, with the degree of expansion being similar. The steam involved in the work can be extracted from the steam turbine. The steam turbine can be used to provide heat or as an afterheat refrigerating unit to drive the heat source, thereby realizing the combined heat and power effects or cooling and power supply. The process of joint production can promote heat efficiency that ranges from 30–40% to 60–70%.

Based on its intake pressure parameters, steam turbine units can be divided into seven categories: low-pressure steam turbines with main steam pressure of

Table 4 Technical parameters of common pressure-grade steam turbine

Parameter	initial steam pressure (MPa)	inlet steam temperature (°C)
Low pressure	1.27	340
Sub-medium-pressure	2.35	390
Medium-pressure	3.43	435
Sub-high-pressure	4.90–5.88	435–470
High-pressure	8.80	535

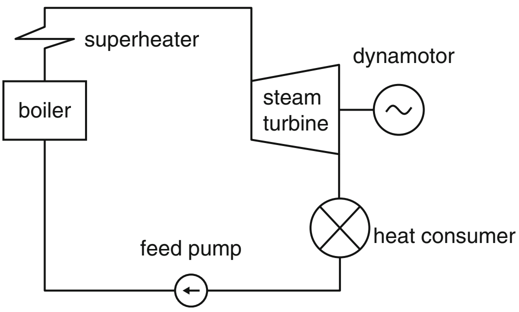
0.12–1.5 MPa; mid-pressure steam turbines with pressure of 2.0–4.0 MPa; high-pressure turbines with pressure of 6.0–10.0 MPa; super-high pressure turbines with pressure of 12.0–14.0 MPa; subcritical-pressure turbines with pressure of 16.0–18.0 MPa; supercritical-pressure steam turbines with pressure of >22.1 MPa; and ultrasupercritical-pressure steam turbines with pressure of >32.0 MPa. Table 4 shows the common pressure ratings for steam turbines. Steam turbines also can be classified according to their thermodynamic characteristics: back pressure, extraction back pressure, extraction condensing steam, and condensing steam turbines. The first three types are driven by combined heat and power for use in combined cooling, heating, and power (CCHP) systems. Their main features are listed in Table 5.

1. **Back pressure turbines**
   A back pressure turbine is indicated for an exhaust-heated users with exhaust pressure greater than atmospheric pressure. When the steam is used as another medium or a low-pressure steam turbine, it is also called a superposed turbine. The main characteristics of this unit are its remarkable economic efficiency and energy-saving effects. In addition, it has a simple structure, requires a low investment, and operates reliably. The major disadvantage is that it only operates in a “thermal follow” mode, in which power generation is determined by the heating capacity. The heating capacity cannot be adjusted independently to account for the needs of both thermal and electrical users or the power supply needs for power grid compensation when the system addresses the needs of a thermal load. Therefore, the reserve capacity of the power system is increased. In addition, the back pressure of this turbine is high, whereas the enthalpy drop of the whole machine is small. If the operating conditions differ from design conditions, the relative internal efficiency of the unit may be significantly reduced, thus decreasing power generation; this can affect the compensation capacity and cause power grid surges. Figure 1 shows a diagram of the heating and thermal systems.
2. **Extraction back pressure turbines**
   In an extraction back pressure turbine, the extraction steam comes from the intermediate stage of a steam turbine. Heat users require a high pressure level while maintaining a certain back pressure of exhaust steam, whereas a low pressure level is required for heat users of steam turbines. This type of unit has similar design conditions of economy as back pressure turbines. However, the adaptability of load change is relatively weak. It is suitable for two different

Table 5 Characteristics of steam turbine units with cogeneration systems

Project		back pressure	extraction of steam back pressure	extraction condensing steam type
Under the same boiler capacity and parameters	Heating capacity	More	More	Less
	Generating capacity	Less	Less	More
Coal consumption for power generation	Design conditions	Low	Low	Superior
	Load dump	High	High	Slight improvement
Relation between electric load and steam load		How much steam to use, how much power to produce	How much steam to use, how much power to produce	Steam, electricity ratio can be adjusted
Structural complexity		Simple	Complex	Complex
Number of auxiliary facilities		Few	Few	Much
Number to meet the steam pressure rating		One	Two	One, two, or more
Ability to adapt to steam load changes		Little	Little	Larger
System complexity		Simple	Simple	Complex
Applications		The heat load is stable, and the electric load is not obvious For example: Textile, printing, dyeing	The heat load is stable and requires more than two kinds of pressure levels For example: Chemical fertilizer, chemical fiber	The change of heat load is large, the change is frequent, and hope to generate electricity For example: Paper

Fig. 1 Back-pressure steam turbine heating and cooling system



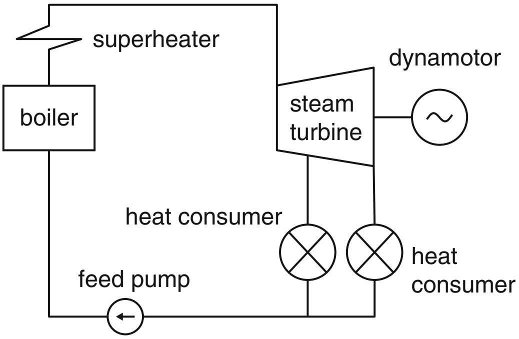


Fig. 2 Steam supply and back-pressure steam turbine heating and cooling system

parameters of heat load, with an expanded application range compared with back-pressure steam turbines. A diagram of the heating and thermal systems is shown in Fig. 2.

3. **Extraction condensing steam turbines**
   An extraction condensing steam turbine extracts some steam from the middle level of a steam turbine. In this unit, excess steam can continue to swell after the steam turbine extraction point, when the steam load suddenly falls. The advantage of this unit is its flexibility, which can be used to meet the needs of the heat load and electrical load at the same time. Therefore, it is suitable for situations that require frequent major changes or for regional variations at a thermal power plant. The disadvantage of this unit is that its heat economy is lower than that of a back pressure turbine. Furthermore, the auxiliary engine and overall systems are more complex and expensive. A diagram of the heating and thermal systems is shown in Fig. 3.
4. **Condensing steam turbines**
   The steam discharged from a condensing steam turbine flows into a condenser. Because the exhaust pressure is lower than the atmospheric pressure, the thermal performance is good. This unit is simply used for the generation of steam. China is experiencing challenges with electricity shortages, the cost of fuel resources, and the availability of low-calorific fuels with large amounts of coal gangue and flue gas waste heat. A condensing steam turbine can solve the problem of an insufficient power supply. To meet the needs for varying thermoelectric loads at different times, a thermal power plant can be configured within the appropriate condensing unit.

Based on its thermal performance, a steam turbine can be classified as an exhaust steam turbine or a multipressure steam turbine, among others. A steam turbine uses low-pressure exhaust from other steam equipment, whereas a multipressure steam turbine uses steam from other sources that is sent into the corresponding intermediate stage of the steam turbine, working together with the original steam. In the comprehensive utilization of steam heat, it is also used in the industrial production process. In addition, according to the steam flow direction, a steam turbine can be classified as

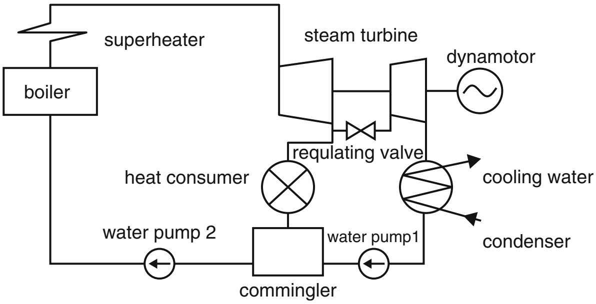


Fig. 3 Heating and cooling system with a condensing steam turbine

Table 6 Parameters of a back-pressure turbine (MPa)

Rated back pressure	0.294	0.49	0.981	1.275
Adjusting range	0.196 ~ 0.392	0.392 ~ 0.686	0.784 ~ 1.275	0.981 ~ 1.567

Table 7 Extraction steam pressure parameters of an extraction steam turbine (MPa)

Rated steam pressure	0.118	0.49	0.981	1.275
Adjusting range	0.069 ~ 0.245	0.392 ~ 0.686	0.784 ~ 1.275	0.981 ~ 1.567

Table 8 Exhaust steam parameters of a condensing steam turbine

coolant temp (°C)	10	15	20	25	27	30
Exhaust steam pressure (kPa)	2.9 ~ 3.9	3.9 ~ 5.0	5.0 ~ 5.9	5.9 ~ 6.9	6.9 ~ 7.8	7.8 ~ 9.8

axial or radial flow and circumfluence (reflux, net flow) steam turbines. Based on the number of cylinders, a steam turbine can be classified as a single-cylinder, twin-cylinder, or multicylinder steam turbine. According to its usage, a steam turbine can be classified as a power plant steam turbine, an industrial steam turbine, or a marine steam turbine. Based on its arrangement, a steam turbine may be a single-shaft or double-shaft turbine. Finally, depending on its working state, a steam turbine can be considered as a fixed or mobile (e.g., train power station) steam turbine. The parameters of back pressure turbines, extraction steam turbines, and condensing steam turbines are shown in Tables 6, 7, and 8.

The efficiency index for thermal analysis and calculations for a steam turbine generator set include the relative inner efficiency, mechanical efficiency, and generator efficiency of the steam turbine. These indexes can be obtained using the following formulas.

1. **The relative internal efficiency of a steam turbine**
   A steam turbine's relative internal efficiency can be calculated as the ratio of its effective enthalpy drop and isentropic enthalpy drop (the absolute enthalpy drop), as follows:

$$\eta_{\mathrm{ri}} = \frac{h_0 - h_{\mathrm{c}}}{h_0 - h_{\mathrm{ca}}}$$

In this equation, $\boldsymbol{h_0}$ represents the turbine's inlet enthalpy, kJ/kg;h_{c} represents the turbine's exhaust steam enthalpy, kJ/kg;h_{ca} represents the ultimate enthalpy of the turbine's ideal process (isentropic process), kJ/kg.

2. **The mechanical efficiency of a steam turbine**
The mechanical efficiency of a steam turbine can be calculated as the ratio of the turbine's shaft coupling output power (effective power) and its inner power after calculating the mechanical loss, as follows:

$$\eta_{\mathrm{m}} = \frac{P_{\mathrm{ax}}}{P_{\mathrm{i}}}$$

In this equation, P_{ax} represents the turbine shaft's coupling output power, kW; and P_{i} represents the turbine's inner power, kW. The turbine's inner power without heat extraction steam can be calculated by the following equation:

$$P_{\mathrm{i}} = \frac{D_0(h_0 - h_{\mathrm{c}})}{3600} = \frac{D_0(h_0 - h_{\mathrm{c}})\eta_{\mathrm{ri}}}{3600}$$

Here, D_0 represents the turbine's inlet gas.

The steam turbine's inner power with heat extraction steam is calculated using the following formula:

$$P_{\mathrm{i}} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \frac{D_{\mathrm{i}} \Delta h_{\mathrm{i}}}{3600}$$

Here, D_{i} is the flow of steam extraction or exhaust steam at all levels, kg/h; Δh_{i} represents the various extraction or effective exhaust steam enthalpy drop, kJ/kg; and n represents the passage parts of the steam turbine according to the number of extraction segments.

3. **Generator efficiency**
Generator efficiency can be represented by the ratio of electric output power and the turbine shaft's coupling output power after considering the electromagnetic, mechanical, and air blower loss:

$$\eta_{\mathrm{g}} = \frac{P_{\mathrm{e}}}{P_{\mathrm{ax}}}$$

Here, P_{e} is the generator output power.

Where there is incomplete data, the relative internal efficiency, mechanical efficiency, and generator efficiency of the steam turbine can be approximated according to the rated power of the turbine, as shown in Table 9.

Table 9 Relative internal efficiency, mechanical efficiency, and power generation efficiency of steam turbines

Efficiency	Turbine rated power(kW)		
	750 ~ 6000	12,000 ~ 25,000	50,000
Relative internal efficiency of steam turbine	0.7 ~ 0.8	0.75 ~ 0.85	0.85 ~ 0.87
Mechanical efficiency of steam turbine	0.95 ~ 0.98	0.97 ~ 0.99	~0.99
Generator efficiency	0.93 ~ 0.96	0.96 ~ 0.97	0.98 ~ 0.985

Gas Turbines

Air and ground gas turbines are classified according to their power as large, medium, small, micro, and ultra-micro. CCHP systems generally use a small-scale turbine that ranges in capacity from 10 kW to 50 MW. A gas turbine is internal combustion power machinery that uses continuously flowing gas as the working medium to drive the impeller to rotate at a high speed, thus converting the energy of fuel into useful work. Its structure is similar to a steam turbine.

A gas turbine mainly consists of three parts: the compressor (axial or centrifugal), combustion chamber, and turbine. An axial compressor is suitable for mass flow situations because of its high efficiency. For smaller flows, an axial compressor has a lower efficiency when combined with a centrifugal compressor due to the several-stage short blade in the back. Some compressors in gas turbines have several megawatts of power by using an axial compressor plus a centrifugal compressor in the last stage, which increases the efficiency and shortens the axial length at the same time. In addition to having perfect adjustment and security of the main components, gas turbines need to be equipped with a subsidiary system and equipment, including a starting device, fuel system, lubrication system, air filter, and intake and exhaust mufflers.

The turbine is the core component of a gas turbine, turning the energy contained in the liquid working medium into mechanical work. The most important part of a turbine is the rotating component—namely, the rotor or impeller—which is installed on the turbine shaft and equally arranged along the circumference of the blade, as shown in Fig. 4. During the process of flow, the energy contained in the liquid is transformed into kinetic energy. The liquid impacts the blade when it flows past the impeller, accelerating the impeller's rotation and thus driving the turbine shaft's rotation. The turbine shaft drives the other machinery and outputs mechanical work directly or through the transmission mechanism. The working medium of turbine machinery can be steam, air, another gas, or mixed gases. It can also be the liquid, such as water or oil. When water is used as the working medium of the turbine, it is called a water turbine; by this analogy, there are also gas turbines and air turbines.

Figure 5 shows a diagram of a gas turbine plant. The compressor continuously intakes air from the atmosphere and compresses it to a certain pressure into the combustion chamber, combusting it with mixed nozzle injection fuel. High-temperature gas of a certain pressure is generated and then flows into the gas turbine to drive

Fig. 4 Turbine

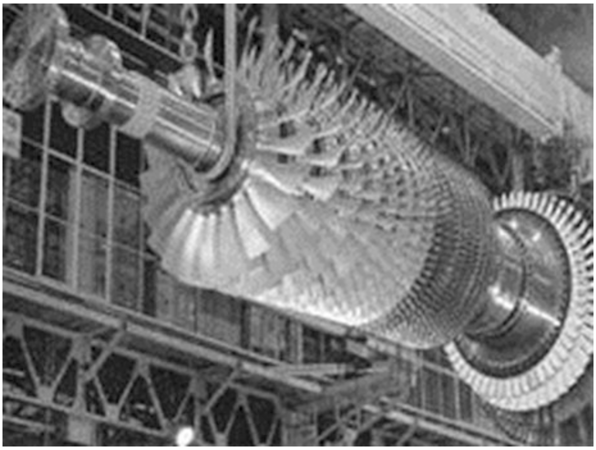
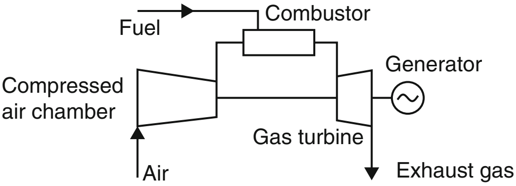


Fig. 5 Working principles of a gas turbine



the turbine rotor, which rotates together with the compressor rotor. In the meantime, the pressure and temperature of the gas decreases; the gas is discharged into atmosphere at the end of the process. A gas turbine can partly covert the chemical energy in the fuel into mechanical work. When a gas turbine starts from a static situation, it requires a starter with spin. The starter is released after the gas turbine is accelerated, allowing it to run independently.

The Characteristics of Gas Turbines

More than a half-century ago, the BBC Corporation in Switzerland produced the first 4-MW industrial gas turbine. With progress in thermodynamics, gas dynamics, high-temperature materials, cooling technologies, and manufacturing technologies, great developments have been made in gas turbines since then. In recent years, the maximum power of a standalone industrial gas turbine has reached approximately 480 MW. The highest inlet temperature of a turbine exceeds 1400 °C and the highest pressure ratio is above 30. Furthermore, the highest efficiency of a simple cycle gas turbine is more than 40%, a gas-steam combined cycle power plant is more than 60%, and a CCHP system is close to 90%. By 2010, as a result of economic development, adjustments in power structure, generating efficiency, and lower power consumption, the power capacity in China exceeded 600 million kW; of this, the capacity of the country's gas turbines was at least 32 million kW, accounting for approximately 5% of the overall capacity.

Gas turbines use air as the working medium. Air temperature and proportion change with site conditions. The international standard working conditions (per the ISO) are an ambient temperature of 15 °C, atmospheric pressure of 101.3 kPa, and relative humidity of 60%. The factory design and manufacturing of gas turbine occur under ISO working conditions.

A gas turbine is constant volume equipment, whose performance is closely related to the environmental temperature. When the environmental temperature increases, the air density decreases; thus, the mass of air that enters the compressor and gas turbine also decreases and leads to a reduction in the gas turbine's output. Increases in environmental temperature can also reduce the compression ratio and amount of work produced by the gas turbine. At the same time, the work consumption of the compressor decreases, which results in further reductions in the turbine's output. With every 1 °C increase in ambient temperature, the turbine's output falls by 1%. For example, the Alstom Company reported the relationship between the performance of some gas turbine generators and environmental temperature as follows: when the air temperature is 5 °C, the gas turbine's power output is 107% of its rated power; however, when the air temperature is 35 °C, its output is only 85%.

In China, 30% of the total installed capacity of gas turbine power plants is mainly located in perennial higher temperature areas, such as the Yangtze River delta and Pearl River delta. In these locations, it can be difficult to achieve the optimal performance of gas turbine and combined cycle power plants. Therefore, it is imperative to correct for the lower gas turbine output in high-temperature environments by using a cooling gas turbine inlet. The inlet air cooling technology has been adopted for a gas turbine system. Its function is to reduce the gas turbine inlet's temperature and to improve the inlet's total air volume. Furthermore, it can reduce the compressor's power consumption and hence improve the power output and thermal efficiency of the gas turbine generator. Various inlet air cooling technologies and methods have been used, including evaporative cooling, surface cooling, electric refrigeration cooling, and ice storage.

A gas turbine uses the compressor's inlet guide vane to adjust the air volume; the adjustment can range from 100% to 70%. When the load is less than 70%, the only options for adjustment are to control the fuel and the output of the gas turbine. With the gas turbine in low load operation, the efficiency drops substantially; for example, with a 50% load, efficiency decreases by 5–7% or more. Therefore, gas turbines are not suitable for partial load operations. In addition, a gas turbine engine's starting time is very short—usually less than 30 minutes from startup to full capacity. If it is part of the steam combined cycle and starts under high temperatures, it also will not exceed 70 minutes. After using heat preservation measures during downtime, the unit can quickly start loading.

Because the waste heat output of a gas turbine is high-quality (high-temperature) thermal energy, it can be used in most cooling and heating projects. The high-pressure steam it produces can be used directly in special dry heating processes, such as paint in an industrial process. Gas turbines can use a wide variety of fuels, including natural gas, synthetic fuels, methane gas, and oil. Usually, fuel gas and liquefied petroleum gas can be used as alternate fuels. Gas turbines have very high reliability and relatively low maintenance costs compared with internal combustion engines, whose equipment overhaul cycle is very long. At the same time, gas turbines have very low emissions and are environmental friendly. Their specific performance parameters are shown in Table 10.

Compared with piston-type internal combustion engines and steam power plants, the main advantage of the gas turbine is that it is small and light. With regard to power quality, a heavy-duty gas turbine is generally 2.0–5.0 kg/kW (an aircraft generally requires less than 0.2 kg/kW). Gas turbines cover a small area. When used in vehicles, ships, and other transportation machinery, it can save space; furthermore, it can be equipped with a more powerful gas turbine to increase the speed of vehicles and ships. A gas turbine's main disadvantage is that its efficiency is not high. The partial load efficiency decreases quickly, with high fuel consumption.

The demand for gas turbines varies by use situation. Gas turbines that exceed 10 MW are mostly used to generate electricity. A gas turbine's generating set can start rapidly without an external power supply. It has good maneuverability, so it can be used to drive the peak load in a power grid and in an emergency, guaranteeing the safe operation of the power grid. They are widely used in motor vehicle and train power stations. In addition, gas turbines are often used as portable power supplies, with the smallest being less than 10 kw. With technological advances, the gas turbine's capacity, inlet temperature, and ratio of the booster compressor have increased significantly.

Table 10 compares the performance profiles of several heavy-duty gas turbines manufactured by GE, ABB, Siemens, and Westinghouse. The main parameters and performance of modern gas turbines have greatly improved over recent decades, with unit capacity reaching 250 MW and the initial temperature being constant at approximately 1288–1300 °C. A single-spindle compressor's compression ratio has

Table 10 Typical performance parameters of a gas turbine generator set

Corporation	Model	ISO Basic Power/ MW	Compressor Ratio	Initial Temperature of Gas (°C)	Efficiency of Power Supply (%)
GE	PG9231 (EC)	169.0	14.2	–	34.93
	PG9331 (fa)	226.5	15.0	1288	35.66
ABB	GT13E2	164.3	15.0	1260	35.71
	GT26	240.0	30.0	–	37.79
Siemens	V64.3A	70.0	16.6	1310	36.81
	V84.3A	170.0	16.6	1310	38.00
	V94.3A	240.0	16.6	1310	38.00
Westinghouse	501G	235.2	19.2	1427	39.00
	701F	236.7	15.6	1349	36.77

reached up to 30, air flow rate is approximately 685 kg/s, and power generation efficiency ranges from 36% to 38%. In the future, a gas turbine's temperature expected to increase to 1427 °C and its power generation efficiency will be closer to 40%.

Small Gas Turbines

A gas turbine has certain advantages, such as high thermal efficiency, low pollution, and low or even no water consumption. A combined-cycle gas turbine results in the system's high efficiency. Therefore, a gas turbine can provide clean, quiet, and efficient energy to power aircraft, marine propulsion, and pipeline pumps, among others. However, internal combustion engine generators of hundreds of kilowatts power and small generators have been available for some time, so there is almost no place in the market for small and micro gas turbine. Because a small gas turbine's single cycle efficiency is low, it cannot compare with an internal combustion engine. Furthermore, a small gas turbine's rotational speed is high, which usually requires a gear reducer; this gear reducer is heavy, thus negating the advantage of a low-speed generator's lightweight gas turbine structure. Of course, the efficiency of the cycle can be improved, but the volume and weight of a conventional regenerator usually exceed the gas turbine itself. In addition, a compact regenerator's manufacturing cost is very high, so the demand for small gas turbines with regenerator applications is not always there.

In the early 1990s, no reduction gear could be driven directly by the gas turbine alternator in a high-speed gas turbine generator; this was needed to greatly simplify the structure and significantly reduce the generator's size and weight. However, the high-speed fin heat regenerator achieved a technological breakthrough and decreased the manufacturing cost when it moved from military to civilian use. The fuel gas compressor and gas pipeline supply pressure create a high-pressure gas. The high-pressure air compressor heats the air through the heat exchanger to make high-temperature and high-pressure gas, as with the pressure of pipeline gas in the combustion chamber. To meet environmental requirements, the combustion chamber is designed to have low emissions. After burning, the high-temperature and high-pressure gas is emitted to the air compressor turbine to drive the generator's power turbine. To comply with the speed requirements of each unit, the turbine does not use the same mechanical shaft but is coupled to a respective driven unit. After the gas turbine uses a heat exchanger to heat the compressed air, it is used in cooling and heating sysstems to make more effective use of heat energy.

Usually, a 300–20,000 kW gas turbine is considered to be a small gas turbine. Its excellent quality of waste heat, with almost 500 °C of smoke flow, is very suitable for cooling and heating systems in industrial enterprises, apartment buildings, hotels, shops, hospitals, and schools, among others. The central hospital of Shanghai Huangpu District and Shanghai Pudong District has its own cooling and heating installations, engineering, and other projects that use a small gas turbine as the prime mover of heat. Small gas turbines provide heat and electricity through steam/hot water and emission of high-temperature flue gas after gas turbine power generation as waste heat boiler steam, used in refrigeration and heating. When combined with a cycled gas turbine and heat pump, the gas turbine can provide the electricity or mechanical energy needed to power heat pump units for refrigeration or heating. A directly used gas turbine produces flue gas, which can then be used in the drying of ceramics and other building materials. When a gas turbine is used with a cycle in agriculture, its flue gas heat, carbon dioxide, water vapor, and nitrogen oxide can be used in agricultural greenhouses. A gas turbine can also be used for the pumps of large-scale power plants; the oxygen from coal-fired boiler flue gas can be injected to improve combustion and reduce the coal consumption.

The characteristics of industrial gas turbines include solidness, reliability, and wide applications for use. They can be used as a fixed power supply or for mobile power to cogenerate cooling and heating; they can also directly be used for industrial power or in thermal power plants. When used for cogeneration or cooling/heating installations, the adjustment of the thermal load is more flexible when electricity consumption is large. When the temperature is high, the turbine can be used in a gas turbine-back-pressure machine coaxial combined cycle. When there is low power consumption and high heat, a complementary combustion technology can be used to adapt to various changes in needs. Based on their individual purpose and demand, enterprises can change capacity and optional configurations; using the start-stop condition and an automated fuel switch, the scene can be unmanned.

Light gas turbines are mainly used in retrofitted aircraft engines, which require a small and light body, fast start-stop, advanced technology, and higher degree of automation. Eddy current technology and axial flow technology are also used in products made by the Solar Company in the United States and Pratt & Whitney Canada. These industrial gas turbines are specially designed for ground applications, such as small aviation turbine engines and retrofitted products; they are also called light gas turbines. The Solar Company produces a 1- to 13-MW turbine with a total output of more than 10,000 units; it has a large number of applications in cogeneration and cooling/heating installations. Tables 11 and 12 list the performance parameters for turbines manufactured by the Solar Company and Pratt & Whitney Canada.

Small gas turbines have strong adaptability for heating and cooling installations. For example, the ST6L-721 gas turbine has a basic output of 508 kW, an exhaust temperature of 514 °C, a flue gas flow rate of 10,800 kg/h, and recycled waste heat of up to 1337 kW. With direct discharge, the heat produced is not only wasteful but can also cause great harm to the environment. If a wasted heat boiler is used, the total thermal efficiency can be as high as 85%. A dual-effect lithium bromide absorption refrigerating unit can achieve very good cooling effects up to 1800 kW, with a cold electric comprehensive efficiency rate as high as 106%.

Three technological revolutions for small gas turbines are important to note:

1. **Regenerative technology**. Using air as the carrier after combustion for flue gas recycling energy can improve efficiency. The Solar Company adopted this

Table 11 Performance parameters of Solar Company's small gas turbine cogeneration systems

Items	Saturn 20	Centaur 40	Mercury 60	Taurus 60	Taurus 70	Mars100	Titan 130
Gas engine contribution (kW)	1181	3418	4072	5069	6728	10,439	12,533
Burn-up rate (kJ/kWh)	14,987	13,166	9209	12,093	11,281	11,265	11,115
Gas consumption (m^3/h)	503	1280	1066	1743	2158	3344	3961
Gas turbine proficiency (%)	24.0	27.3	39.1	29.8	31.9	32.0	32.4
Gas turbine exhaust temperature (°C)	512	443	351	496	482	491	482
Flue gas volume (t/h)	22.7	65.8	60.6	77.7	95.9	147.3	176.0
Waste heat boiler heating directly (1034 kPa steam pressure, saturation)							
Quantity of steam (t/h)	3.7	8.3	4.6	12.0	14.1	22.0	25.8
Steam folding net heat energy (GJ/h)	9.03	20.25	11.22	29.28	34.40	53.68	62.95
The efficiency of cogeneration (%)	75.03	72.35	69.02	77.53	77.24	77.60	77.58
Waste heat boiler combustion to 927 °C and then direct heating (1034 kPa steam pressure, saturation)							
Afterburning fuel consumption quantity (GJ/h)	11.20	37.90	40.80	40.00	50.90	76.10	93.50
Gas consumption (m^3/h)	318	1078	1160	1137	1447	2164	2659
Quantity of steam (t/h)	8.4	24.7	22.5	29.1	35.9	54.7	66.0
Heating efficiency (%)	70.92	72.70	70.11	70.09	69.08	68.90	69.18
Efficiency of cogeneration (%)	85.63	87.54	88.84	88.11	88.18	88.31	88.56

Table 12 Technical performance parameters of Pratt Whitney's light gas turbine

Items	Unit	ST5R	ST5S	ST6L-721	ST6L-795	ST6L-813
Generated output	kW	395	457	508	678	848
Fuel consumption	GJ	4.35	7.00	7.82	9.88	11.74
Specific fuel consumption	KJ/kWh	11,009	15,319	15,385	14,575	13,846
Generating efficiency	%	32.7	23.50	23.4	24.70	26.00
Exhaust gas temperature	°C	365	587	514	589	566
Gas flow	Kg/h	7992	8280	10,800	11,664	14,112
Waste heat recycled	kW	511	1196	1337	1655	1924
Efficiency of comprehensive thermoelectric	%	75	85	85	85	85

technology for a power generation efficiency of more than 39%. A Pratt & Whitney Canada unit used the regenerator for a base load efficiency of 32.7%.

2. **Magnetic high-power crystal controllable frequency conversion technology**. Because a small gas turbine's shaft speed is very fast (>10,000 r/min), power loss is great when a variable-speed gear is used, with a high failure rate. If a permanent

magnet generator does not need excitation, the power efficiency can be as high as 95%. Controllable frequency conversion technology supports a safe and reliable grid to improve the ability for automatic control and reduce the production cost. Germany and Japan already produce these units at the 400-kW level.

3. **Combined residual heat, refrigeration, and air conditioning units.** For waste heat absorption or adsorption-type air conditioning units, as well as refrigeration and heating, equipment such as boilers should be omitted for the chemical water system to greatly facilitate the end use.

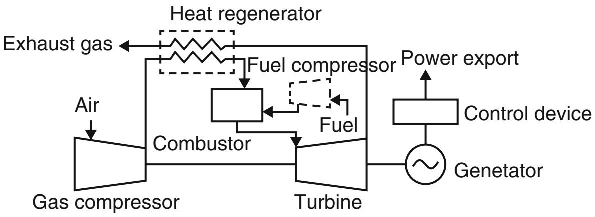
Micro Gas Turbines

The micro gas turbine is a new type of engine, with stand-alone power ranging from 25 to 300 kW. Since the 1990s, it has really developed as a kind of advanced power plant. Its basic technology is characterized by the use of radial flow impeller machinery (a centripetal turbine and centrifugal compressor), which are both in the rotor impeller for a back-to-back structure. The regenerator is generally an efficient fin type. Some units also use air bearings, which do not need a lubricating oil system so the structure is simpler. A micro gas turbine uses the Brayton cycle, which mainly includes a compressor, combustion chamber, turbine, regenerator, generators, and a control device. Its main fuel are natural gas, methane, gasoline, and diesel. Figure 6 shows its working process.

Early micro gas turbines generally used a single-stage centrifugal compressor. The single stage to the heart or single-stage axial flow turbine and the generator on the centrifugal compressor through the reducer are linked together. The combustion chamber has two kinds of rings and a single tube combustor, with ball bearings, a roller bearing support system, and a lubrication system for the entire unit. Because they are not connected to hot devices and the consumption is higher, some units have poor economy.

With technological developments, the micro gas turbine's structure evolved. A high-speed permanent magnet generator connects the generator and compressor, which no longer needs to slow down. The unit's weight, size, and cost have also decreased greatly. The use of air bearings instead of rolling bearings means that a lubrication system is no longer required. Substantially reduced unit parts have further reduced manufacturing costs. To improve the thermal efficiency of the unit, an efficient compact regenerator is generally used; its thermal efficiency is as high as

Fig. 6 Micro gas turbine power generation workflows



90%, which results in a cycle efficiency of up to 30%. To further improve the circulation efficiency, the outlet temperature of the combustion chamber can be increased, which improves the turbine's inlet temperature. However, the turbine inlet temperature is limited by the turbine's materials, so it cannot be too high. To overcome this contradiction, some research institutions have investigated ceramic for combustion.

Currently, micro gas turbines often use a centrifugal compressor (and rarely, an axial flow compressor), with compressor pressure ratio between 3.0 and 4.0. The micro gas turbine often has a centripetal turbine and centrifugal turbine. A centripetal turbine is simple, low cost, high performance, and easy to assemble. It is not sensitive to the blade tip clearance. However, it has large inertia, although the axial flow turbine expansion ratio is limited. Despite the relatively low expansion ratio of the micro gas turbine, it also has the ability to work. A micro gas turbine may have a high-speed generator, permanent magnet generator, reluctance generator, unipolar induction generator, or Rendell generator. Permanent magnet materials are superior to winding magnetic generators, continuing to improve efficiency and speed at temperature less than 260 °C.

Air cushions are used to support a new type of bearing, air bearings. Based on the inherent nature of air (low viscosity and small temperature changes), air bearings have certain advantages for operations at high speed, low friction, high temperature, and low humidity. Currently, two kinds of air bearings are mainly used: air static pressure bearings and air dynamic pressure bearings. The capacity of aerostatic bearings is relatively high based on the external pressure of the gas supply. Air dynamic pressure bearings depend on the pressure of the shaft surface's gas film under the load produced by the relative motion. Because aerostatic bearings require the pressure of an external gas source, they are not used in micro gas turbines. Instead, micro gas turbines use air dynamic pressure bearings.

Micro gas turbines often use one of two combustion chamber types: single tube combustors or annular combustion chambers, which can be further divided into baffle annular combustor chambers and reflux annular combustion chambers. To reduce emissions, these are widely used in micro annular catalytic combustors, where they ensure the air-fuel ratio of the combustion chamber under low and stable combustion conditions. When the combustion temperature is below that required for NOx combustion, the combustion efficiency is as high as 99.5%.

A prototype of the micro gas turbine dates back to the 1960s. However, as a new small distributed energy system and power supply device, its development history is short. In the United States in 1995, AlliedSignal demonstrated a 25- to 75-kW micro gas turbine prototype, followed by a rapidly developing prototype every year. A variety of products followed in the market, including AlliedSignal's 75-kW products, Capstone's 30-kW and 60-kW products, Elliott Company's 45-kW and 80-kW products, Ingersoll Rand's 30- to 250-kW range of products, GE's 75- to 350-kW products, and British Bowman's 35- to 200-kW products. Other companies also developed micro gas turbines that were available in international markets, including Allison Engine Company, Williams International, Teledyne Continental Motors, Volvo, ABB, Toyota, IHI, and Kawasaki. The key performance indicators of these internationally available products are shown in Table 13. The efficiency of micro gas turbines reached 25–29%, with energy utilization rates of 70–90% and NOx emissions that were less than 9×10^{-6}. The scope of power ranged from tens to hundreds of kilowatts.

Figure 7 shows Capstone's model 830 that was launched in 1998, a 28-kW micro gas turbine whose main components include a centrifugal compressor, single cylindrical combustion chamber, centripetal turbine, regenerator, and generator. This single-shaft generator has speeds of 96,000 r/min, with noise below 60 dB, nitrogen oxide emissions of 9 PPM with natural gas as fuel, and carbon monoxide emissions of 25 PPM. The whole engine placement includes a cylindrical shell, compressor, turbine impeller, and a back-to-back generator with a permanent magnet rotor, backed up with a gas turbine rotor. The single rotor structure supports the three air bearings. Air flows from the generator through the cooling fin of the generator stator periphery, then into the compressor after cooling the engine. A plate regenerator is included in the unit, in which compressed air is heated in the annular combustion chamber. In the outward gas turbine combustion chamber, the air flow is guided to the regenerator from the center out; the outflow of regenerator is collected from the upper unit after discharge. The arrows in this figure indicate the air flow direction and flow components.

Micro gas turbine units are composed of an impeller compressor, turbine impeller, and permanent magnet generator rotor, which is the only rotating part in the whole unit. Because the number of moving parts are kept to a minimum, the working reliability is greatly improved. A starter generator is used in a gas turbine generator for motor start, after the working state of the generator begins. When the power supply is a battery, the direct current (DC) inverter is used for alternating current (AC). The fuel pump and compressor motor driving unit need lubricating oil; these are driven by a motor unit. Therefore, there is no direct drive of the auxiliary machinery. Because the gas turbine structure is simple, the unit's reliability is greatly improved.

The micro gas turbine, which has good efficiency under small flow rates because of its structure, also has the following features:

1. **A single-stage centrifugal compressor.** This compressor has high efficiency, high pressure ratio, a simple structure, small size, low weight, low manufacturing cost, good mobility, and easy installation compared with an axial flow compressor.
2. **A single-stage centripetal turbine.** With a small flow rate, the efficiency of a single-stage centripetal turbine is greater than that of a single-stage axial flow turbine. Also, the difference between the gas temperature and leaf temperature is large, which can improve the thermal efficiency of the turbine.
3. **Return-flow, single-tube, or annular combustion chamber.** With return flow, the gas turbine combustion chamber's structure is compact. The return flow of a single-tube combustor has a simple structure and easy maintenance, which is suitable for ground uses.

Table 13 Performance parameters of various micro gas turbines

Manufacturer	Capstone	Allied Signal	Bowmen	Elliott	IHI	NREC	Honeywell
Product model	C30	AS75	TG80CG	TA45, 60, 80	Dynajet2.6	Power work	Parallon75
Rated power (kW)	30, 60	75	80	45, 60, 80	2.6	70	75
Generating efficiency (%)	25(±2)	28.5	27	25 ~ 30	8 ~ 10	33	28.5
Rotate speed (r/min)	96,000	65,000	99,750	110,000	100,000	60,000	65,000
Pressure ratio	3.2	3.7	4.3	4.0	2.8	3.3	3.7
Fuel consumption rate (m^3/h)	9.3	22.2	17.3	15.6	1.4	18.4	22.2
Fuel type	Natural gas, diesel oil	Natural gas, diesel oil	Natural gas, diesel oil	Natural gas, diesel oil	Diesel oil	Natural gas, diesel oil	Natural gas, diesel oil
Exhaust gas (air inflow) temperature (°C)	270(840)	250(920)	300(680)	280(920)	250(850)	200(870)	250(930)
NOx ($\times 10^{-6}$)	<9	9 ~ 25	<9	<25	/	<9	9 ~ 25
Noise (dB)	65 (10 m)	65 (10 m)	75 (1 m)	65 (10 m)	55 (10 m)	/	65 (10 m)
Lifetime (h)	40,000	40,000	/	54,000	40,000	80,000	40,000

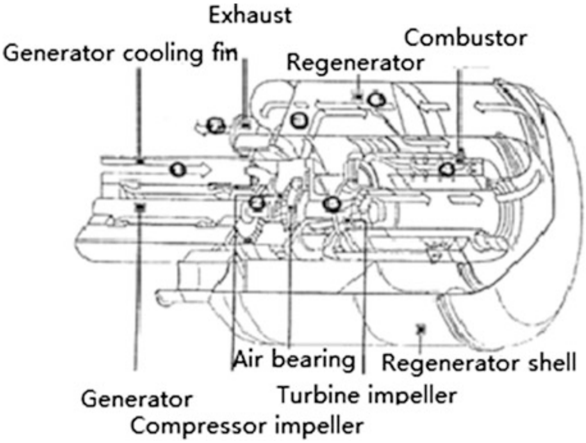


Fig. 7 Capstone's 28-kW gas turbine generator

4. **Single-spindle structure.** A single-stage centrifugal compressor and single-stage centripetal turbine are present in a micro gas turbine with a single-shaft structure. The structure control of motor speed performance is good, being able to adapt rapidly to load changes.

Micro gas turbines can be divided into two types. One type uses a regenerator to recycle its exhaust heat, which increases the compressed air temperature of the burner, thus improving the efficiency of power generation. These turbines with regenerative equipment have electrical efficiency of 26–32%. The other type has no heat recovery equipment, so its electrical efficiency is 15–22%. Although the efficiency of these turbines is worse, they are less expensive.

In recent years, micro gas turbines have developed swiftly, with the regenerator's technical progress playing a key role. Regenerators can be divided generally into two categories: the surface type and the regenerative type. Depending on the type, the regenerator's shell surface, tube, plate, plate heat exchanger, and the original surface have different structures. Micro gas turbines have three types of structures: the main rotary regenerative heat regenerator, the fin-type heat regenerator, and the original regenerator surface type:

1. **Rotary regenerative regenerator.** This regenerator is composed of a heat storage element regenerator and a low-speed rotor, which rotate alternately by fixed gas and air flow through the fuel gas. When the air flows through the components of the heat storage element, the heat is transferred with the absorption of heat. The heat storage element is made of gauze and corrugated metal. The heat transfer area per unit is large. Furthermore, the unit is highly compact, lightweight, and produces high heat. However, the structure is complex, has significant air leakage (typically 12–20%), its flow pulsation is intense, and the import and export pressure loss is large. In addition, to increase flow with the rotation of the body or valve requires increased complexity.

2. **Plate-fin regenerator.** The regenerator is close to a metal plate on the heat transfer surface. The secondary heat transfer surface is the bow or tooth fin regenerator and metal plate form flow. Every plate (~0.5 mm thick), fin (~0.1- to 0.2-mm thick), and seal direct the general gas flow and air flow into the unit body, then through every plate and fin into the air. This regenerator has high heat transfer efficiency, a compact structure, and a large heat transfer area per unit volume (up to 1500–2500 m^2/m^3, equivalent to more than a dozen tube and shell types). It is also lightweight and strong, with a large of range of operating temperatures and pressures; these qualities make it especially suitable for gas in heat transfer. However, it has a complex structure, many requirements for processing technology, low flow, and large pressure loss.
3. **Original surface regenerator.** This heat transfer surface was developed in the 1980s as a compact high-efficiency regenerator. This regenerator is similar to a fin regenerator but uses heat transfer over different surface structures. It has a highly efficient heat transfer surface and a large heat transfer area per unit volume (~3000 m^2/m^3). It is lightweight, small in volume, easy to maintain, with a high heat return that can reach more than 90%. Its working pressure is 0.6 MPa and working temperature is 620 °C. The Solar Company in the United States developed a model with an air flow rate of 6.3 kg/s and heat return of 92.8% to the regenerator, with a hydraulic diameter of only 1.8 mm. However, the material is very thin (<0.1 mm) and thus is difficult and expensive to produce. The coin-type bus bar requires a space curve, which causes a large pressure loss and congestion. The import and export interface design and processing are also difficult.

These three regenerator differ in structure, manufacturing difficulty, air leakage, pressure loss, and applications. The original surface regenerator is light, efficient, and suitable for use in a small gas turbine, but the manufacturing conditions are not mature. The fin-type heat regenerator is both compact and efficient, with more mature materials and manufacturing process. If its performance can meet the requirements of gas turbines, this would be the preferred model.

Micro gas turbines are integrated, use a variety of fuels, and have low fuel consumption, low noise, low emissions, low vibration, and low maintenance. They can be controlled and diagnosed remotely and have a number of other advanced technical features. Therefore, the micro gas turbine has a wide range of uses. It can be used in distributed generation and heating/cooling systems, backup power stations, grid generation, and peak load power generation. It can provide clean, reliable, high-quality, multipurpose, small distributed generation and cogeneration, which is the ideal for center city, suburban, rural, and remote areas alike. The United States, Japan, and European countries are researching and further improving a new generation of micro gas turbine systems. This new generation of micro gas turbines aim to achieve the following:

1. **High efficiency:** For fuel and electric power conversion, the efficiency is at least 40%.

2. **Environmental advantages:** For natural gas systems, NOx emissions are $<7 \times 10^{-6}$.
3. **Durability:** The overhaul interval is 11,000 h, with a design life of 45,000 h.
4. **Economy:** A system costs less than USD 500 per kilowatt. Thus, the unit cost of electricity compared with other forms (including public power grid) should be competitive. A variety of fuels can be used, including gas, diesel, ethanol, trash, and microorganisms.

A micro gas turbine can be used with a combination of fuel cells to generate power directly. Currently, this is one of the world's most advanced efficient clean power generation methods. A combined cycle power generation system with high-temperature fuel cells uses a molten carbonate fuel cell (MCFC) and a solid oxide fuel cell (SOFC). The combined power generation efficiency can reach more than 60%, with NOx emissions of $<1 \times 10^{-6}$. The underlying cycle of MCFCs uses gas turbine exhaust as the cathode air source. The turbine inlet air is used again by the high-temperature fuel cell's anode exhaust as residual fuel for combustion heat. MCFCs can work under atmospheric pressure. The top loop can use SOFCs instead of a combustion chamber, with the high-temperature exhaust gas being used for the turbine's expansion work. This combined cycle system is a kind of distributed generation system. Commercial products should be available in the next 5–10 years, with industrial gas turbine-high temperature fuel cells being suitable for central station systems. This technology may not become commercially available, but the technology is feasible in theory.

Micro gas turbines and small gas turbines have distributed energy supply systems that can be applied in two kinds of important hosts. For micro gas turbines with regenerative cycles, the power generation efficiency can reach 30% or higher, with an exhaust temperature of 200–300 °C under 300 kW of power. More than one modular combination can be used simultaneously and can be run through a switch to prevent the unit from operating under low load and low efficiency, which improves the partial load performance. For a simple cycle gas turbine, power can range from 300 kW to several megawatts, with an exhaust smoke temperature of ~500 °C. Its thermal quality is high and it can use large amounts of residual heat, so its kW unit cost is lower than that of a micro gas turbine. However, its efficiency is low: a megawatt-grade small gas turbine has a power generation efficiency that is generally <28%, with an even poorer the partial load performance.

Liu et al. established restrictions for maximum and minimum output of a device, such as temperature and output to distributed installations and system optimization operation of the equipment performance using a mixed integer nonlinear programming method. Depending on the load conditions, this method can optimize the different configuration of distributed system installations, calculate the economy and energy conservation, reduce emissions, and analyze load characteristics. We analyzed four types of urban buildings that used micro gas turbines and small gas turbines for heating and cooling systems. Micro gas turbines and small gas turbines both resulted in favorable economic situations in office buildings. Energy savings and emission reductions were greatest in a distributed energy system, but a small gas turbine system had greater energy efficiency. The environmental temperature did affect a gas turbine's performance, however.

Combined Gas-Steam Turbine Units

Many heaters use a simple cycle and a fixed working medium. Thus, due to the limits of the working medium and temperature tolerance of the metallic material, they are confined to a narrow temperature range with relatively low heat transfer efficiency. If heat cycles with different operating temperature ranges are combined to complement each other, such as a high-temperature cycle and a low-temperature cycle, the total heat loss can be greatly reduced, thereby enhancing the overall cycle efficiency. In this combined-cycle setup, there is complementary energy, first energy, a top cycle, and a bottom cycle, along with other basic concepts.

One part of the system can be used in the discharge of waste, called residual energy. Generally speaking, there are two forms of waste heat, with a gas turbine discharge temperature often up to 400–500 °C and a blast furnace exhaust pressure of 0.2 MPa, which can drive the flue gas turbine-generated power. *First energy* refers to the apparent exergy loss that has occurred in the primary stage of energy conversion, because this part of the exergy has not yet entered the system with the energy phase that was lost, which is the so-called first energy. The most typical example is the boiler in a steam-powered cycle. A modern large boiler's thermal efficiency can reach more than 90%; that is, most of the chemical energy of coal is converted into steam enthalpy. However, the exergy efficiency is very low, only about 40%. Thus, 60% of the total input energy is lost—half due to low-temperature combustion and the other half by the large temperature difference in heat transfer between the furnace gas and steam. The two cycles together constitute a combined cycle, which are front and rear.

The gas turbine uses the Brayton circulation mode, and the average heat absorption temperature is high. In recent years, with the development of materials and cooling technology, the initial temperature of the gas turbine (inlet temperature) has continued to increase, such that a large ground gas turbine's power generation has reached 1150 °C. This simple gas turbine plant's thermal efficiency is ~33–38%. At present, an air-cooled blade and water-cooled blade can increase the initial temperature of a gas turbine to ~1370–1500 °C, which further improves the efficiency of circulating heat. However, the gas turbine's exhaust temperature is higher (~450–600 °C or even higher); a lot of heat from the high-temperature gas flows into the atmosphere, so the gas turbine's cycle thermal efficiency is limited. With temperature-resistant materials, pressure limits, and turbine inlet temperature, a steam turbine with the Rankine cycle cannot be too hot, with the highest being 600 °C; latent heat and water, which aim to improve the heat efficiency, are limited. However, the steam power cycle has an obvious advantage—the average temperature is very low, at ~30–38 °C.

In recent decades, the steam power's cycle efficiency has been greatly improved, but its average endothermic temperature is low. The subcritical power supply efficiency is ~38%, the supercritical power supply efficiency is <42%, and the ultra-supercritical power supply efficiency is <46%; therefore, using supercritical steam parameters to improve power efficiency has limited effectiveness. The initial investment has greatly increased; thus, it is difficult to operate and maintain. Furthermore, the thermodynamic process used in gas and steam turbines is flawed. Taking into account their respective operating temperature ranges, gas turbines are suitable for high and medium temperatures as a function of thermal power conversion components, whereas steam turbines are suitable for low to medium temperatures. If they work in series with an exhaust gas turbine to produce steam and then drive the steam turbine, gas turbines can be used pre-cycle to form a comprehensive combined-cycle power generation system. This gas-steam combined cycle is the most commonly used conventional combined cycle for natural gas or liquid fuels currently in use.

Gas-Steam Composition, Characteristics and Development of the Combined Cycle

Gas-steam combined-cycle generating units are generally composed of an air compressor, gas turbine, waste heat boiler, steam turbine, generator, and condenser. An impeller compressor on the outside absorbs the air that will be compressed into the combustion chamber later, while the fuel (usually a gas fuel or liquid fuel) is injected into the combustion chamber and compressed to be an air mixture, which is under constant pressure to burn. The generated high-temperature and high-pressure flue gas flows into the gas turbine expansion to work, driving the blades to rotate at a high speed so that the generator can produce electricity. The high-temperature exhaust gas (400–600 °C) is discharged by the gas turbine, which is later sent to the exhaust-heat boiler; the gas flow rate is also very large, with the power of the unit being >300 kg/s). The heating surface in the exhaust-heat boiler absorbs the heat of the flue gas and generates steam, which is then injected into the steam turbine to drive the rotor's rotation and the generator's electricity generation. Gas turbines play a key role in the combined cycle. Because of their high initial temperature, the airflow volume is large, with good aerodynamic performance. The thermal efficiency of a gas turbine is more than 40%, which means there are more than 300,000 kW of power per unit of gas. The inlet temperature is more than 1400 °C, with an exhaust temperature of ~520–640 °C.

The development, design, material, and fabrication process of a gas turbine are high-tech products. Sophisticated equipment is required to produce such a product, especially for high-temperature cooling, combustion chambers, and automatic control. These products are manufactured in developed countries around the world, such as the United States (Westinghouse and Siemens's MS series), Switzerland (ABB's GT series), Germany (Siemens's V series), and Japan (Mitsubishi). These units have been standardized and mass-produced, with high reliability, high mobility, and high efficiency.

The steam turbine is another key component in the combined cycle. The choice of a steam turbine should be matched with the gas turbine and exhaust heat boiler, which mainly involves the selection of the initial temperature and initial pressure of the steam turbine. For the initial temperature selection, the exhaust gas temperature of the turbine determines the maximum value of the new steam temperature. To limit the size of the super heater, it is necessary to ensure that there is a sufficient temperature difference between the exhaust gas and the new steam. Siemens recommends the following initial temperatures for the turbine: single-pressure cycle, 480–540 °C; double-pressure cycle, 500–565 °C, and three-pressure cycle, 520–565 °C. When the temperature is less than 568 °C, GE recommends that the exhaust temperature is more than 30 °C hotter than the initial steam temperature. For initial pressure selection, the overall efficiency of the steam cycle is the product of the waste heat utilization of the turbine and the efficiency of the turbine itself. Siemens recommends the following initial pressures: single-pressure cycle, 4–7 MPa; double-pressure cycle, 5.5–8.5 MPa; three-pressure cycle, 11.0–14.0 MPa. Because their product power is different, GE recommends the following initial pressures: single-pressure cycle, 4.13 MPa; double-pressure cycle, 5.64–8.26 MPa; and even up to 9.98 MPa by heating.

The waste heat boiler is a heat exchanger that utilizes the exhaust heat of the gas turbine to convert it into steam heat energy. The requirements of the waste heat boiler and the requirements of the conventional boiler are not the same, but they should have a high efficiency of waste heat utilization. The pressure loss of the combustion gas side is small, so the power and the efficiency of the combustion engine can be reduced, low-temperature corrosion can be prevented, changes to the quick start-stop and load can be adapted, and the overall size is small. The additional waste heat boiler combustion equipment can be classified as nonafterburning and afterburning. In accordance with the flow direction of flue gas, they can be divided into horizontal and vertical layouts. According to the cycle of the evaporation system, they can be divided into natural circulation and forced circulation boilers. Finally, in accordance with the structure, they can be classified as shell tube or flue type.

A supplementary combustion waste heat boiler can increase the amount of steam generated in the waste heat boiler, thereby enhancing the steam thermal parameters. A tubular waste heat boiler is generally a compact boiler, whereas a large waste heat boiler is generally the flue type; this has a wide range of applications, but is mainly used for cogeneration or cold combined heat and power supply. The three kinds of circuits are low pressure, medium pressure, and high pressure; each circuit consists of a drum, evaporator, economizer, superheater, reheater, and corresponding header. Yang Song drew schematic diagrams of a horizontal waste heat boiler and the vertical structure of the waste heat boiler, as shown in Figs. 8 and 9. The flue gas of a horizontal waste heat boiler is installed in a horizontal direction through the vertical heating surface module, which uses a suspension structure. The waste heat boiler flue gas flows in a vertical direction; the horizontal direction is used to install the heating surface module, while the heating surface module has intermediate support partitions. The waste heat boiler of a large-capacity evaporator does not use a membrane water wall structure; rather, it uses a spiral finned tube, which improves the heat transfer efficiency. The spiral finned tube may be a spiral serrated finned tube or spiral finned tube; the former type has a higher heat transfer efficiency.

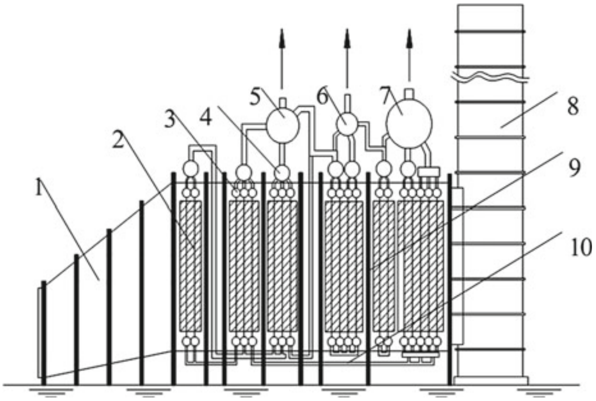


Fig. 8 Schematic diagram of a horizontal waste heat boiler. 1 – inlet flue, 2 – heating surface module, 3 – small collecting header, 4 – distributing header, 5 – high-pressure steam drum, 6 – medium-pressure steam drum, 7 – low-pressure drum, 8 – chimney, 9 – steel framework, 10 – joint duct

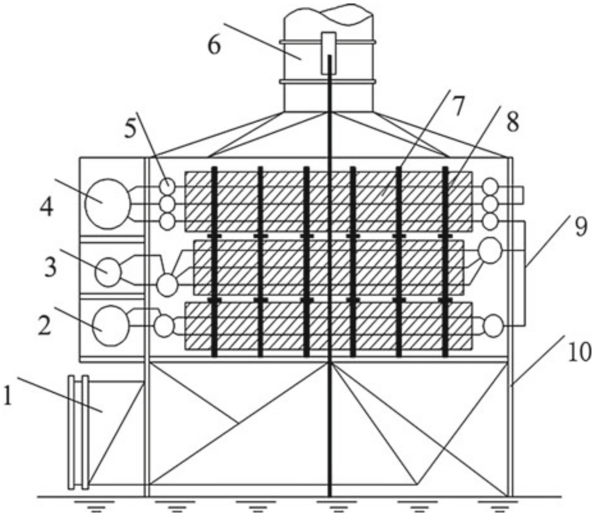


Fig. 9 Schematic diagram of a vertical waste heat boiler. 1 – inlet flue, 2 – high-pressure steam drum, 3 – medium-pressure steam drum, 4 – low-pressure drum, 5 – collecting header, 6 – chimney, 7 – heating surface module, 8 – supporting plate, 9 – joint duct, 10 – steel framework

Gas-steam combined cycle generators have the following advantages:

1. **A high level of availability of energy resources and good economic efficiency of heat.** Through the proper matching of power from the gas and steam, reasonable development of thermal systems and correct parameters can be achieved. Advanced cooling technology can increase the combined cycle efficiency up to 45% or more. If the initial gas temperature is increased to 1100 °C, the efficiency can reach 50–58%, which greatly exceeds the current supercritical steam turbine unit thermal efficiency.
2. **Environmental pollution is small and limited in area.** The fuel used in the combined cycle includes oil, natural gas, liquefied natural gas (LNG), and coal. Most of these are clean fuels that produce little environmental pollution. A coal combustion combined cycle can be divided into two types: integrated gasification

combined cycle (IGCC) and pressurized fluidized bed combustion combined cycle (PFBC-CC). They can create high sulfur, high ash, and low calorific value of low-grade coal gasification and fluidized combustion to achieve desulfurization and dust abatement, which is a kind of environmental pollution, with a high-efficiency power generation device.

3. **Low cost, rapid manufacturing, and low maintenance.** To reduce SO_2 emissions, conventional coal-fired steam turbine power plants use flue gas desulfurization (FGD) equipment. The installation cost of the FGD equipment accounts for 20–25% of the total investment in the power plant; the operation and maintenance costs of the FGD unit is also expensive. For example, the annual operating cost of China's Sichuan Luohuang power plant's 2 × 360-MW unit FGD is 40 million yuan. The FGD device decreases the power supply efficiency of power plants by 1%. The investment cost for a combined cycle power plant is USD 500–600 per kilowatt, whereas the investment cost for a steam turbine power plant with an FGD unit is USD 1100–1400 per kilowatt.
4. **Perfect peak regulation and fast start-stop.** Gas turbines with a time from startup to full load operation of less than 20 min are considered to be quick starting. Combined-cycle units run with a high degree of automation; they can start and stop every day, with a working efficiency of 85–95%. Because gas turbines do not need large amounts of cooling water, a combined-cycle power plant can use much less cooling water than a steam turbine power plant, making it suitable for hydroelectric stations in water shortage areas or with challenging water sources. A simple cycle only accounts for 2–10% of the water consumption in a thermal power plant, while a combined-cycle and thermal power plant uses approximately 33%.

In the 1940s, gas turbines were put into commercial operation, using a combined cycle almost from the start. In 1949, the world's first gas-steam combined cycle operation, a gas turbine exhaust heat boiler, was installed in the United States. In 1960s, the parameters for a combined-cycle power plant were very low, with thermal efficiency of only 35%. After the 1980s, the initial temperature of a gas turbine increased to 1100–1288 °C, so that the efficiency of combined-cycle power generation was more than 50%-more than that of a large-scale coal-fired power unit at the time. In 1990, the global production of combined-cycle plants with burning natural gas was estimate to produce total power up to 14,019 MW. Between 1991 and 1996, it was estimated that the sum of the new generating units put into operation was no less than 27,400 MW.

From the end of the twentieth century to the beginning of this century, the technology of combined-cycle units made great leaps forward. Companies have introduced advanced high-power and high-efficiency gas turbine series and combined cycle units. The initial temperature of the gas is over 1300 °C, and the combined cycle efficiency reaches 55–58%. The 400- to 1000-MW single-or dual-axis combined cycle devices have been put into commercial operation in batches. In recent years, the initial temperature of the new generation of gas turbines has increased to 1430 °C. The corresponding combined cycle efficiency is more than 60%, which indicates the bright future of their development prospects. Their share of the world's power generation capacity has been

Table 14 Performance parameters of gas-steam combined cycle generator sets

Corporation	Model	ISO prime power (MW)	Installed condition	Power supply efficiency (%)
GE power generation	S-109EC	259.6	One MS9001EC	53.5
	S-109FA	348.5	One MS9001FA	54.8
	S-209FA	700.8	Two MS9001FA	55.1
ABB	KA13E2–1	241.6	One 13E2, double-pressure steam turbine	52.5
	KA13E2–1	244.2	One 13E2, triple-pressure steam turbine	53.0
	KA13E2–2	490.8	Two 13E2, triple-pressure steam turbine	53.3
	KA13E2–3	737.3	Three 13E2, triple-pressure steam turbine	53.4
	KA13E2–4	983.5	Four 13E2, triple-pressure steam turbine	53.5
	KA26–1	361.5	One GT26	56.9
	KA26–2	725.9	Two GT26	57.1
Siemens	GUD1.94.2	235.0	One V94.2	51.9
	GUD1S.94.3A	354.0	One V94.3A	57.2
Westinghouse	1 × 1501F	250.5	One 501F	54.8
	1 × 1501G	248.8	One 501G	58.0
	2 × 1501G	697.6	Two 501G	58.0

growing rapidly as well: By the end of 1998, 81% of new generators in 21 European countries were installed with gas turbines and combined-cycle devices. Almost all new generators in the United States have been installed with gas turbines and combined cycles. According to U.S. Department of Energy estimates, the generating capacity of natural gas power plants range from 509 × 109 kWh to 1582 × 109 kWh. Natural gas-fired power generation in Japan must now use combined cycle. In 2004, approximately 35% of the world's annual capacity growth was created by gas-steam combined cycle units. From 2000 to 2001, the world's gas turbine orders were about 1357 units, which means the total capacity was nearly 110 GW. Thus, combined-cycle power generation technology is well developed and widely used. Table 14 shows the performance parameters of some combined-cycle power plants.

In the early 1970s, China began to develop the combined cycle. The Tianjin Second Thermal Power Plant built a supplemented combustion waste heat combined-cycle boiler using a 2.24-MW gas turbine manufactured by Harbin Turbine Plant. Sichuan Dongshan Wutongqiao Power Plant and Nanjing Steam Turbine Plant use a 1.5-MW gas turbine and a 13.5-MW gas-steam combined-cycle device. In 2004, there were more than 10 newly built combined-cycle power plants, with a total capacity of more than 1000 MW. Huaneng introduced a French/British 100-MW combined cycle unit into Shantou and Chongqing, which respectively combined two 36-MW gas turbines and a 35-MW steam turbine. The thermal efficiency is 45.6% and 45.9%, respectively.

The first 51-MW waste heat boiler unit cycle in China was built in 1996. The main equipment included the 9G6541B type 37-MW gas turbine and N15–3.43 steam turbine produced by Nanjing Steam Turbine Plant. Hangzhou Boiler Factory produced China’s first waste heat recovery boilers with natural cycles; their efficiency is 42% for the entire cycle, with an output of ~53 MW and a heat consumption rate of 8597.56 kJ/(kWh). These units are comparable to other foreign equipment.

Nanjing Steam Turbine Factory, in cooperation with GE Company, developed a gas turbine with 100- to 123.4-MW single unit capacity and a 300-MW combined cycle. WING Group, a joint venture, built a 2400-MW LNG combined-cycle power plant in northern Jiangsu. Shanghai and Nanjing negotiated to introduce a foreign-manufactured combined-cycle device with capacity of less than 1000 MW. Guangdong, Hainan, and other regions are also actively building 300- to 450-MW combined-cycle devices. Zhejiang Zhenhai Power Plant expanded its production and installed two sets of 300-MW heavy-oil combined-cycle devices. In short, the development of combined-cycle units in China is not limited to areas that are rich in oil or special economic zones, but has begun to expand to inland areas.

The Basic Types of Gas-Steam Combined Cycles

There are five basic types of the traditional combined cycle: waste heat boiler combined cycle without supplementary combustion, waste heat boiler combined cycle with supplementary combustion, exhaust combustion combined cycle, circulation supercharged boiler combined cycle, and feed water heating combined cycle. These five types of combined cycles can be used in CCHP systems. They can be further divided into six types—single-pressure, single-pressure reheat, double-pressure, double-pressure reheat, triple-pressure, and triple-pressure reheat—based on the process used (Rankine cycle).

In general, a combined-cycle waste heat boiler without supplementary combustion is the most efficient type, so it is the most widely used and most suitable for basic and intermediate loads. The output of the supplemented waste heat boiler combined cycle has been significantly improved. In most cases, the cycle efficiency has decreased with cogeneration to expand the thermoelectric load scale adjustment range or improve the heat load output based on user needs. The existing equipment can be used to reduce the investment required for a power station renovation, which is common for existing turbine mechanical and electrical stations. The advantages of a supercharged boiler combined cycle include low gas temperature conditions, including a cyclic initial temperature of less than 1100 °C. A combined-cycle feed water heating system is simple, but the efficiency is decreased compared with a gas turbine combined cycle.

Table 15 summarizes the main characteristics of the five types of conventional combined cycles:

Table 15 Comparison of five conventional gas-steam combined cycles

Combined cycle type	Unfired waste heat boiler	Complementary combustion waste heat boiler	Full-combustion exhaust	Booster boilere	Water-heating
System integration characteristics	Main part is gas turbine; the waste heat boiler serves as the two circulating connection points	Main part is gas turbine or steam turbine; waste heat boiler is cycling connection with two points	Main part is steam turbine; waste heat boiler is cycling connection with two points	Main parts are both gas and steam turbine; supercharged boiler is a two-cycle connection point	Main part is steam turbine; hot water boiler serves as the two circulating connection points
System performance	Mainly depends on the performance parameters of the gas side; the initial steam parameters are subject to the gas turbine's exhaust parameters	Depending on the fuel injection ratio and the performance parameters of the two sides, the initial parameters of the steam cannot be controlled by the gas turbine's exhaust parameters	Mainly depends on the performance parameters of the steam side; the initial steam parameters are not restricted by the gas turbine's exhaust parameters	Two cycle performance parameters have a great impact	Mainly depends on the performance parameters of the steam side; the initial steam parameters are not restricted by the gas turbine's exhaust parameters
Fuel adaptability	High-performance fuel	High-performance fuel	Inferior fuel with bottom cycle	Different types of fuel with different forms	Mainly uses inferior fuel
Gas turbine function	Main equipment of power production	Main power supply equipment and hot air supply	Replace the boiler fan to send hot air	Main equipment of power production	Heating boiler feed water
Steam turbine function	Top circulating heat utilization equipment	Top circulation heat removal utilization equipment or production main equipment	Main equipment of power production	Main equipment of power production	Main equipment of power production
Steam fuel power ratio	0.45 ~ 0.77	0.5 ~ 7	3 ~ 7	1.4 ~ 5	>5
Relative to the growth rate of simple cycle efficiency	Efficiency of the combined cycle efficiency and the efficiency of the corresponding simple cycle gas turbine		The difference between the efficiency of the combined cycle and the efficiency of the corresponding simple cycle steam turbine		
	1.3 ~ 2.2	1.03 ~ 2.15	2% ~ 5%	/	1% ~ 2%
Operation characteristics	Gas turbine can be operated separately	Gas turbines and steam turbines can be operated separately	Steam turbines and gas turbines can operate separately	Steam turbines and gas turbines cannot operate alone	Steam turbines and gas turbines can operate separately

1. **Unfired waste heat boiler combined cycle:** As shown in Fig. 10, a unfired waste heat boiler combined cycle uses a combined thermal cycle in which all heat in the system is fed from the circulating gas turbine section. An exhaust gas turbine boiler is introduced. Using a waste heat boiler combined cycle, the water is transferred into steam by the remaining heat to drive a turbine. This not only increases the total output power, but also improves the utilization rate of the waste heat of the gas turbine and the thermal efficiency of the cycle. This is the basic principle of a gas-steam combined-cycle power plant. The recycling process is as follows: air compression in the compression process, combustion of air and fuel in the combustion chamber, gas expansion in the gas turbine, exhaust heat release in the gas turbine, compression, water and steam heat absorption, work in the steam turbine, and exhaust steam condensation and heat release in the steam turbine.
2. **Complementary combustion waste heat boiler combined cycle:** As shown in Fig. 11, a complementary combustion waste heat boiler combined cycle is part of the system's heat energy in the working fluid, which is added in the gas turbine cycle after the joint thermal cycle. In addition to the introduction of exhaust gas from the gas turbine into the boiler, it is also possible to replenish some of the fuel (which may be in the exhaust gas passage of the gas turbine, able to be introduced into the waste heat boiler). As the amount of additional fuel is increased, the turbine capacity also increases. Based on the exhaust gas temperature in the gas turbine, the optimum charging capacity for maximum efficiency can be determined; available coal and other inexpensive fuels can be supplemented. With increased filling, the amount of cooling water also should increase. In a supplemented waste heat boiler, the exhaust gas from the gas turbine is supplied to the boiler. Then, the injected fuel that was heated by combustion is cooled. The released thermal energy is used to heat the feed water and increase the temperature of superheated steam. In this scheme, the initial steam temperature is not restricted by the exhaust gas temperature of the gas turbine. Furthermore, the amount of steam and the power generated by the steam turbine can be greatly increased.
3. **Full-combustion exhaust combined cycle:** In this process, the boiler gas turbine exhausts oxygen and the remaining fuel from almost all chemical reactions. The gas turbine exhausts gas when the combustion medium increases pressure in the boiler. The circulation system is similar to the previously described heat recovery boiler combined cycle without supplementary combustion. There is not much difference between a waste heat boiler and an ordinary boiler, except that a gas turbine is used instead of a boiler blower, blowing high-temperature air into the boiler. The gas turbine exhaust is about 500 °C, increasing the economizer's heating surface. Compared with an afterburning boiler, the temperature of furnace is not restricted and the amount of afterburning fuel can be large, so it can use higher steam parameters with an efficient configuration of a large steam turbine system. In addition, another feature of this cycle is the full-combustion boiler that uses combustible low-grade fuel, including coal.

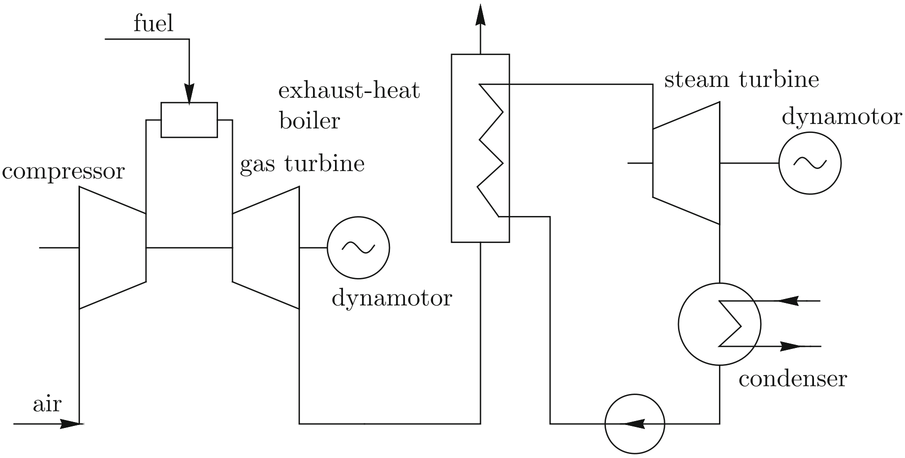


Fig. 10 Schematic diagram of an unfired waste heat boiler combined cycle

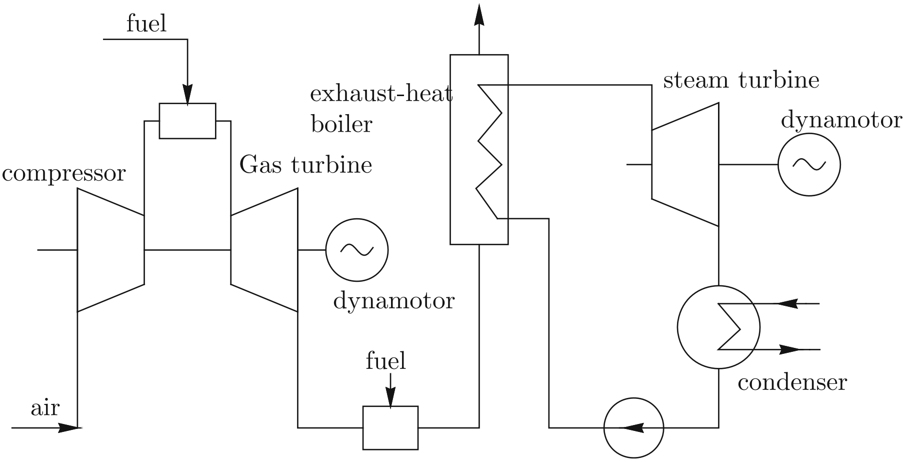


Fig. 11 Schematic diagram of a complementary combustion waste heat boiler combined cycle

4. **Booster boiler combined cycle:** As shown in Fig. 12, the booster boiler combined cycle has a combined heat cycle with a vapor generator in the front of the gas turbine and the back of the steam generator on the circulating gas side combustor. The combustor of the gas turbine is combined with the supercharged boiler of the steam cycle, so the air sent by the compressor is first heated in the supercharged boiler. The released heat energy is used to heat the

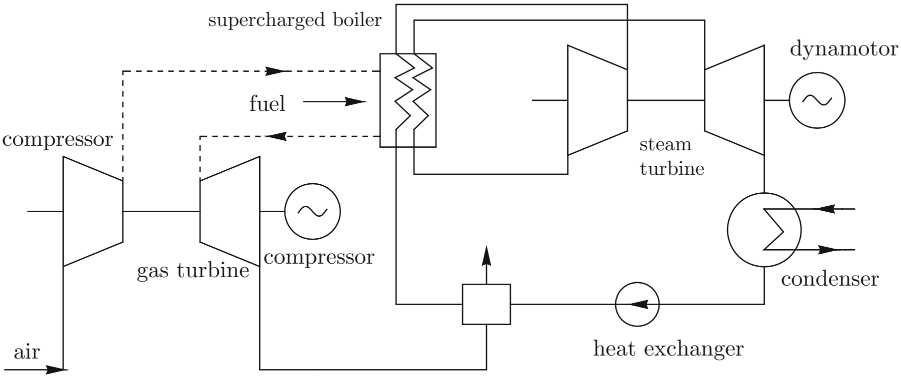


Fig. 12 Schematic diagram of a turbocharged boiler combined cycle

feed water, transferring it to superheated steam for use in the steam turbine. The gas in the supercharged boiler is sent to the gas turbine for expansion after the temperature is reduced. The exhaust gas from the gas turbine is used to heat the feed water to raise the temperature. The booster boiler has a compressor instead of a blower. The air is compressed by 0.6–1 MPa in the introduction to the supercharged boiler. Because the booster boiler exhausts through the gas turbine, the boiler can only burn liquid fuel or natural gas; it cannot burn coal directly. When the initial temperature of the gas turbine is increased to 1300 °C, the power supply efficiency of the booster boiler combined cycle is expected to exceed 50%. A theoretical study showed that when the initial temperature of the gas turbine is lower than 1250 °C, the thermal efficiency of the booster boiler combined cycle is always greater than that of a non-combusted waste heat boiler combined cycle. However, due to the high cost of a supercharged boiler, it is rarely used. Therefore, even if the initial temperature of the gas turbine is higher than 1250 °C, a noncombusted waste heat boiler is usually preferred.

5. **Feed water heating combined cycle:** In this thermodynamic combined cycle, exhaust gas from the gas turbine is used for heating in the steam cycle. Because of the limited amount of heating required for the boiler feed water and the much smaller capacity of the gas turbine compared with a steam turbine, combined cycles are dominated by steam turbines. The heating temperature of boiler feed water is not high and the exhaust heat utilization of the gas turbine is reasonable, so the combined-cycle efficiency is lower. Therefore, new designs for high-performance combined-cycle gas turbines do not use this configuration. Older steam turbine power stations are being renovated using gas turbines. When renovating existing steam turbine power stations, the gas exhaust from the gas turbine is used to heat the boiler feed water. The corresponding heat exchanger needs to be installed to partially or totally replace the steam

turbine for steam extraction and heat recovery. Because the steam turbine reduces the amount of steam extraction, the flow rate at the back of the steam turbine steam and the power are increased. If it is necessary and possible, the original extraction steam heating system can be retained. The original boiler can remain basically unchanged. Only the steam turbine flow area and the condenser heat transfer area need to be updated, which allows for less investment and is more feasible.

Integrated Gasification Combined Cycle

At present, coal is still the main energy resource of mankind. However, this traditional approach to direct combustion is facing increased pressure with regard to energy rates and environmental protection. The world's major industrial countries are seeking to replace traditional coal-fired boiler technology with efficient, clean, and advanced coal-fired power generation technology. How can the efficient, clean combined cycle burn fuel-rich coal? The coal-fired combined cycle (CFCC) is an advanced coal-fired power generation system that combines clean coal or coal conversion technology with an efficient combined cycle. IGCC and PFBC-CC are the two main CFCCs.

IGCC is a clean coal power system that combines clean coal gasification technology with efficient combined cycle technology, including coal storage and transportation, pretreatment, preparation and supply subsystems, coal-based gas subsystems, pulverized coal ash subsystems, pink gas sensible heat utilization subsystems, gas-steam power generation subsystems, air-oxygen subsystems, and cinder and waste water treatment subsystems. Coal is transformed into high-calorific value gas (10467–20,943 kJ/m^3) or low-calorific value gas (4187–10,467 kJ/m^3) through a coal gasifier. Then, through the purification equipment, the coal gas of the solid ash and the sulfur-containing material are removed and sent to the combustion chamber of a supercharged boiler or gas turbine for indirect combustion in a gas-steam combined cycle. IGCC is a conventional and mature technology in gas turbines, waste heat or booster boilers, and steam turbines, with the ability to increase coal gasification and purification (Fig. 13).

In 1972, the world's first IGCC plant with a supercharged boiler gas-steam combined cycle was put into operation at Lunke's Stiker plant in Germany. The power generation capacity was 170 MW, the actual power supply efficiency was 34%, and a fixed-bed Lurgi gasifier using coal was used as a gasifying agent. This power station was the first to use coal in a gas-steam combined cycle. However, due to the unusual operation of the Lurgi gasifier, crude coal gas containing more coal tar and phenol was not easy to handle. The demonstration project could not be maintained and operated over the long term; ultimately, the plant closed. The most successful IGCC trial run was built in Daggett, California in May 1984 using a waste-heat boiler gas-steam combined cycle. The net power of the plant was 93 MW

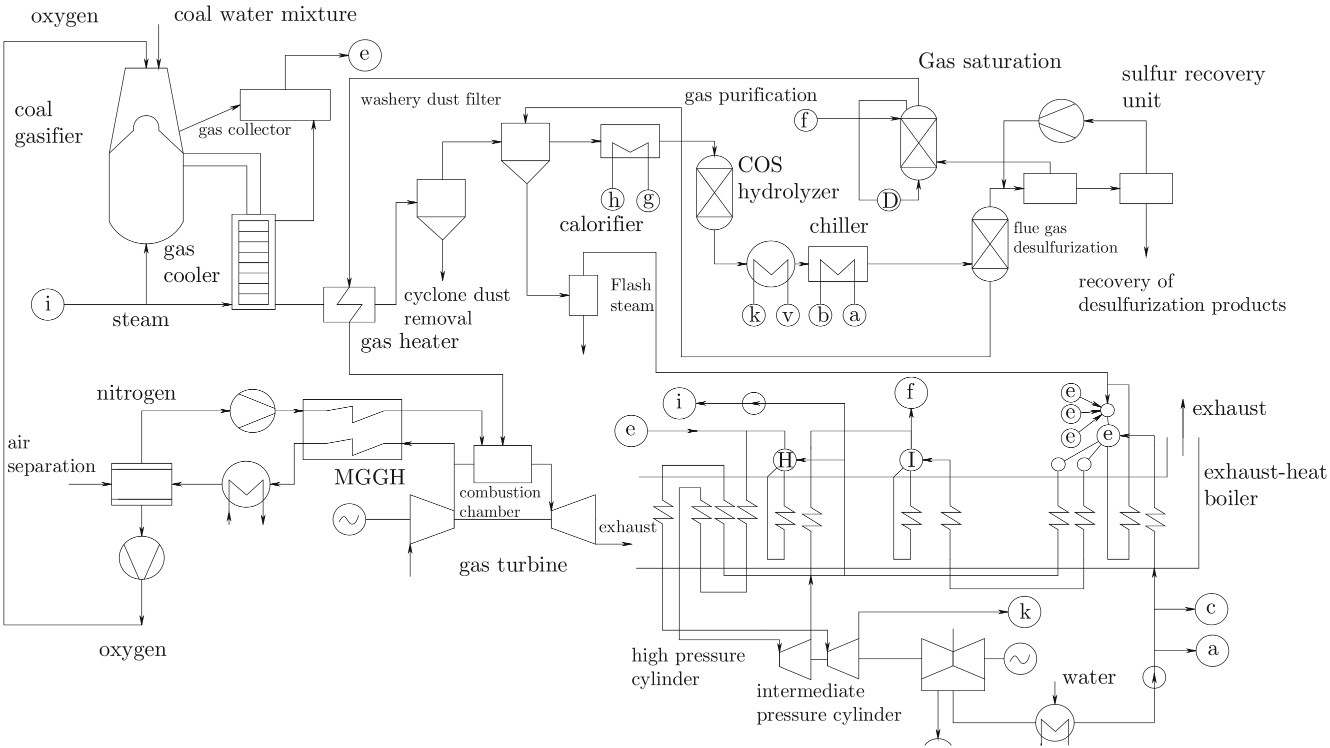


Fig. 13 Schematic diagram of a typical IGCC system

and the power supply efficiency was 31.2%, using 99% oxygen as gasifying agent in a Texaco entrained flow gasifier. The plant operated successfully for 4 years (25,000 h), solving the serious problem of the inherent pollution of coal-fired power plant emissions. It also demonstrated that IGCC power generation has enough operational availabilities and load factors. IGCC is a promising clean coal power-generation technology and may be the most promising for coal-fired power generation in the twenty-first century, in addition to a breeder reactor.

IGCC power generation technology has the following characteristics:

1. **Great potential to improve the efficiency of the power supply capacity.** The current power supply efficiency is up to 42–45%, which is expected to increase to 50–52% in the twenty-first century.
2. **Large capacity.** Stand-alone capacity can reach more than 300 MW.
3. **Excellent environmental performance.** High-sulfur coal can be used with minimal waste treatment. When burning sulfur content greater than 3% of high-sulfur coal, the advantage is greater.
4. **Full use of coal resources.** The polygeneration system can produce electricity, heat, fuel gas, and chemical products, but it is also easy to produce methanol, gasoline, ammonia, urea, and other chemical processes.
5. **Less water consumption.** The typical water consumption is 50–70% of a conventional power plant, so it is also suitable for dry areas.
6. **Mature technology.** A demonstration plant has an operating availability of 80% or more, meeting the requirements for commercial operation.

Furthermore, IGCC promotes the development of advanced industrial and high-tech industries, such as subcritical or supercritical steam parameters for IGCC, integrated gasification wet air turbine combined cycle (IGHAT), and integrated coal gasification fuel cell combined cycle (IGFC-CC). When natural gas and oil resources are exhausted, the gas-steam combined cycle can be reformed using these fuels, which is convenient for retrofitting existing steam power stations and facilitating the construction of new power stations (gas turbine power station → combined natural gas-fired power station → coal-fired IGCC power plant).

IGCC has high costs for investment and power generation. In 2000, the cost was about USD 1400–1600 per kilowatt. In the twenty-first century, the cost is expected to decrease to USD 1000–1200 per kilowatt. Its power capacity is in the range of 300–600 MW. IGCC also requires advanced technology, such as a high-efficiency/high-capacity gasifier, high-performance gas turbine, and high-temperature purification technology. The gasifiers can be divided into three types: fluidized bed gasifiers, fixed bed gasifiers, and fluidized bed gasifiers. Each of the three gasification furnaces has its own advantages and disadvantages, and each of them is under development. In addition, to improve furnace gas production, an IGCC power station often has a special oxygen-generating air separation system and equipment to provide pure oxygen or oxygen as a gasification agent. In this way, plant electricity rates can be as high as 10% to 13%. If compressed air is used as a gasifier or part of the integrated air separation system, the plant electricity rates can be reduced to 5%.

Since the 1980s, dozens of IGCC demonstration power stations have been established around the world. These power stations have been put into commercial operation with a maximum capacity of 330 MW and a power supply efficiency of approximately 45%. Table 16 shows the equipment overview and technical and economic indicators for IGCC power plants that target pure generation on a relatively large scale. Through the collaborative efforts of various research institutions and developers, IGCC units have been put into operation and carried out experimental research; in this way, thermal performance and operational reliability have reached high levels. An IGCC system scheme with more advanced performance has been proposed using an optimization design. The net efficiency of a newly designed IGCC system is up to 51%. Practice has proven the technical feasibility of IGCC units, along with their environmental protection superiority and better operation reliability.

The international community has placed great importance on the IGCC technology. Many countries regard IGCC as a key technology for major national research programs. In 2012, IGCC's power supply efficiency was 60% (higher heating value [HHV]) and cost was USD 1000 per kilowatt, with zero CO_2 emissions and NO_x of 3–9 ppm. By 2015, IGCC's power supply efficiency was 65% (HHV) and cost was USD 850 per kilowatt, with zero CO_2 emissions and NO_x of ≤ 3 ppm. At present, China has IGCC units that were developed independently or in cooperation with foreign organizations for research and development the IGCC technology. These 200- to 400-MW IGCC power plants use key technology.

Fluidized Bed Coal Combustion Combined Cycle

A fluidized bed coal combustion combined cycle (FBC-CC) uses fluidized bed combustion (FBC) coal technology and a combined- cycle thermal system with the combination for a coal-fired combined cycle power system, mainly a pressurized fluidized bed coal combustion combined cycle (PFBC-CC) or atmospheric fluidized bed coal combustion combined cycle (AFBC-CC). Fluidized bed combustion uses coal and an absorbent (limestone, dolomite) mixed in certain proportions. After adding material to the bed of the combustion chamber from the bottom of the blast furnace as a suspension, the advanced technology achieves combustion in a fluidized state. The turbulent fluidization formed from the mix can occur between coal and air with strong relative motion. Increasing the contact and stay of coal and oxygen can strengthen and stabilize the combustion and combustion efficiency. In coal burning, the desulfurization agent adsorbed with SO_2 generates calcium sulfate to the overflow pipe discharge or into the regeneration device. Fluidized bed combustion can be bubbling bed combustion or circulating bed combustion type; it can be further divided as either atmospheric fluidized bed combustion or pressurized fluidized bed combustion.

PFBC-CC uses a pressurized fluidized bed combustion boiler and boiler and gas turbine combustion chamber, so the structure is compact, equipment volume is small, metal consumption is low, the investment cost is low, and large-scale setup are easier

Table 16 Overview of the current generation and operation of pure IGCC globally

Project Name	The Netherlands	Spain	United States	United States	United States
System name	DEMKOLEC	ELCOGAS	Wabash River	Tampa	Pinõn pine
Purpose	Set an example	Set an example	Commercial transformation	Set an example	Set an example
Start date	At the end of 1993	1996.1	1995.8	1997	1997.2
Net electrical power (MW)	253	300	265	260	95
Design value of power supply efficiency	43% (LHV)	45% (LHV)	40% (LHV)	42% (LHV)	42% (LHV)
Measured value of power supply efficiency	43% (LHV)	/	40% (LHV)	37% (LHV)	/
Gasifier	Shell 95% O_2 Dry coal supply	PRENFLO 85% O_2 Dry coal supply	Destec 95% O_2 Coal water mixture	Texaco 95% O_2 Coal water mixture	KRW dry air supply
Efficiency of carbon con version	0.99	0.99	0.99	0.95	0.98
Gasification temperature (°C)	1500	1400	1400	1370	1093
Hot gas efficiency	0.93	0.93	/	<0.90	/
Cold gas efficiency	0.80 ~ 0.84	0.78	/	0.7 ~ 0.73	/
Ash removal and desulfurization	Wet ash removal and desulfurization	Dry and wet methods	Dry ash removal and wet desulfurization	Wet ash removal and desulfurization	Dry ash removal and desulfurization
Gas turbine	Siemens/KWU V94.2	Siemens/KWU V94.3	GE7001FA	GE7001FA	GE7001FA
Steam turbine	12.5/2.9/0.5 MPa/511 °C	12.7/3.7 MPa	10.3/3.1 MPa/510 °C	/	6.363 MPa
Plant power consumption rate	11%	/	11.5%	19.75%	7%
Investment cost (USD/kW)	1858	2303	1511	1900 ~ 2000	2842

to achieve. The current capacity has reached 300–350 MW. AFBC-CC uses atmospheric fluidized bed technology. The atmospheric fluidized bed steam boiler still needs boiler air; thus, the size of AFBC-CC is very large, which is difficult use in a large-scale unit. At the same time, due to the limitation of materials for the air turbine and heating tube cluster for AFBC-CC, the air turbine inlet temperature is not more than 780 °C. The compressed air exported by the heating tube cluster to the air turbine inlet has much more air flow resistance loss than PFBC-CC, making the power supply efficiency at the bottom of the steam cycle less than that of PFBC-C. Therefore, PFBC-CC developed more rapidly. The first generation of PFBC-CC systems had an efficiency between 35% and 42%. To further improve the efficiency of the system, it is necessary to improve the gas turbine temperature. The second generation of PFBC-CC systems use internal combustion afterburning measures to increase the gas turbine temperature to 1100–1300 °C, which significantly improves the efficiency.

In PFBC-CC, the coal combustion and desulfurization process is carried out in the pressurized fluidized bed boiler. Some of the heat generated by the combustion is absorbed and discharged by the boiler heating surface (about 900 °C) after purification by a high-temperature separator into the gas turbine. The gas turbine is connected to the compressor and the generator, which supplies combustion air, fluidized air, and cooling air from the compressor to the pressurized fluidized bed boiler and changes accordingly with the boiler load. The pressurized fluidized bed boiler discharges high-temperature, high-pressure flue gas after purification for gas turbine power generation and to drive the compressor, with a total output of the unit cycle of 20–25%. The gas turbine exhausts flue gas through the economizer of boiler feed water heating, which is cooled to around 150 °C. The superheated steam generated in the supercharged boiler is sent to the steam turbine for power generation. The exhaust heat from the gas turbine is used to heat the boiler feed water to complete the combined operation of the Bordon cycle of the gas turbine and the Rankine cycle of the steam turbine. The PFBC-CC process is shown in Fig. 14 using a 100-MW commercial PFBC-CC system.

The first generation of PFBC-CC is available on the market. Due to the technical limits of the temperature of fluidized bed combustion, the inlet temperature is less than 900 °C. Therefore, the power supply efficiency is under 43%. In view of the above shortcomings, some developed industrialized countries are researching high-temperature dust-removing technology and advanced gas turbine technology to develop the second generation of PFBC-CC systems. This technology concentrates on the advantages of coal gasification technology and pressurized circulating fluidized bed combustion, forming a combined cycle of a pressurized circulating fluidized bed with gasification. In this system, a pressurized gasification unit is added to decompose the raw coal into coal gas and coke. The coke is fed into a pressurized fluidized bed combustion boiler as fuel, and the fuel gas is fed into the combustion chamber of the gas turbine after high-temperature purification. After mixing the hot flue gas from the pressurized fluidized bed boiler and raising the temperature, the gas turbine is fed into the gas turbine for power generation. The compressed air is also divided into three parts, which are respectively sent to the pressurized circulating fluidized bed boiler, the pressurized coal gasification

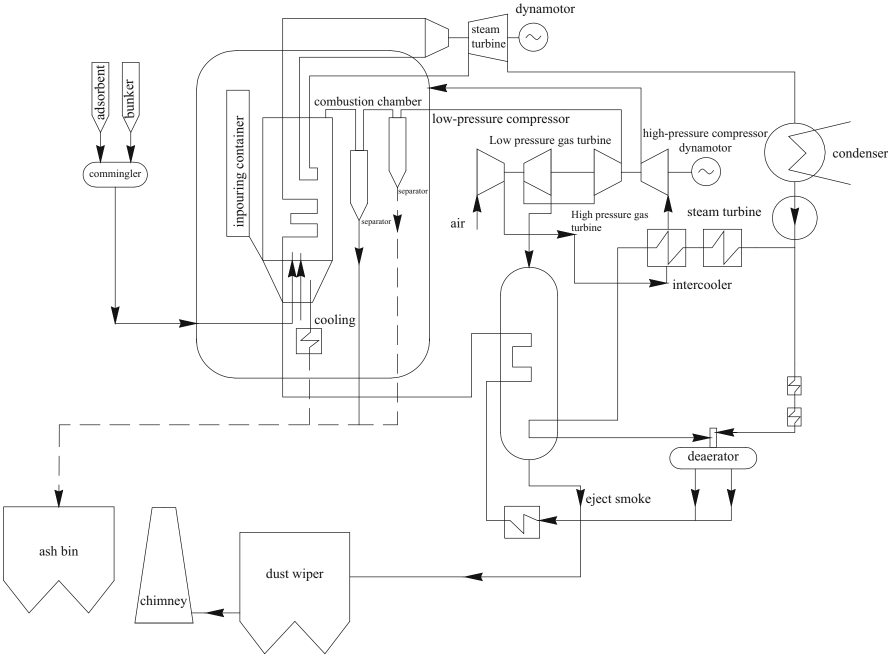


Fig. 14 Schematic diagram of a typical PFBC-CC system

chamber, and the gas turbine combustion chamber. The system flow chart for this technology is shown in Fig. 15.

The idea for PFBC-CC was first proposed by STAL ASEA in the United Kingdom in 1974. Research and development was conducted in a number of countries (Britain, Sweden, the United States, Germany, etc.), from laboratory-scale research to the development of the intermediate test device. In 1983, a PFBC-CC ASEA component test plant was built in Sweden. It was tested on all kinds of equipment to ensure the availability and reliability of the PFBC-CC power station. In the early 1990s, PFBC-CC entered the commercial power plant application phase. In 2002, there were eight first-generation PFBC-CC operating around the world, as outlined in Table 17. Generally speaking, the first generation of PFBC-CC provided some practical experience. Research on the second generation of PFBC-CC has been conducted in the United States for clean coal combustion technology. The technology uses a carbide furnace to produce low-calorific value coal partial gasification gas; the residual gasification is charred in pressurized fluidized bed furnace combustion. The gas turbine inlet temperature can be improved by the combustion gas in the gas turbine combustion chamber, so the combined cycle efficiency can be further improved.

Because China has 10–20% high-sulfur coal ash (bituminous coal and lignite) and some anthracite coal, a conventional power station is not an option. PFBC-CC power stations burn coal at the same time, so China has adopted PFBC-CC to reform

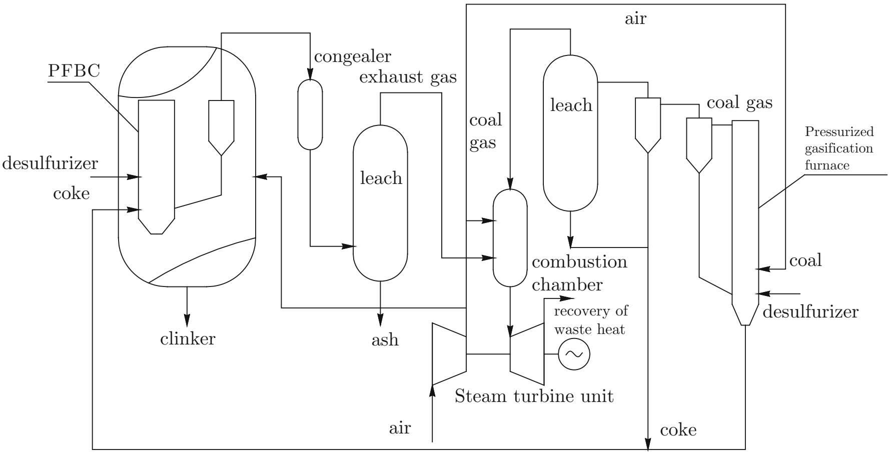


Fig. 15 Schematic diagram of a second-generation PFBC-CC system

the old power plants with tremendous market potential. China has a large number of 100- to 200-MW steam turbine generator sets, so this part of the unit's efficiency is low (between 32% and 35%). Furthermore, they generally do not have a desulfurization denitration device, so most do not conform to environmental emission standards. If these units use PFBC-CC units, power generation efficiency can be increased by at least 3%, and the power-generating capacity can be increased by 20%. After years of research, a successful pilot plant in Xuzhou Jiawang was built in 1998. Its total capacity is 15 MW, including 12 MW of steam power generation and 3 MW of flue gas power. When the boiler is at full capacity, combustion efficiency can reach 99.6%, desulfurization efficiency can reach 92%, and NOx emission values are less than 140 mg/kg. These data suggest that a PFBC-CC unit has excellent energy conservation and environmental protection features.

Internal Combustion Engines

The internal combustion engine has been developed and perfected over a century of research and development. Due to its high thermal efficiency, wide power and speed range, and good mobility, it has been widely used in industry, agriculture, and transportation. Automobiles, tractors, agricultural machinery, engineering machinery, small mobile power stations, ships, some small planes, and other vehicles are powered by internal combustion engines. The internal combustion engine is a heat engine in which fuel combustion occurs inside the machine and directly turns heat energy into power. In the broadest sense, internal combustion engines can be classified as reciprocating piston engines, rotary piston engines, free piston engines, rotating impeller gas turbines, and jet engines, among others. However, the term "internal combustion engine" usually refers to a piston-type engine.

Table 17 Operating PFBC-CC power plants around the world

Power station	country	Start date	Output power (MW)	Gas-fired power (MW)	Steam-electric power (MW)	Main steam condition	Coal	Environmental Index
Värtan	Sweden	1990	135 224	2 × 17	108	13.7 MPa, 530 °C	Soft coal	SO_2: 30 mg/MJ NO_x: 50 mg/MJ Dust: 5 mg/MJ
Escatron	Spain	1990	79.5	16.5	62.5	9 MPa, 513 °C	Black lignite	Desulfurization: 90% NO_x: 150 mg/MJ Dust: 40 mg/MJ
Tidd	United States	1990	70	15.4	57.1	9 MPa, 496 °C	Soft coal	Desulfurization: 90% NO_x: 150 mg/MJ Dust: 5 mg/MJ
Wakamatsu	Japan	1993	71	14.8	56.2	10.3 MPa, 593 °C	Imported bituminous coal	SO_2: 50 mg/MJ NO_x: 40 mg/MJ Dust: 7 mg/MJ
Hokkaido	Japan	1995	85	11.1	73.9	16.57 MPa, 566/538 °C	Imported soft coal	SO_2: 119×10^{-6} NO_x: 98×10^{-6} Dust: 28 mg/m^3
Cuttbus	Germany	1998	74 220	14	60	14.2 MPa, 537 °C	Local soft coal	SO_2: 115×10^{-6} NO_x: 115×10^{-6} Dust: 20 mg/m^3
Karita	Japan	1999	36	70	290	24.6 MPa, 566 °C	Imported soft coal	SO_2: 76×10^{-6} NO_x: 60×10^{-6} Dust: 30 mg/m^3
Osaki	Japan	2000	250	36.5	213.5	16.9 MPa, 566/593 °C	Imported soft coal	SO_2: 76×10^{-6} NO_x: 19×10^{-6} Dust: 9 mg/m^3

The Working Principles of Internal Combustion Engines

The most common piston internal combustion engine is the reciprocating piston type. In piston internal combustion engines, fuel and air mix and burn in the cylinders, and then release the heat energy to produce high-temperature and high-pressure gas in the cylinder. Gas expansion forces the pistons to work, and mechanical work is output through the connecting rod or other components to drive machinery to work. The main parts of the reciprocating piston engine include the crank connecting rod, cylinder head, oil valve-train system, starting gear, lubrication system, and cooling system,

Traditional internal combustion engines can be generally divided into two categories: compression ignition engines (e.g., diesel engines, in which the ideal cycle by constant pressure heating; namely, the diesel cycle) and spark ignition engines (e.g., gasoline engine, in which the ideal cycle uses constant volume heat; namely, the Otto cycle). The main characteristics of the two types of combustion modes are as follows:

1. Compared with a spark ignition engine, the thermal efficiency of a compression ignition engine is higher and the fuel economy is better. Due to the high compression ratio that can be used, the thermal efficiency is higher, the economy is better, and hydrocarbon and CO emissions are lower.
2. A compression ignition engine creates vibrating noise. Before the checkpoint in the first phase of the heterogeneous premixed combustion, it will cause a greater pressure increase, so this kind of combustion creates more vibrating noise than a spark ignition engine.
3. A high-compression ignition engine exhausts smoke. Because the fuel and air are not entirely premixed, priority is given to the mix and combust diffusion combustion, resulting in high exhaust smoke, especially at high loads.
4. A high-compression ignition engine creates NOx and PM emissions. The first phase of heterogeneous premixed combustion has higher combustion temperatures and richer combustion air, so the NOx emissions are greater. At the same time, due to the incomplete diffusion combustion, emissions are higher than in a spark ignition engine.

The work cycle is composed of inlet compression combustion and expansion of the exhaust process. In these processes, only the expansion process uses external work; the other process better achieves the work required for the process. The work cycle can be divided into two categories: a four-stroke cycle and a two-stroke cycle. In a four-stroke cycle, four inlet compression expansion strokes and four exhaust strokes are required to finish a work cycle. The crankshaft takes two laps with the intake stroke. When the intake valve opens, the exhaust valve closes through the air cleaner, or by the carburetor blended with a gasoline mixture, formed by the inlet pipe. The inlet valve enters the cylinder in a compression stroke. The gas in the cylinder is compressed, then the pressure and the temperature increase. The expansion stroke occurs before compression on the checkpoint for fuel injection and ignition. The mixture combusts, produces high-temperature and high-pressure gas,

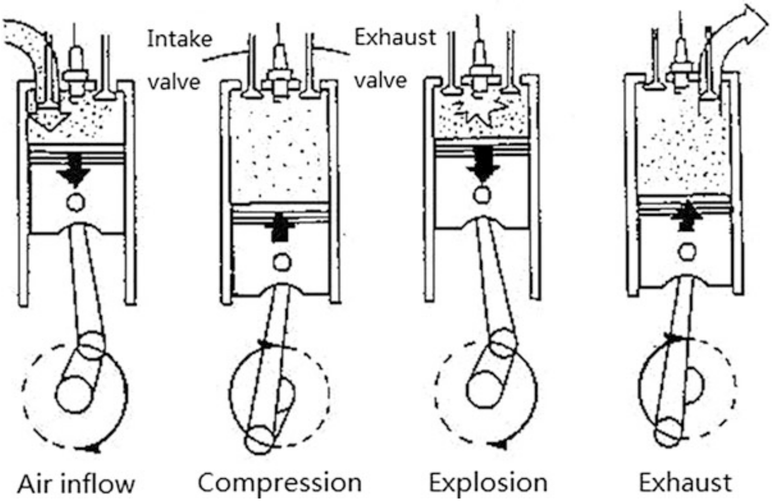


Fig. 16 Schematic diagram of a four-stroke compression ignition engine

and pushes the piston downward for work. In the exhaust strokes, the piston pushes exhaust gas in the cylinder by exhaust valve discharge and then by an intake stroke, which begins the next work cycle. Figure 16 shows a schematic diagram for a four-stroke compression ignition engine.

In a two-stroke cycle, the crankshaft rotates first. When the piston is in the next checkpoint, air intake moves into the cylinder and eliminates the gas inside the cylinder. It discharges from the vent; the piston moves upward, then the vent closes. The cylinder's filling volume begins to be compressed, until the piston is near the end of the ignition and fuel injection, with the combustible mixture in the cylinder. The gas in the cylinder expands and moves the piston downward for work/ When the vent opens, exhaust gas is discharged. The piston continues downward through the checkpoints to complete a working cycle. Figure 17 shows the schematic diagram of a two-stroke compression ignition engine.

An internal combustion engine's performance mainly includes power performance and economic performance. Power performance is measured by the engine's power (torque), including the size of the engine and energy conversion. The economic performance refers to fuel consumption, including energy conversion, thermal efficiency, and the fuel consumption rate. The future development of internal combustion engines will focus on improvements in the combustion process and mechanical efficiency, reducing the heat loss and the fuel consumption rate, development and utilization of non-oil products for fuel, reducing the harmful ingredients in exhaust, improving noise and vibration, reducing environmental pollution, using high-pressure technology, improving the stand-alone power, and developing a composite engine. To improve the working reliability and life expectancy, improvements in the internal combustion engine should be

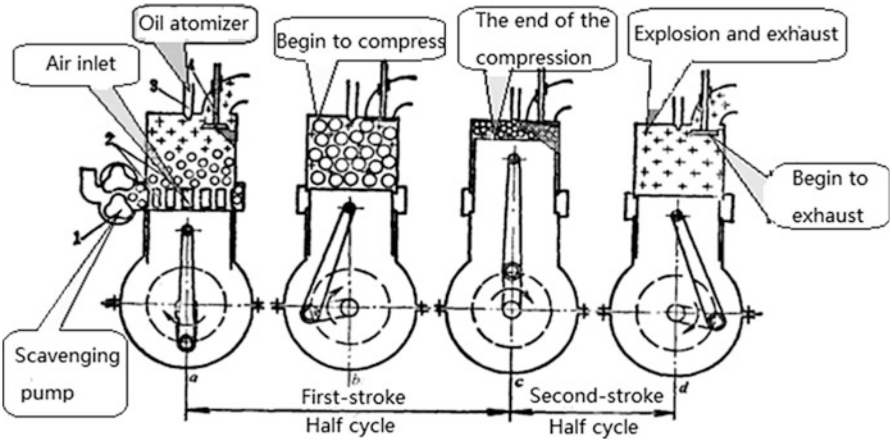


Fig. 17 Schematic diagrams of a two-stroke compression ignition engine

constantly researched and developed. Reciprocating internal combustion engines can use natural gas as fuel, at a capacity from 5 kW to 50 MW. Reciprocating internal combustion engines of less than 1 MW were originally used to move power, then gradually were also used to generate electricity. Reciprocating internal combustion engines are mainly used for small- and medium-sized installations and systems.

An internal combustion engine's power depends on the type of fuel used. The unit power of burning gas is usually 50 kW to 10 MW, diesel is usually 50 kW to 50 MW, and heavy oil is usually 2.5–50 MW. There are three main kinds of internal combustion engines: diesel engines, gasoline engines, and gas engines (i.e., natural gas, liquefied petroleum gas, or other fuel gas. The gasification of alternative fuels is also being investigated for reciprocating piston engines, such as ethanol, hydrogen, and methanol.

1. **Diesel engines:** Diesel engines are compression-ignition engines. The air inside the cylinder has a higher degree of compression for the movement of the piston. The engine uses high temperatures of 500–700 °C and then fuel to mist spray into the high-temperature air, which is mixed with air to form a mixture that combusts under automatic ignition. The energy is released on the top of the piston surface, forcing the pistons into and through the connecting rod and crankshaft, which rotates for mechanical work.

   Diesel engines may be classified by their rotating speed (high, medium, or low) and other characteristics. The combustion chambers of a diesel engine include the injection type, swirl chamber type, and pre-combustion chamber type. Diesel engines can be classified by mode as charging and supercharged cylinder inlet mode. They can also be classified according to gas pressure methods: single acting, double acting, or opposed piston. They are also classified by purpose (marine, locomotive, etc.).

   Usually, high-speed diesel engines use light diesel oil, whereas low-speed diesel engines use heavy diesel oil. Heavy diesel engine fuel in the injection pump and injector can be sprayed into the cylinder with high pressure. Then, the fuel injection mists the fuel oil, which is mixed with air to combust. Diesel engines using volatile heavy fuel or inferior fuel, such as crude oil and residue, are not available. When burning crude oil and residue, in addition to the requirement of filtering out impurities and moisture, diesel engines also need to preheat the insulation of the oil supply system and reduce the viscosity of conveying and injection. The right kind of diesel engine combustion chamber can be combustible for lightweight fuel, ethanol gasoline, and methanol gasoline. To improve the ignitability of light fuel, additives or diesel-hybrid fuels can be used, such as methane, natural gas, and liquefied petroleum gas. Generator gas also can be used as diesel fuel. However, at present, fuel gas is given priority for use, usually with a small amount of diesel ignition. This kind of engine is called a dual fuel engine.

The diesel engine combustion process is generally divided into four stages: ignition delay, fast-burning, slow-burning, and the combustion period. Ignition delay refers to a series of physical and chemical preparation processes from fuel injection to combustion. During this process, fuel oil goes through spray scattering, heating, evaporation, diffusion, mixing with initial oxidation, and so on. It is an important parameter in the process of combustion because the heat-releasing properties of combustion have a direct influence on the ignition delay period in the process of spraying fuel into the combustion chamber. In a rapid combustion period, it almost burns at the same time, so the heat release rate is very high and the pressure is particularly fast. Therefore, strengthening the combustion chamber's air turbulence accelerates the mixing of air and fuel, ensuring that the fuel near the top center is quickly and completely burning. The diesel mixing and combustion time is short, so some fuels cannot burn down near the top center in a timely manner, which causes the expansion strokes to drag. Meanwhile, the full quantity of heat cannot be fully used; therefore, this process avoids burning fuel in the combustion period.

The characteristics of the combustion chamber affect the performance of the diesel engine. Therefore, the combustion chamber should be designed according to the specific combustion process and structure. The combustion chamber can be classified as open, half-open, and swirl; the first two types are direct injection combustion chambers, whereas the latter is a separated combustion chamber. A low-speed diesel engine and parts of the high-speed diesel engine mainly use an open chamber without a vortex combustor. A porous injector allows for good fuel atomization and uniform distribution in the combustion chamber space. As a result, the opening of the space should match the oil beam shape and distribution. It has the advantage of low fuel consumption on starting; however, fuel atomization demand is high, which makes it difficult to adapt to variable speed work. Most small high-speed diesel engines use an eddy-current half-open combustion chamber (including an oil film combustion chamber or compound combustion chamber, among others).

The oil film combustion chamber was invented in 1956 in Germany by Moeller. Within the combustion chamber, it is located in the piston crown. When spherical fuel enters the combustion chamber wall, most of the fuel oil, under the action of a strong eddy current, is sprayed on the combustor walls and forms a very thin film; a small amount of fuel spray is distributed in the combustion chamber space. This kind of combustion chamber can make the working process simple, result in complete combustion, ignite without smoke, and use lightweight fuel. However, it can be difficult to start in low temperatures.

The composite combustion chamber was invented in China by Shi Shaoxi in 1964. The combustion chamber has a deep basin shape at the top of the piston, and the mouth is slightly contracted. The inlet vortex is formed by the special shape of the intake. It uses a single hole shaft needle injector. The injector axis is substantially parallel to the combustion chamber's wall base, and the fuel is injected into the surrounding space of the combustion chamber. Under the effects of eddy currents, thick oil grains are scattered on the wall of the combustion chamber to form an oil film, and tiny oil grains are mixed with air in the space. When the speed is high, the combustion chamber's eddy speed is high, and the oil film on the wall increases with the characteristics of combustion. At low speed and startup, the vortex speed is low. The quantity of mixed fuel increases with the combustion space, which can improve the performance at cold temperature. The composite combustion chamber combines the oil film evaporation from mixed combustion with space mixing, with advantages of both; it is also called a compound combustion system. Its working process is simple and can use a variety of fuels. It requires little for the fuel injection system and starts easily. However, the low-load exhaust has a higher unburned hydrocarbon.

The combustion chamber consists of two parts: the pre-combustion chamber and the main combustion chamber. The pre-combustion chamber is in the cylinder head, with one or several holes communicating with the main combustion chamber. The fuel is injected into the pre-combustion chamber, then ignites part of the fuel combustion. Then, at high speed the unburned mixture will spray into the main combustion chamber, further mixing with the air combustion. This type of combustion chamber is suitable for small- and medium-sized power diesel engines.

A swirl combustion chamber is composed of a swirl chamber and a main combustion chamber. The swirl chamber is located on the cylinder head. It is spherical or bell-shaped, with tangential channels connected to the main combustion chamber. At the time of the compression stroke, the air that is pressed into the swirl chamber produces a strong vortex motion, prompting the fuel injected into it to mix with the air. After ignition, the blend flows into the main combustion chamber, forms a secondary flow, and is further mixed with the air in the main combustion chamber. Both the swirl and the pre-combustion chambers are equipped with shaft needle injectors with low fuel injection pressure and reliable operation. Because the eddy current of the chamber increases with increasing speed, the diesel engine and air are still able to mix well.

With a swirl chamber, a diesel engine's speed can reach more than 4000 r/min. The working process is simple, with less harmful ingredients in the exhaust. However, heat loss, gas flow loss, and after burning are significant, so the rate of fuel consumption is higher. Cold-temperature starting difficulties often require the addition of a preheating plug.

Diesel engines have the obvious advantages of high thermal efficiency, and the scope of their application is wide. With improvements in reinforcements, the weight of the diesel engine's unit power is also significantly reduced. To save energy, researchers investigate how to improve the combustion process and burn low-quality fuel oil and non-oil products. In addition, reducing friction loss, extensively adopting exhaust gas turbo, and further improving the supercharging degree in lightweight, high-speed, low-fuel consumption, low-noise and low-pollution engines are the important directions for the future development of diesel engines.

2. **Gasoline engines.** Gasoline engines use a reciprocating piston structure, with the following components: crankcase, cylinder head, cylinder, crank agency with air system, oil supply system, lubrication system, ignition system, and other parts. They can be divided into two categories according to their distribution system: two stroke and four stroke. A two-stroke gasoline engine is only used to provide a small amount of power, allowing it to be lightweight and low cost. A four-stroke gasoline engine can be divided into three types: side valve, overhead camshaft valve, and overhead camshaft. The best performance is associated with the overhead camshaft engine. According to the different methods of cylinder inlet, gasoline engines can be classified as pressurization or non-boost. A plane is equipped with a pressurized gasoline engine, as are some automobiles.

   The engines have one of two oil supply systems: carburetor or gasoline injection. Until the 1980s, the applications for gasoline injection increased rapidly; many products were already using gasoline injection instead of a carburetor. Gasoline injection can be divided into two kinds: multipoint injection and single-point injection. Multi-point injection has the best performance, but the cost is higher. Gasoline engines may use one of three types of mixture formations: uniform mixture, flame ignition (i.e., after the spark is lit, a small amount of rich mixture from the auxiliary chamber uses the extrusive flame from the main lean mixture), and hierarchical inflatable (i.e., in the same combustion chamber, part of it is a mixture and the other part is just air). Commercial products typically use a uniform mixture.

   Gasoline is a liquid mixture of a variety of hydrocarbons with a distillate temperature of 210 °C; it can easily evaporate as a gas. When a gasoline engine is at work, air flows through the carburetor in proportion to carry a moderate amount of gasoline into the air inlet pipe. During the process of flowing through the inlet pipe, the cylinder, and the compression chamber, the gasoline evaporates rapidly. At the end of compression, it has been completely transformed into the gas phase, and then is mixed into a fairly uniform mixture with air. At this point, the ignition system provides instantaneous high-voltage sparks from the spark plug, which leads to the chemical reaction and heat accumulation. After the temperature increases, there is a layer-heated reaction mixture. When it gradually develops to the stage where pressure in the cylinder obviously increases, a bright flame core is formed. The time from spark ignition to this point is called the ignition delay. The formation of the flame core and the length of ignition delay period both depend on the chemistry of the spark gap mixture, the spark energy, and the air velocity at that point. After the formation of the flame core, flame propagation is ignited, which will burn out the mixture in the cylinder and lead to a rapid increase in cylinder pressure.

A gasoline engine's thermal efficiency and compression ratio have a direct relationship. Once the engine compression ratio is improved, the thermal efficiency then increases proportionally. The compression ratio can be improved by 4.5–10 or more. When the compression ratio reaches more than 9, carbon deposits will be produced in the cylinder. The carbon deposits will ignite the mixture, which can create an abnormal combustion phenomenon called surface ignition. After these internal combustion engine emission problems were recognized by researchers, the practical compression ratio declined. The compression ratio can be improved by the combustion chamber's structure design and increased gasoline quality. In the 1920s, it was found that the addition of tetraethyl lead to gasoline improved the compression ratio of gasoline engines. (Lead is a harmful ingredient in the exhaust, so more modern engines have not used leaded gasoline.) In addition, the combustion chamber was designed to reduce the octane number required for gasoline engines.

Smaller gasoline engines (70-mm diameter) common are air-cooled, whereas larger multipurpose engines are water-cooled. Because the gasoline engine compression ratio is lower than that of diesel engine, the combustion pressure is low, with lighter parts and low inertia; therefore, it can run at high speeds. Not considering the service life of an automobile, engine speed can be as high as 10,000 r/min or more. Gasoline engines are lighter than diesel engines and have low manufacturing costs, reduced noise, and better low-temperature startup; however, their thermal efficiency is low and fuel consumption is high. Motorcycles, chainsaws, and other lightweight and inexpensive small power machinery commonly use a two-stroke air-cooled gasoline engine. Most cars and light trucks use overhead-valve water-cooled gasoline engines; however, the issue of fuel consumption is getting increased attention, so diesel engines are being more widely used for these types of vehicles. Small aircraft engines generally use a half-spherical air-cooled gasoline engine.

3. **Gas internal combustion engines.** Internal combustion engines that use gas fuel (e.g., natural gas, liquefied petroleum gas) can significantly reduce emissions (by 33–50%) and fuel use (by ~50%) compared with diesel and gasoline engines. Table 18 compares the differences in emissions by fuel. Natural gas is increasingly being used as a low-pollution substitute for petroleum fuels. The engines can be distinguished based on their work cycle, fuel supply, and control: gas internal combustion engine with a spark ignition, low-pressure dual-fuel engine

Table 18 Comparison of NOx emissions of different internal combustion engines

Engine type	Fuel	NO_x (ppm)	NO_x (mg/kWh)
Diesel engine	Light oil	450–1350	7–18
Diesel engine	Heavy oil	900–1800	12–20
Gas engine	Natural gas	45–150	0.7–2.5

with a compression ignition, and high-pressure dual-fuel jet engine with a compression ignition; the latter two types of engines are sometimes simply referred to as dual-fuel engines.

In a spark ignition engine, the fuel gas and air flows through the fuel gas mixer into the cylinder. The compression process starts from the front of the checkpoint on one point, with the spark plug flame in the combustion chamber igniting the core formation and burning the mixture. The cylinder pressure increases and forces the pistons to work. The engine works with commonly used gas fuels with low antiknock performance, such as city gas oil associated with coke oven gas. Due to the low compression, the effective pressure and thermal efficiency are low.

In a low-pressure dual-fuel engine, the fuel gas and air mixture flows into the cylinder, with the compression process starting from the front of the checkpoint on one point. Approximately 6–10% of the total heat input of diesel or heavy oil is sprayed into the combustion chamber. After hybrid beam atomization evaporation under high temperature and high pressure, a partial combustion flame core forms and starts the burning process. Oil beam combustion can spontaneously form multiple ignition cores, which reduces the flame propagation distance in the cylinder and increases the combustion rate and antiknock ability. This type of engine has higher effective pressure and thermal efficiency than a diesel engine. By gradually increasing the ignition fuel injection quantity and reducing the gas fuel supply, this kind of engine can use whole diesel combustion.

In a high-pressure dual-fuel jet engine, the air flows into the cylinder alone to the front of the checkpoint in the compression process. At 25 MPa, the gas fuel and ignition diesel simultaneously or successively spray into the combustion chamber, where the oil beam is locally compressed to ignite. The gas fuel and air mixture are formed during the mixing combustion process. The compressed air in the cylinder can further improve the compression ratio, reduce the deflagration tendency, and improve pressurization, thus improving the thermal efficiency. This type of engine can use fuel directly from a natural gas field or compressor pressurized gas fuel. The runtime is not sensitive to fuel gas composition changes and is conducive to expanding the scope of fuel used.

Gas internal combustion engines may be used due to the small investment and overall convenience. Pollution is low, and the engines can provide a few kilowatts to thousands of kilowatts for all sorts of equipment. Table 19 lists some of the manufacturers of internal combustion engine manufacturers around the world and their product capacity grade. Table 20 lists the thermal technical performance parameters of a Caterpillar gas combustion generator.

Energy Distribution of Internal Combustion Engines

The internal combustion engine is used in cold and hot electrical installations and systems. There are two ways to recover waste heat: high-temperature and low-temperature waste heat recovery. High-temperature waste heat recovery can be carried out within the waste heat boiler, with recycling from high-temperature flue

Table 19 Internal combustion engine manufacturers and product capacity grades

Manufacturer	Capacity (kW)	Manufacturer	Capacity (kW)
Caterpillar	100–3000	MAN diesel engine	400–51,500
Cooper energy services international	350–6500	Mirrlees Blackstone	600–10,000
Fairbanks Morse	1200–21,400	Rawls Roy energy	3000–51,000
Genergy electric power company	60–2000	Tecogen	60–75
Hess	85–450	Wabash electrical equipment	60–100,000
International power technology	<15,000	Wartsila diesel engine	300–16,000
Yan Bach	250–2000	Wacker, Fuzhou branch	75–2400

gas heat. Low-temperature waste heat recovery uses the internal combustion engine cooling system itself, such as the lubricating oil cylinder liner, cooling water, and cooling system; its recycling is from the cooling system. Internal combustion engine installations are very suitable for small and medium-sized energy systems, especially those systems where the quality and quantity for heat load demand are not high, such as with low-pressure steam or hot water heating. In addition, the system starts quickly and is affected by the environment, which makes it better in some ways than a gas turbine engine installation. However, the system has high maintenance costs due to engine wear.

A typical internal combustion engine energy equilibrium diagram is shown in Fig. 18. As can be seen from the diagram, the heat transfer work efficiency is about 36.5%. A larger generating unit is more efficient, at more than 40%. An heat recovery with an oil cooling system (including the cooling water and inlet air cooler) is about 25%. However, the quantity of heat is low and the temperature is around 90 °C. A high-temperature internal combustion engine with exhaust heat has a waste heat recovery of approximately 24.5%. The cooling system's heat recovery phase is similar, but has a higher grade of waste, commonly 350–550 °C. A problem of the internal combustion engine heat is loss, including discharge loss, heat loss, and mechanical loss. Compared with gas turbines, an internal combustion engine's heating quantity is smaller and more suitable for hot air, low-pressure steam, and hot water supply. In addition, the internal combustion engine's exhaust oxygen content is larger, reaching 15%. If medium-pressure steam is needed, it can be used in waste heat boiler combustion to meet the demands of the user.

Stirling Engines

A Stirling engine (also known as a heat engine or gas-fired engine) is a closed-loop reciprocating piston-type external combustion engine. The ideal heat cycle is called the Stirling cycle or Kano cycle. In theory, this engine has the highest efficiency. The Stirling engine was invented in the 1800s by a Scottish priest named Robert Sterling. Through the nineteenth century, thousands of units were manufactured and put into

Table 20 Performance parameters of Caterpillar gas combustion generators

Type	G3306TA	G3406TA	G3406LE	G3412TA	G3508LE	G3612SITA	G3616SITA
Rated output power (kW)	110	190	350	519	1025	2400	3385
Engine speed (r/min)	1500	1500	1500	1500	1500	1000	1000
Turbo compressor compression ratio	8.0: 1	11.6: 1	9.7:1	12.5:1	11.0:1	9.0:1	9.0:1
Minimum inlet manifold pressure (kg/cm^2)	0.11	0.11	0.11	0.11	0.11	3.02	3.02
Natural gas consumption (m^3/h)	41.6	59.4	107.7	144.6	309.9	685.9	957.0
Waste gas emissions (m^3/h)	418	904	1278	2509	4815	37,472	51,928
Waste flue gas temperature (°C)	540	415	450	453	445	450	446
Waste gas heat (MJ/h)	263	382	616	1166	2199	5438	7445
Waste flue gas oxygen content (%)	0.5	8.5	4.0	10.2	8.2	12.3	12.2
Cylinder water outlet temperature (°C)	99	99	99	99	99	88	88
Cylinder liner water heat (MJ/h)	594	612	1350	936	2937	2218	2986
Cold inlet temperature (°C)	54	32	32	32	32	54	32
Cold/lubricating oil exhaust heat (MJ/h)	18	97	83	216	695	1462	2366
Thermal efficiency of electricity generation (%)	27.29	33.00	33.53	37.04	34.14	36.11	36.51
Heating efficiency (%)	54.27	47.37	49.07	41.36	48.55	34.30	34.50
Overall thermal efficiency (%)	81.56	80.36	82.60	78.40	82.68	70.41	71.01
Ratio of heat to electricity (%)	199	144	146	112	142	95	95

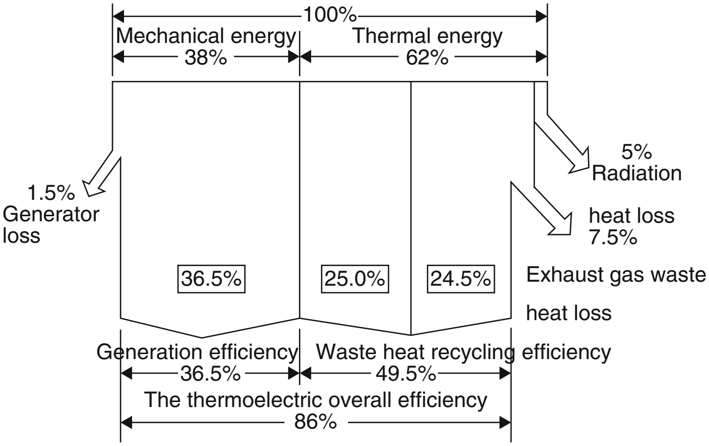


Fig. 18 Internal combustion engine energy equilibrium

practice. By driving the fan engine to use tens of watts, Eric Sen created a giant four-cylinder engine. Due to the limitations of materials and processes, the efficiency of the Stirling engine is very low and it is quite heavy; thus, it was replaced by internal combustion engines.

In 1938, Philips originally intended to use the engine for a low-power tube radio or similar device. Through the company's research, the performance of the Stirling engine was significantly improved, with efficiency increasing from 5% to 38% and power unit volume being 85 kW/L. Philips later successfully installed the engine on a yacht and mower. After 1958, American General Motors, Ford, Germany's MAN and MWM companies, and Sweden's United Stirling continued the research and development of Stirling engine technology. In 1978, the U.S. Department of Energy implemented a $97 million, 5-year Stirling Automotive Engine development program, which was later extended to 10 years with an actual investment of $117 million. The Japanese government also funded $8 billion (400 million yen) for the Stirling engine's development as a gas heat pump in an air conditioning machine. The successful completion of these two projects greatly boosted the development of Stirling engine technology.

As people became increasingly concerned about the global problems of energy and environment, there has been a growing awareness about the positive effects of Stirling engine technology on environmental protection and resource conservation. Therefore, more countries and organizations have resumed participation in the research and development of Stirling engine technology, making considerable progress in practical ways toward this engine technology.

The Working Principles and Characteristics of Stirling Engines

A Stirling engine uses hydrogen, nitrogen, helium, or air as the working fluid, according to the Stirling cycle. This heat engine is different from the thermal engines

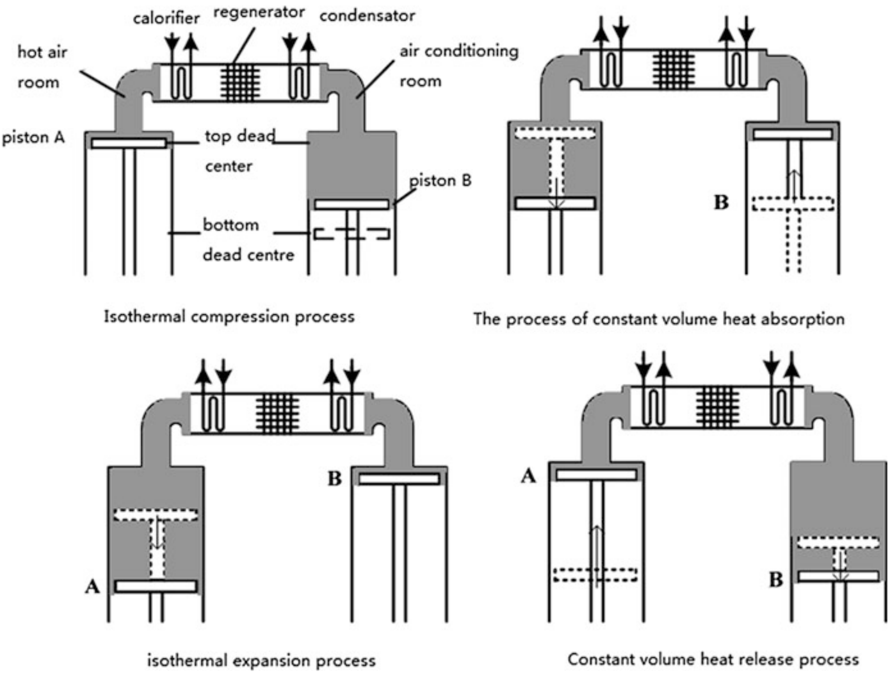


Fig. 19 Working principles of a Stirling engine

of the past: its working gas is enclosed in the machine and circulated in the chamber. The air cylinder is filled with a certain amount of working fluid; one end of the cylinder is a hot cavity, whereas the other end is a cold chamber. The refrigerant is compressed in a low-temperature cold chamber, and then flows into a high-temperature heat chamber for rapid heating and expansion. Fuel in the cylinder is outside the combustion chamber for continuous combustion, through the heater to the workers; the working fluid is not directly involved in the combustion, nor the replacement. The Stirling engine successively undergoes the four processes of isothermal compression, constant volume heat absorption, isothermal expansion, and constant volume heat release. The structure is composed of a combustion system, a hot end component (a heater, a regenerator), a cold end member (cooler, a cooling system), a transmission system, and an auxiliary system.

The engine's working principles are shown in Fig. 19. As shown in the figure, during the isothermal compression process, the valve piston stops at the top dead center when the piston's power (B) compresses the working fluid from the bottom dead center, and the heat generated by the working fluid flows through the cooler. When the power piston reaches the top dead center, the compression process is over. In the process of constant heat absorption, the power piston is still in its near top dead center, piston A moves toward the underside, forcing the cold refrigeration regenerator into the valve chamber piston. The low-temperature refrigerant flows through the heat absorption heat exchanger, causing the temperature to increase. During the isothermal expansion process, the gas distribution piston (A) continues downward. The working medium is heated by the heater, and the heat chamber is expanded. The power piston (B) is pushed downward and the external work is done. During the constant-temperature heat release, the power piston is kept at the lower end, the air distribution piston is upward, and the working fluid is returned from the hot cavity to the cold chamber. In theory, The heat release in constant volume process is equalt to that of heat recovery process, and the cycle efficiency is equal to the efficiency of Kano cycle. The motion law of the two pistons is guaranteed by the diamond drive mechanism.

The main characteristics of Stirling engines are as follows:

1. **The diversity of fuels.** The main advantage of the Stirling engine is that a variety of fuels can be used—gaseous, solid, and liquid fuels. Because the burning process of a Stirling engine is continuous and the cylinder is close to atmospheric pressure, the fuel quality does not need to be high. The combustion temperature can reach 450 °C. Any kind of fuel gas can be used, such as kerosene, heavy diesel oil, coal, firewood, straw, coal gas, natural gas, methane, alcohol, and vegetable oil. When using a heat carrier system (e.g., heat pipe indirect heating), almost any heat source can be used (e.g., solar energy, radioactive isotopes, nuclear reaction) without any changes to the engine itself (except heater outside).
2. **Higher heat transfer efficiency.** A Stirling engine is an efficient energy converter. The Stirling cycle is composed of two isothermal isochoric processes. At the lower limit of Kano, theoretical efficiency can reach 66–70% or higher. The current actual efficiency of a Stirling engine is generally 25–35%, with a maximum of 47%. The power generation efficiency of a Stirling engine can still reach 35% under partial load.
3. **Favorable environmental characteristics.** The engine has low exhaust pollution and noise. The maximum potential for the purification of exhaust gas from a Stirling engine is mainly due to the fact that the Stirling process is continuous; the air ratio has little effect on efficiency or the power, which can be excessive with excess air. Fuel combustion Is carried out at high temperatures, so the combustion is perfect. Stirling vehicle exhaust has ultralow NOx and CO emissions. Any noise from the internal combustion engine is mainly due to the large pressure gradient of the combustion cylinder pressure and the rapid increase in combustion exhaust gas from the sudden formation of the decline. Stirling machine cylinder pressure is based on sinus law changes; changes to the working fluid within the machine pressure are slow, so there will be no combustion and exhaust gas explosion wave. In addition, a Stirling engine has no valve and a balanced operation, so there is no impact on the valve and the piston percussion. It generally has less noise than a internal combustion engine (15–20 dB). The rated power of an STM-120 Stirling engine generator is 25 kW and its 1-m distance noise is 65 dB; a 50-kW machine has 75 dB of noise.
4. **Good operating characteristics.** The pressure change in the cylinder of a Stirling engine are stable. The maximum pressure and the minimum pressure

ratio are approximately 2, so the torque is uniform with stable operation. As for speed range, the ratio of the maximum speed and minimum speed is generally 8–10 (3–5 for an engine). In addition, the Stirling engine's overload capacity is large. At normal operation, it can do more than 50% of the rated load under the conditions of an internal combustion engine, with generally only 15% overload. A Stirling engine can be used in applications such as plateau conditions.

5. **Reliable work, low maintenance costs, and long service life.** The mechanisms of this engine are simple, with 40% fewer parts than an internal combustion engine. Without pollution from combustion products, there is no need to replace the lubricating oil for a long time.

The main shortcomings of a Stirling engine are due to its complex structure. The manufacturing process is expensive, the refrigerant sealing technology is challenging, the sealed reliability power control system is problematic, the service life is complex, and the machine is heavy. The future development of Stirling engines will explore the application of new materials (e.g., ceramics) and new technologies to reduce costs, modifications to the actual cycle improve the structure, and improvements to the performance index. For a Stirling engine, the ideal working fluid would have a high heat transfer coefficient and low friction or loss of gas pump. At a certain pressure and temperature, with hydrogen as the working fluid of the heat, helium or air can be used as working fluid to achieve a hot fan speed and higher specific power.

Because the work of a Stirling engine is enclosed in the working chamber, the working chamber of the piston and the outside through the piston rod are connected, so there is a sliding seal problem. Because the pressure of the working fluid is directly proportional to the working power of the Stirling engine to obtain a greater power output density, the maximum working fluid pressure of a high-power thermal engine has generally reached about 20 MPa. It is necessary to ensure the gas seal and oil, but also that the piston rod is sliding, which is a difficult point. The Stirling engine now uses polytetrafluoroethylene filler as a sealing material, which basically solved the problem. The sealing structure mainly consists of a rod seal and a cap seal. The seal structure can control the working fluid leakage of the Stirling engine with a maximum working fluid pressure close to 20 MPa within the range of 5–10 NL/h.

The Stirling engine can be divided into two different types: a single-acting Stirling engine and a dual-acting Stirling engine. The existing single-acting Stirling engines can be further divided into three types: a double-piston Stirling engine, a power piston and gas piston in the same cylinder, and a power piston and piston with the gas distribution in two cylinders. The dual-acting Stirling engine piston is also a dynamic piston—that is, the upper part of the piston acts on expansion, whereas the lower part of the action is gas compression. A double-acting Stirling engine may be composed of more than four cylinders, but the most practical Stirling engines use a four-cylinder double-acting structure; this structure is compact, lightweight, and has smaller feature sizes, which allows them to be used as forestry machinery.

The Main Applications of Stirling Engines

Stirling engines can be used as a kind of electrical generator on vehicles and ships, with better environmental characteristics than a diesel engine. Its emissions can reach California's ultra-low standards with little vibration or noise. Acceleration and response time are similar to those of the internal combustion engine and it can use a variety of fuels. Thus, it may be suitable for hybrid vehicles. A conventional motor is about 40 kW, whereas the Stirling engine power is only about 15 kW; both engines can be connected in series or in parallel. Motor propulsion can be used for city driving, with the main push on the highway coming from the Stirling engine, supplemented by the motor. The Stirling engine has also been used for underwater power in submarines with satisfactory results. A V-type four-cylinder double-acting Stirling engine had continuous output power of 75 kW, speed of 2000 r/min, and a weight of 750 kg. This type of Stirling engine has been installed in two Swedish Navy submarines.

The Stirling engine can also be used for land-based power generation and power supplies for remote areas and isolated residences, including communication stations, geological exploration, roadways, border posts, expedition camps, islands, travel caravans, and military installations. At present, the existing generator units are unit-based, with power ranging from the hundreds to thousands of watts. The fuel can be burning biomass, natural gas, or others. Depending on the situation, a different energy can be selected, thus avoiding the problem of long-distance transport of fuel. Its low noise also allows for concealment. It can be used in a CCHP system to greatly improve the comprehensive utilization of energy efficiency in residential areas, hotels, and remote enterprises. A Stirling CCHP system has obvious advantages, including that it can make use of various fuels, with low pollution and low noise. New Zealand's Whisper Tech developed a small Stirling heat and power combined system (Whisper Gen 800) using gasoline, diesel, and natural gas. The system generates 800 W to provide 5 kW with 50–60 °C water and 44 dB of noise (at a distance of 7 m). In areas like rural China, where oil demand exceeds supply, biomass (e.g, straw, rice husk, animal excrement) can be used in a Stirling power plant. The United States and some European countries are actively developing such devices. The theoretical experimental research has developed a series of prototypes for practical applications.

The Stirling engine can also be used for landfill gas and combustion for power generation. Municipal solid waste poses a serious threat to human environment and health. However, incineration power generation is restricted because of its high cost and pollution (e.g., cancer-causing dioxin and NOx). Most areas in China are still dominated by refuse landfills that occupy a lot of land and cause environmental pollution by improper handling. However, garbage is a valuable renewable resource that can be used for power generation. Table 21 shows the composition of municipal waste in China. City garbage landfills also produce landfill gas, with the main components being CH_4 (50%), CO_2 (30%), N_2 (17%), and small amounts of O_2, H_2, and other harmful gases such as H_2S. It is estimated that a ton of dry waste in a city's landfill can produce 30–180 m^3 of methane, which is a flammable, explosive greenhouse gas. In addition,

Table 21 Composition of domestic waste in a large city (Unit: %)

Kitchen waste	Paper	Plastics	Fiber, vegetation	Organics	Ash and soil	Glass	Metal	Inorganic substances
25	3	1.5	1.5	31	65	2	2	69

biological and chemical reactions occur after a city landfill produces mercaptan, vinyl chloride, toluene, xylene ethane, methyl chloride, and other toxic gases. These landfill gases finally enter into the atmosphere through irregular migration of landfill soil and adjacent soil, causing the greenhouse effect, the surrounding environment stench, explosions, and destruction of nearby vegetation. Therefore, recycling landfill gas for power generation is not only an important way to address resource waste, but it also can effectively reduce harm to the environment. A Stirling engine uses a cylinder of combustible gas to burn with pretreatment requirements, strong corrosion resistance, low maintenance, and low cost, which is very suitable for the recovery and use of landfill gas. A Stirling engine has the advantage of environmental protection, with no need for a three-element catalytic and discharge filter. Its NOx emission is less than 0.23 g/kWh (a small internal combustion unit is 8.63 g/kWh), which meets the 2003 California distributed power plant and Dezhou emissions standards. Its continuous combustion mode can also avoid the excessive noise caused by knock. However, the Stirling engine has unstable gas adaptability. Its calorific value is about 17.6 MJ/m^3 for landfill gas power generation; the methane content of landfill gas has reached more than 45%. When the methane content is reduced, the unit cannot run if the engine output reduces. However, a combustion machine is almost equivalent to the Stirling boiler, so the combustible gas component has great adaptability. The content of methane in landfill gas can be efficiently used at 30–60%.

A Stirling engine can be used for gas pretreatment. Because the supply of gas in a Stirling machine has a certain pressure while landfill gas pressure is low, the machine must be pressurized. However, it can only increase to a certain flow of the air blower. The Stirling engine uses external combustion of landfill gas with low components. However, because there are impurities and water in landfill gas, the fuel supply system may become clogged and corroded. Therefore, it still requires simple pretreatment. Moreover, a Stirling engine has low maintenance costs. It uses a cylinder combustion mode and prevents harmful gas contamination in the engine piston and cylinder parts, which reduces the unit cost and maintenance work. For a 1-MW power-generation unit using a large-scale biogas engine, the maintenance cost is 0.15 yuan/kWh; this cost for a Stirling engine is only 0.06 yuan/kWh, with the annual maintenance costs reduced by about 749,000 yuan. Although the unit capacity of a Stirling single machine is small, the unit can use a modular design. The capacity of the system can also be changed at any time according to the landfill gas production. Table 22 shows how landfill gas is used in different ways to compare the cost efficiency ratio. A smaller value in the table indicates a lower cost of investment/use and a higher cost efficiency ratio. We can see that the Stirling engine has obvious advantages in the recycle and utilization of landfill gas.

Table 22 Comparison of cost-benefit ratios of landfill gas.

Engine type	Pretreatment requirements	Nonrecurring investment	Operating expense	Technical requirement	Utilization efficiency	Secondary pollution
Gas engine	Dehydration, removal of impurities	3	2	2	3	1
Gas turbine	Deep dehydration, removal of impurities	4	3	3	2	3
Steam turbine	Dehydration	4	4	4	3	5
Boiler oil	Simple dehydration	1	1	1	4	5
Civil gas	Dehydration, removal of acid gases and impurities	4	4	4	4	4
Automotive fuel	Dehydration, removal of CO_2, H_2S impurities	5	5	5	5	1
Stirling engine	Simple dehydration	1	1	1	4	1

A Stirling engine can also be used for solar thermal power generation. At present, the main method for solar power generation is photovoltaic cells, but concentrated solar power is attracting increasing attention. This kind of power generation is an important aspect of solar energy heat utilization by using the focusing device to generate high temperatures and heat energy through the thermal cycle. Since the 1980s, the United States, Europe, Australia, and other countries have established different forms of demonstration devices to promote the development of thermal power technology. There are three kinds of solar thermal power generation systems: the slot-type line focus system, tower system, and disc-type system. A trough system makes use of a parabolic trough reflector to focus sunlight on the receiver to the tube and heat the transfer tubes. Fig. 20 shows a location map of trough solar thermal power plants. In the tower system, the sunlight is gathered on a fixed receiver in the top of the tower to produce high temperatures. These two systems are being used commercially, with generating capacity of 10–100 MW. Figure 21 shows a location map of tower solar thermal power plants.

Dish solar energy using a Stirling engine for power generation has developed rapidly in recent years. This experimental technology has high efficiency and a flexible layout. The system consists of a concave solar concentrator (dish), cavity absorber, Stirling engine, and generator set. The solar dish concentrator uses a mirrored area on the solar radiation device. The system has a dual-axis tracking

Fig. 20 Exterior view of a trough solar thermal power plant

Fig. 21 Exterior view of solar tower power plant

receiver and a Stirling engine that is usually tubular or a heat pipe. The heat absorber is placed in the dish. The refrigerant in the Stirling engine is usually hydrogen or nitrogen. The system's typical power range is 10–5 0 kW. Multiple disc interconnections can be formed to increase the system to the megawatt level. The operating temperature is about 690 °C and power generation efficiency is up to 20.3%. Fossil fuels and mixed usage are currently being investigated. Fig. 22 shows a location map for dish solar thermal power plants.

Table 23 lists the experimental conditions and parameters for dish solar power generation with a Stirling engine. Stirling engine dish solar power generation systems are mainly divided into two types: mechanical transmission and free piston types. Both systems have high reliability and long live. To achieve certain economic benefits, the system life is generally at least 20 years, with only a small amount of maintenance required during the operation. The life expectancy of the Stirling engine for general needs is 40,000–60,000 h—approximately five times longer than a conventional automobile engine's life.

Fig. 22 Exterior view of disk solar thermal power plant

Advantages of Stirling Engines in CCHP Systems

The main advantages of using a Stirling engine as the energy conversion device in a CCHP system are as follows:

1. It can use a variety of energy sources.
2. It has high energy efficiency (85%).
3. Low-grade fuel heat can be converted to high-grade electrical energy.
4. According to user needs, heat and electricity can be adjusted for the appropriate output ratio.
5. The work of the machine can be reversed as a refrigerator to meet the cooling needs.
6. For household energy installations, it has low vibration, low noise, and other favorable characteristics. (A 750-W micro combined supply system has only 50 dB of noise at 7 m).
7. It has low emissions and creates no environment pollution. (A 750-W small cogeneration system's emissions are only 1% of a conventional generator).

At present, there are (available or forthcoming) small Stirling power plants as follows: a 0.75-kW household cogeneration heating gas turbine; a 1-kW biomass fuel free piston Stirling engine generator; a 3.5-kW biomass fuel Stirling engine generator; a 7-kW solar dish/Stirling engine power with a 25-kW STM unit; a swash plate drive Stirling engine generator; a 50-kW STM oblique disc drive Stirling engine generator; a double-acting Stirling engine generator; and a 75-kW underwater generator. Figure 23 shows a 25-kW gas combustion engine produced by STM(Stirling Thermal Motors,Inc) in the United States. Its performance parameters are shown in Table 24.

Table 23 Parameters of several solar dish machines and a Stirling engine

System	MDAC	SES/Boeing	SunDish	ADDS Mod2	DISTALII + II	EuroDish
Performance period	1984–1988	1998	1994	1999	1990–2000	2001
Peak output power	25 kWe	25 kWe	22 kWe	9 kWe	9 kWe	10 kWe
Peak efficiency	29–30%	27%	18–23%	22%	18–21%	22%
Cumulative elapsed time	12,000 h	8350 h	900 h	5000 h	40,000 h	50 h
Stirling engine						
Manufacturer	USAB	USAB/SES	STM	SOLO	SOLO	SOLO
Model number	4-95MKII	4–95	STM4–120	SOLO161	V-161	SOLO161
Power	25 kW	25 kW	20–25 kW	10 kW	9 kW	10 kW
Working medium	Hydrogen	Hydrogen	Hydrogen	Helium	Helium	Helium
Working fluid pressure	20 MPa	20 MPa	12 MPa	15 MPa	15 MPa	15 MPa
Cumulative elapsed time	80,000 h	17,900 h	/	80,000 h	/	80,000 h
Solar dish						
Diameter	10.57 m	10.57 m	12.25 m	8.8 m	7.5–8.5 m	8.5 m
Form	Multi glass mirror	Multi glass mirror	Stretched film mirror	Multi glass mirror	Single mirror design of metal stretch film	Glass fiber thin shell structure
Character of surface	Glass/silver plating	Glass/silver plating	Low iron glass mirror	Glass/silver plating	Glass/silver plating	Glass/silver plating
Number of mirrors	82	82	16	24	/	12
Single mirror size	0.91 × 1.22 m	0.91 × 1.22 m	3.0 m	/	7.5–8.5 m	8.5 m
Reflectance rate	91%	>90%	>90%	>90%	94%	94%

Fuel Cells

Hydrogen is the future of human energy, and fuel cells are the best way to use hydrogen. Fuel and oxygen can create chemical energy through an electrochemical reaction rather than burning, which is more efficient with less pollution. Fuel cells can be used for all power needs. They are regarded as a modern, efficient, and clean method, ranking fourth in generation after thermal power, hydropower, and nuclear

Fig. 23 A 25-kW Stirling engine by STM Corporation

Table 24 Performance parameters of a 25-kW Stirling engine produced by STM Corporation

Parameter	Value	Parameter	Value
Power output (kW)	25	Gas consumption (m^3/h)	8.65
Efficiency (%)	29.6	Rotation rate (r/min)	1800
Heating power (kW)	44	Size (length/width/height)/cm	201/76/107
Heating efficiency (%)	52.1	NOx (g/kWh)	0.05
Fuel consumption (MJ)	304.05	CO (g/kWh)	0.25
Total power output (kW)	69	Overhaul life (h)	50,000
Thermoelectric total efficiency (%)	81.7	–	–

power generation. With constantly breakthroughs being made in their research and development, miniature fuel cells are now widely used for power supplies.

The Working Principles of Fuel Cells

The chemical energy of a fuel cell is from a chemical reaction directly creating electrical energy in the device. Although different types of fuel cells have different electrode reactions, they are made up of several basic units—an anode, cathode, and electrolyte, as shown in Fig. 24. Fuel (e.g., hydrogen, methane) in the anode catalyst undergoes an oxidizing reaction, generating cations and free electrons. Under the action of the cathode catalyst's reduction reaction, oxide (usually in the form of oxygen) is created and produces anions. An anode of cations or cathodes produces anions by proton conductivity and electrical insulation of the electrolyte of another electrode. The reaction product of corresponding reaction does not fully react to the outside of the battery. At the same time, anodes move to the cathode through the external circuit. The whole reaction process achieves the balance of material and a charge balance. External electrical appliances can use electricity provided by the fuel cell.

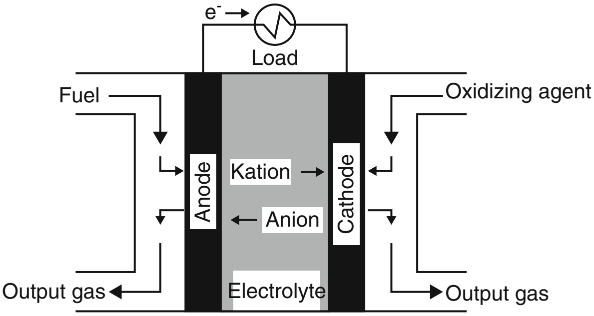


Fig. 24 Fuel cell diagram

The fuel cell's electrode reaction is closely linked with the acidic or alkaline electrolyte. The following simple hydrogen fuel cells, for example, have a fuel going into the fuel cell anode, following an oxide electrode reaction:

When the electrolyte solution is close to neutral: $2H_2 - 4e^- \rightarrow 4H^+$
When the electrolyte solution is acidic: $2H_2 - 4e^- \rightarrow 4H^+$
When the electrolyte solution is alkaline: $2H_2$ - $4e^- + 4OH- \rightarrow 4H_2O$

Hydrogen gas as the catalyst was oxidized into protons and released free electrons through the electronic anode to cathode, while the protons transferred from the cathode through the electrolyte. Reduction of oxygen occurred on the electrode or the cathode. The reduction electrode reactions are as follows:

When the electrolyte solution is close to neutral: $O_2 + 4e^- + 2H_2O \rightarrow 4OH^-$
When the electrolyte solution is acidic: $O_2 + 4e^- + 4H+ \rightarrow 2H_2O$
When the electrolyte solution is alkaline: $O_2 + 4e^- + 2H_2O \rightarrow 4OH^-$

Oxygen molecules, under the effect of the catalyst, generate water molecules passed from the electrolyte proton and circuit electronics. The overall reaction for the battery is: $2H_2 + O_2 \rightarrow 2H_2O$. Thus, it can be seen that the fuel cell is an energy conversion device. As long as the outside world continuously provides fuel and oxidant, fuel cells can continue to generate electricity. Fuel cells need to have a high enough current density, thus enhancing the rate of electrode reaction; this the main factor affecting the electrode reaction rate of catalytic activity and electrode surface area. Fuel cell electrodes are not simple solid electrodes. The so-called porous electrode surface area has 10^2–10^4 times as much electrode geometry of electrode catalytic activity as low-temperature fuel cells, which is particularly important. The rate of the electrode reaction is very low at low temperatures. In addition, the fuel cell electrodes also require good electrical conductivity, high temperature resistance, and corrosion resistance. The fuel cell electrolyte provides ionic conduction in the electrode reaction and isolates the reactions between materials and electrolytes.

Anode and cathode electrolytes consist of a single fuel cell, with a working voltage of 0.7 V. To obtain the necessary voltage, several dozen or even hundreds of fuel cells are connected to form the cell stack. Two adjacent fuel cells are connected by a double plate. The two sides of the plate are connected with the anode of the fuel cell; the other side is connected with the cathode of the fuel cell. The double plate connects the fuel cell to the electrode reaction gas supply to prevent the current reaction substance infiltration between the poles. In addition, the double plate also reinforces the fuel cell.

A low-temperature fuel cell (less than 300 °C) is usually made of graphite plate material, whereas high-temperature fuel cells with the double plate are made of stainless steel or conductive ceramic. For any kind of material, the design and production of the double plate are very critical. Of course, in the cost of fuel cell manufacturing, the double plate makes up a considerable proportion. For a proton exchange membrane fuel cell, for example, the double plate accounts for approximately 70% of the total quality of the proton exchange membrane fuel cell, and the cost accounts for about 40–50% of the total cost. A high-quality, light, thin plate with good mechanical properties, high surface and bulk conductivity, low permeability, and corrosion-resistant material with lower cost technology are the development goals for the double plate.

A fuel cell power generation system is the core part of the electrolyte and electrode plate. However, the whole system is bigger than the peripheral system in a cogeneration power plant, whereas the fuel cell volume accounts for only a small proportion. The type, size, and quantity of the peripheral system is related to the type of fuel cell and the fuel used. A gas supply subsystem may use a fuel storage device. An air compressor pump in a power regulation subsystem may have a DC-AC converter electrode cooling system and various types of heat exchangers in addition to the different control valves and other auxiliary equipment.

The Types of Fuel Cells

Fuel cells can be classified using a variety of methods. A common classification method of fuel cells is based on the electrolyte: alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), proton exchange membrane fuel cell (PEMFC), and solid oxide fuel cell (SOFC).

Alkaline fuel cells were among the first to have actual applications. NASA used an alkaline fuel cell in the Apollo spacecraft to provide power and drinking water for the astronauts. Alkaline fuel cells using 35–50% KOH as the electrolyte, are immersed in a porous asbestos membrane or loaded in a double-hole electrode base cavity. Pressure on the porous cathode and anode forms the working temperature of the fuel cell battery, generally of 60–220 °C. It can work under the conditions of normal pressure or inflating. Alkaline fuel cells have a high working voltage (generally 0.8–0.95 V), with an output rate as high as 60–70%. If cold and hot electric installations are excluded, the AFC's electrical efficiency is the highest of the types of fuel cells.

AFCs also have obvious disadvantages. The alkaline electrolyte in an AFC very easily reacts with CO_2 ($CO_2 + 2oh^- \rightarrow CO_3^{2-} + H_2O$). Substances generated by the carbonate will jam the pores of the electrode and electrolyte channel. The battery life is affected, which means that AFCs cannot directly use air as an oxidant, nor use the reforming gas as a fuel; thus, the applications for AFCs are greatly restricted on the ground. Currently, AFCs are only used in spacecraft or special situations; they are not suitable for civilian use.

In the 1970s, people begin to turn to acidic electrolytes so that the effects of the CO_2 would not occur. Volatile hydrochloric acid and nitric acid are not stable. Sulfuric acid is stable but has strong corrosion resistance, so no suitable electrode material matched. Phosphoric acid, a weak acid with good stability, was selected as the acidic electrolyte for use in PAFC. In a solid state at indoor temperatures, the phase transition temperature is 42 °C, which is suitable for the preparation of electrodes and electrical assembly. PAFCs work at a temperature around 200 °C, so platinum is used as a catalyst at this temperature. Typically, using black carbon as the catalyst supports work at a single battery's voltage of 0.8 V, with power efficiency reaching 40–50%. For cold and hot electrical installations, the system's overall efficiency can be as high as 80% or more. PAFCs can be used in water-cooled, air-cooled, and liquid-cooled. Water cooling is the most common, requiring the addition of a cooling plate between monomer water for water quality, which is suitable for large power plants. The air-cooled structure is simple but has low cooling efficiency. Its power consumption is large, and it is suitable for small power stations. The power of the cooling liquid used in some special conditions in phosphoric acid fuel cell production costs less than other fuel cells. It is the most mature fuel cell technology and has been implemented commercially. UTC (formerly known as IFC) developed a 200-kW PAFC power plant, which is the first commercial fuel cell power plant, with a single plant running time of more than 57,000 h. Japan successively developed 4.5-MW and 11-MW PAFC power plants with electrical efficiency of 41.1% and thermoelectric total efficiency of 72.7%. However, the cost of operating these plants is high: in 2005, it cost approximately \$1500–2000/kW, which makes it is difficult to obtain advantages in commercial operation.

After the 1950s, molten carbonate fuel cells were developed as a kind of high-temperature fuel cell. Its working temperature is 60–-650 °C. Compared to low-temperature fuel cells, a high-temperature fuel cell has obvious advantages. First, it can use fossil fuels, and the fuel reforming temperature is higher. It can even directly reform fuel within the fuel cell, and the system is simplified. Second, a higher grade of waste heat is produced, allowing for use in cold and hot electrical installations and improving the efficiency of the systems. Thus, CO catalyst poisoning is easy at low temperatures, and CO is a high-temperature fuel. Furthermore, under high temperatures, the oxidation reaction of hydrogen and oxygen reduction reaction activity are high enough; they do not require the use of precious metals as catalysts. Finally, the fuel cell reaction carrier does not require water as a medium to avoid the complex water management system of a low-temperature fuel cell.

MCFCs use carbonate as the electrolyte. The oxygen carrier is carbonate ions in the cathode. CO_2 is oxidized under the action of a catalyst into carbonate ions and migrates to the anode in the electrolyte. The total number of electrode reactions of CO_2 and H_2O generated by hydrogen are as follows:

Anode: $H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$
Cathode: $O_2 + 2CO_2 + 4e^- \rightarrow 2CO_3^{2-}$
Overall reaction: $2H_2 + O_2 + 2CO_2$ (阴极) $\rightarrow 2H_2O + 2CO_2$ (阳极)

To maintain the balance of CO_2 in the system, CO_2 needs to be added in the cathodic reaction with the gas inlet anode exhaust or with CO_2 in the gas source.

The electrolyte in an MCFC is Li_2CO_3-Na_2CO_3 or a mixture of molten salt Li_2CO_3-K_2CO_3, immersed in the porous membrane $LiAlO_2$. The anode catalyst uses Ni-Cr, Ni-Al alloy, and generally the Ni_O cathode catalyst, whereas the double plate is usually stainless steel or a nickel-based alloy steel. The power generation efficiency of an MCFC can reach 50–60%. Using high-temperature waste heat from a gas-steam combined cycle, the power generation efficiency can reach 60–70%. The overall efficiency of cold and hot electric installations can reach more than 80%, which is suitable for large-scale regional hot and cold electrical installation systems.

The development of MCFCs is rapid and close to the commercialization stage. A U.S. energy research firm demonstrated a 2-MW power plant in 1996. By the end of 2005, the cumulative generation exceeded 2.5 million KWH. Japan's 1-MW MCFC experimental plant is underway. To achieve the commercialization of MCFCs, further improvements in reliability and power generation costs are needed.

Proton exchange membrane fuel cells have a solid polymer membrane (e.g., nafion) as the electrolyte, hydrogen or reforming hydrogen as the fuel, and air as the oxidizer. The fuel gas and oxygen gas channel are on the double plate to the battery anode and cathode, respectively, through the membrane electrode diffusion layer on the catalytic layer when the working temperature reaches room temperature. On the anode side of the membrane are hydrogen in the anode catalyst surface over the protons and electrons. Protons pass from the sulfonic group on the proton exchange membrane to the cathode, whereas electricity by external circuit passes through the load to the cathode. At the cathode surface of the catalyst, oxygen molecules from the anode pass protons and electrons, generating water molecules. In this process, the protons carry water molecules from anode to cathode, and form water from the cathode. As a result, the proton conduction depends on water. The degree of hydration of the proton membrane greatly affects its electrical conductivity, so it is necessary to add a wet reaction gas.

The main advantage of the PEMFC is the solid electrolyte. There is no corrosion, cell manufacturing is simple, the cell is not sensitive to pressure changes, and there is a long battery life. The main disadvantages include the film's high price, difficult membrane water management, sensitivity to CO, and high catalyst cost. Water management of PEMFC is complex. Too much water can flood the electrode, while too little water can easily cause dry film. However, improving the battery's working temperature would simplify the operation. A working temperature of 180–200 °C would simplify water management, increase the CO tolerance ability to 1%, and still make effective use of the waste heat of the battery. A high-temperature proton exchange membrane is a new direction for future development; it was initially used in the space shuttle. Due to the low working temperature, it can be quickly started at room temperature. Developed countries have applied the technology to electric vehicles and portable power supplies. It also has great potential for small cogeneration plants.

In a solid oxide fuel cell, the electrolyte is a compound oxide. The most commonly used electrolytes are yttrium oxide and calcium oxide doped zirconia, which have oxygen ionic conductivity under high temperatures (800–1000 °C). At such a high temperature, fuel can achieve rapid oxidation and heat balance; it does not need external reforming and CO can be used as a fuel, without precious metal catalysts. A SOFC is a solid-state device that uses oxide ion conductive ceramic materials as the electrolyte. The two phases (solid phase and gas phase) are simpler than other three-phase full cells, without the need for a submerged porous electrode or problems with a catalyst. There are no strict requirements for electrolyte management as with PAFCs and MCFCs. The oxide electrolyte is stable with no loss. Its composition is not affected by the fuel. The oxidizing gas composition of SOFCs can withstand low loads, overload, or short circuiting. The working temperature of SOFCs is very high. Packing material and structural problems, such as the sintering of the electrode, the interface between the electrolyte and electrode chemical diffusion, the matching of the thermal expansion coefficients of different materials, and the stability of the plate material, restrict the development of SOFCs to some extent. Reducing the working temperature to 400–600 °C with new materials will be an important direction of future research on SOFCs. The cells are suitable for regional thermal power plants and CCHP systems.

These five types of fuel cells each have their advantages and disadvantages. Some are more significant and difficult to overcome, so development of these cells is at a standstill. All aspects of the fuel cells' performance are listed in Table 25.

The Characteristics of Fuel Cells

Fuel cells have the advantages of high efficiency, safety, reliability, and good environmental benefits:

1. **High efficiency.** In theory, a fuel cell can change 90% of fuel energy into electricity. The available power generation efficiency of a PAFC is 42% (HHV). Power generation of MCFCs can be more than 60% theoretically. Comparatively speaking, the SOFC is more efficient. Fuel cell power generation efficiency does not change according to size, and the partial load performance is very good. In addition, fuel cells can be placed near the user to greatly reduce the transport cost and transmission losses in the power generation. Fuel cells can

Table 25 Comparison of different types of fuel cells

Fuel cell type	Alkaline	Phosphoric acid	Fused carbonate	Proton exchange membrane	Solid oxide
Abbreviation	AFC	PAFC	MCFC	PEMFC	SOFC
Electrolyte	KOH	Phosphoric acid	Li_2CO_3-K_2CO_3	Perfluorosulfonate membrane	YSZ
Electrolyte form	Liquid	Liquid	Liquid	Solid	Solid
Anode catalyst	Ni, Pt/C	Pt/C	Ni (contains Cr, al)	Pt/C	Metal (Ni, Zr)
Cathode catalyst	Ag, Pt/C	Pt/C	NiO	Pt/C、platinum black	$Sr/LMnO_3$
Conductible ions	Oh^-	H^+	$CO_3{}^{2-}$	H^+	O^{2-}
Operating temperature	65 ~ 220 °C	180 ~ 200 °C	650 °C	Indoor temperature ~ 80 °C	500 ~ 1000 °C
Working pressure	<0.5 MPa	<0.8 MPa	<1 MPa	<0.5 MPa	Ordinary pressure
Starting time	A few minutes	A few minutes	>10 min	<5 s	>10 min
Fuel	Refining hydrogen gas and electrolytic byproduct hydrogen gas	Natural gas, light oil, pure hydrogen and methanol	Natural gas, petroleum, coal, methanol	Hydrogen gas, natural gas, methanol, gasoline	Natural gas, petroleum, coal, methanol
Oxidizing agent	Pure oxygen	Air	Air	Air	Air
Plate materials	Nickel	Graphite	Nickel, stainless steel	Graphite, metal	Ceramics
Specialty	Need to use high purity hydrogen as fuel; low corrosive and easier to choose materials at low temperature	Touch the coal CO in the intake can lead to poisoning; waste heat to use	It is not affected by inlet CO; reaction to recycle CO2; waste heat available	High power density, small volume, light quality. Low corrosion resistance and low temperature, easier to choose materials	It is not affected by inlet CO; touch high temperature reaction, do not need to rely on the special role of coal; waste heat available
Advantage	Start the fast; work under the room temperature and pressure	It is not sensitive to CO2; the cost is relatively low	Can use air as oxidant; can use natural gas or methane as fuel	Can use air as oxidant; solid electrolyte; at room temperature; start quickly	Can use air as oxidant; can use natural gas or methane as fuel

(*continued*)

Table 25 (continued)

Fuel cell type	Alkaline	Phosphoric acid	Fused carbonate	Proton exchange membrane	Solid oxide
Disadvantage	Need pure oxygen as oxidant; the high cost	Sensitive to CO; the high cost	Working temperature is higher	Highly sensitive to CO; the reactants need humidification	Working temperature is too high
The reforming in battery	Impossible	Possible	Highly possible	Impossible	Highly possible
System electrical efficiency	50–60%	40%	50%	40%	50%
Application scenario	Aerospace, vehicle	Cogeneration power plant, distributed power plant	Cogeneration power plant, distributed power plant	Distributed power plant, vehicle power supply, mobile power supply, aerospace	Cogeneration power plant, distributed power plant, vehicle power supply, mobile power supply
Total price (including installation costs, from 2003 data)	\$2700/kW	\$2100/kW	\$2600/kW	\$1400/kW	\$3000/kW

produce hot water and steam at the same time, with an electric heating output ratio of about 1.0. Generally speaking, a fuel cell's power generation efficiency is one-sixth to one-third higher than other distributed power generation devices, such as an internal combustion gas turbine). Existing fuel cells with a lower heating value (LHV) have efficiency between 40% and 55%. The efficiency of existing distributed power generation systems should be the highest. The waste heat produced by fuel cells is very clean, being basically steam and hot air. The waste heat temperature of an SOFC is very high. By the same token, the use value is also very high.

2. **Reliability.** Compared with the heat of a steam turbine engine, the rotating components of fuel cells are quite limited. Therefore, the system is safer and more reliable. The fuel cell never had a major incident that occurred as a result of the failure of a rotating unit of the combustion turbine or internal combustion engine. The only accident that occurs in a fuel cell system is efficiency.
3. **Good environmental benefits.** Ordinary waste is generated from coal-fired power plants with particulate matter (dust) from sulfur oxides (SOx), nitrogen oxide (NOx), hydrocarbons (HC), waste residue, and waste water. Fuel cell power plant emissions of gas pollutants meet nine of the ten most stringent environmental standards. Emissions of the greenhouse gas CO_2 are far less than in a coal-fired power plant. The fuel cell's byproduct is water, in a quantity is minimal

compared with a large steam power plant that uses a large amount of cooling water. Thus, fuel cells not only eliminate or reduce the water pollution problem, but they also do not require an exhaust control system. At the same time, there is no noise and little waste.

4. **Modular and short installation time.** A fuel cell's power generation efficiency does not change with scaleup. Power generation output is determined by the output of the cell stack and the number of cell stacks. A fuel cell manufacturer can produce several kinds of standard fuel cell modules according to the actual needs of an on-site installation, which saves time and makes for a simple and short construction cycle.
5. **Small occupied area.** A 5-kW PEMFC system is only 0.19 m wide and 0.49 m high, with a weight of only 28.5 kg. A German company produces a 100-kW SOFC system, with a complete unit length of 8.59 m, width of 2.75 m, and height of 3.58 m. A Japanese company's 5-MW PAFC power plant is 45 m long, 20 m high, and 20 m wide. Also, because fuel cells take up minimal space and have good compatibility with the environment, there are no specific requirements for site selection. It can be built in the vicinity of the end user as a regional power plant. A system can be built for a single residential building or to power and heat public buildings.

However, fuel cells currently have many shortcomings that prevent their use in large-scale commercial applications, as follows.

1. **Expensive.** Statistics show that the price of a fuel cell in 2003 was 2–10 times greater than the price of other distributed power generation systems (internal combustion gas turbine). The most advanced fuel cell system is equal to the price of a solar power generation system.
2. **Maintenance problems.** The maintenance of a fuel cell is very different than for other power generation devices. Repair is needed after failure occurs and is difficult without available replacement parts.
3. **Fuel problems.** Fuel cells consumes fuel very quickly. Therefore, a highly efficient filter is badly needed. The fuel supply system is far from perfect yet.
4. **Immature technology.** Fuel cells have been used commercially for a very short period of time. If the price of fuel cells can be reduced, they will eventually be in wider use and become more mature.

Development and Research Status of Fuel Cells

The fuel cell's history can be traced back to 1839 when the British physicist W.R. Grove used platinum as an electrode, sulfuric acid as an electrolyte solution, and hydrogen and oxygen as raw materials. Grove successfully conducted traditional electrolysis with a water reverse reaction, causing an electrical current. In 1894, F.W. Ostwald confirmed the thermodynamic theory, proving that low-temperature electrochemical oxidation is better than the high-temperature combustion of fuel; an electrochemical battery's energy conversion efficiency was shown to be higher than the heat engine's efficiency, which is limited by the Carnot cycle.

In the early 1900s, a fossil fuel's chemical energy was transformed into electrical energy directly. Some outstanding physical chemists, such as H.W. Nernst, conducted research in this field. However, materials technology was quite limited at that time. In the 1950s, fuel cells emerged as a power generation device. F.T. Bacon studied the alkali electrode system and successfully developed a porous nickel electrode. Later in 1959, he successfully developed a 6-kW alkaline fuel cell system. The United States successfully used a Bacon AFC on the Apollo moon mission. Afterward, the Gemini spacecraft used a PEMFC in space.

To solve the energy crisis of the 1970s, more scholars focused on the efficient use of limited energy and the development of a fuel cell power plant, with a focus on energy efficiency and environmental impact. Scholars explored the highest levels of AFC space applications; this was gradually replaced by the PAFC, which is more suitable for fuel cell power stations. By the late 1980s, the first megawatt PAFC fuel cell power plant was put into trial operation.

Molten carbonate and SOFCs developed rapidly in the 1980s and 1990s, respectively. However, high-temperature fuel cells were still a problem to be solved. Fuel cells achieved their biggest breakthrough in the 1990s with the development of the PEMFC. Since then, more than 300 prototype fuel-cell cars have been built, especially using PEMFCs. The world's top six car companies have spent more than $10 billion in the development of hydrogen fuel cell car research and development. Canada, Europe, Japan, the United States, and other countries have various types of power stations in operation or under commission – about 250 PAFC and 35 MCFC. Twelve SOFC battery packs have been installed. The maximum capacity has reached 11 MW. In North America, the large-scale application of fuel cells has a market value of approximately $251 million. Currently, more than 1000 companies engage in the business of fuel cell research, development, and management. As of early 2003, they have set up and run more than 3800 fuel cell systems.

In the late 1950s, China began to develop the fuel cell. In the 1970s, because of the push of the aerospace industry, China's fuel cell research reached a climax then declined n the 1980s. In the 1990s, fuel cell technology made great progress in foreign countries, with some products in the commercialization stage. Therefore, China once again resumed fuel cell research and development. The Chinese Academy of Sciences added fuel cell technology as a 5-year college major and special support project. The National Ministry of Science and Technology promoted fuel cell technology as a national 5-year research project and funded the development of PEMFC electric vehicles and battery systems. There are 863 plans for major projects across China. City buses now use electric fuel cells, with a maximum output power of 150-kW battery. Other technology has reached advanced levels internationally. The major fuel battery manufacturers around the world include ONSI, Ballard, M-C power, SOFCo, TMI, Siemens Westinghouse, The PEM Fuel Cell Company, Analytic Power, H-Power, Developers Machinery Company, and Dai.

The Application of Fuel Cell Technology in Heating and Cooling

The technology adopted in the future of green buildings is of great importance. As one of the prime movers in small-scale installations, the fuel cell is a highly efficient and clean power generation device, which is suitable for distributed power supply. It serves as the core of large-capacity power plants and will be an important method of generating electricity in the twenty-first century.

Heating and cooling systems with fuel cells generally consist of the following parts: a DC-AC converter, the fuel cell itself, fuel pretreatment, waste heat recycling to generate steam or hot water for heating, and a driven absorption or adsorption chiller for cooling. The basic composition and installation process for these systems are shown in Fig. 25. For high-temperature fuel cells, due to their high battery temperatures, a high-temperature exhaust gas and steam turbine combined cycle should be used to further improve the system efficiency. Fuel cells often directly use hydrogen as a fuel in practice. Rich hydrogen fuel gas, methane gas from methanol, fossil fuels such as ethanol, or biomass can be used to increase the flexibility of the fuel cells and fuel economy.

In recent years, many countries have invested heavily in fuel cell power generation technology. There are tens of thousands of fuel cell power plants for cogeneration in hotels, hospitals, and residential area. In Japan, the operation of a fuel cell power plant is about 100 seats, which equals a total capacity of 30 MW. In Germany, a 250-kW cogeneration power plant has been built. The city of Dutch Arnhem began operating a 100-kW SOFC cogenerator in December 1997 to provide 109 kW of electricity to the power grid; it operated until November 2000 and ran for more than 16,000 h with a power generation efficiency of 46% and thermoelectric integrated efficiency of about 80%. The Netherlands and several European countries installed

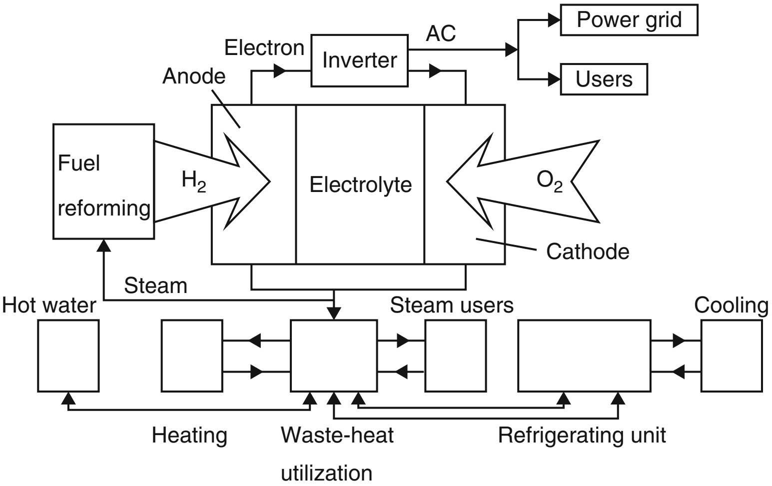


Fig. 25 Fuel cell heating and cooling system flow diagram

31 fuel cell heating devices. These small heating devices can provide electricity and hot water for family shops and hospitals.

The United States is building 40-kW cogeneration field-type fuel cell power generation devices, including two machines that were respectively built by the Tokyo Gas Company and Osaka Gas Company. The rest are scattered around the country. Auxiliary systems of conventional equipment (e.g., a pump steam separator) are prone to failure even though the equipment has been improved. However, the technical performance of the system operation is good. On this basis, the ONSI Company produced a 200-kW cogeneration fuel cell power generation device with thermoelectric integrated efficiency up to 80%.

Plug Power developed a 7-kW household cogenerator that can be directly used to provide the electricity required to run household electrical appliances such as lighting, heating, and air conditioning. The waste heat from the fuel cells can be recovered for use in hot water or heating. It is estimated that the household fuel cell will be able to reduce residential fuel costs by 20%. Households can use pure hydrogen fuel cells, propane gas, and methane to meet the needs of an 280–370 m^2 area with the current residential electricity system. The integrated efficiency can reach 80%. The system is mainly composed of a fuel cell heat exchanger of a gas furnace and control system. Fuel (natural gas) comes through a pipeline into the fuel cell system. It reacts with oxygen in the fuel cell.

With funding from the U.S. Department of Energy, Carnegie Mellon University in Pittsburgh completed a compressed natural gas building energy system for a 32-floor, 57,900 m^2 office building that can accommodate about 3000 people. This building was built in 1987. The original air conditioning and heating system was 2 units of a 2640-kW centrifuge and two 2450-kW gas boilers; a fuel cell cogeneration system transformed the original system. Several retrofitting schemes were considered: meeting the peak electricity and ensuring that the building waste heat would be used to drive the LiBr absorption chiller; the fuel battery capacity needed to be kept at 2700 kW; the average building electricity load and fuel battery capacity needed to be kept at 1500 kW; and the building's basic electricity load needed to be met with a fuel battery capacity of 600 kW. The system provided 250 kW of SOFCs. Thermal power generation used a 250-kW solid oxide fuel cell. Its main characteristic parameters were as follows: net DC output (deducted from the total generating capacity of the fuel cell power system's power consumption) of 226 kW, low calorific value of net power (AC/LHV) with 46% efficiency, fuel flow of 45.4 kg/h, air flow rate of 0.73 kg/s, emissions of 2340 kg/h, exhaust temperature of 755 °C, inlet temperature of 500–550 °C, flue gas waste heat recovery after hot water/steam heat of 150 kW. Afterward, the waste heat recovery boiler heat with cold water needs to create a total quantity of 150-kW steam or hot water. When using SOFCs, the needs for electricity and heat may not be completely met by such as system. In the case of insufficient power supply, they are generated from the grid (or here, from the steam pipe network on campus).

In China, there have been no successful demonstrative projects of heating and cooling electric installations yet. Floor plans from the University of Tsinghua show the adoption of a solid fuel cell cogeneration system and internal combustion engine, with natural gas as a fuel. The basic power supply will be achieved by the internal combustion engine or fuel cell, while the peak power load is generated from the grid after the generation of waste heat in winter for heating and summer as low-temperature heat for fresh air circulation, used for the regeneration of the solution.

Fuel cell technology is maturing—not only in terms of improved energy efficiency and reduced pollutant emissions, but also in terms of its modular characteristics. Fuel cells have the potential to be widely used for energy generation, and they will likely become a mainstream component of heating and cooling systems. With advanced in the fuel cell commercialization process, fuel cell technology could soon be used in CCHP installations.

References

1. Yan Junjie, Huang Jintao, He Maogang (2006) Cold hot electricity co-generation technology. Chemical Industry Press
2. Wang Ruzhu, Ding guoliang, et al (2002) The latest technology of refrigeration and air conditioning. Science Press
3. Li Chongxiang, He maogang, Huang Jintao, et al (2004) The energy-saving principle and technology. Xi 'an Jiaotong University Press
4. Qiu Xinli, Liang Leming, Li Lineng (1997) Engineering thermodynamics. China Building Industry Press
5. Zhang Dingwang (2002) Steam turbine unit and adjustment. Shanghai Jiaotong University Press
6. Yi Baolian (2000) The fuel cell—efficient and environmentally friendly way of generating. Chemical Industry Press
7. Zou Longqing, Liu Hongshuo, Deng Shizhou (1985) Stirling engine. Hunan University Press
8. Zhang Haozhi (2000) The micro turbine literature review. Tsinghua University Press
9. Jin Hongguang, Lin Rumou (2008) Cascade utilization of energy and gas turbine total energy system. Science Press
10. "Small and medium-sized cogeneration project design manual" editorial committee (2006) Small and medium-sized cogeneration project design manual. China Electric Power Press
11. Wang Ruwu (2008) Power plant energy conservation and emissions reduction technologies. Chemical Industry Press
12. Chen Xuejun, listen to Chen wide (1981) Boiler principle. Machinery Industry Press
13. Lin Zonghu, Zhang Yongzhao (1989) Boiler manual. Machinery Industry Press
14. Jin Zhiping (2006) Power plant steam turbine principle and system. China Electric Power Press
15. Li Xinding (2006) Power plant boiler principle. China Electric Power Press
16. Jiao Shujian (2000) Gas – steam combined cycle. Machinery Industry Press
17. Shanghai steam turbine co., LTD (1999) The total teacher office. Gas turbine mt corpus abroad, Shanghai
18. You Han (2000) The application of high speed micro turbine generators and engineering design. Tsinghua University Press
19. Yan Weiping (2002) Clean coal combustion technology. China Electric Power Press, p 2
20. Jiao Shujian (1996) Integrated gasification gas - steam combined cycle (IGCC). China Electric Power Press
21. Zhang Mingyao (1998) Pressurized fluidized bed combined cycle power generation technology. Southeast University Press

22. Liu yongcchang (2005) Principle of internal combustion engine. Huazhong University of Science and Technology Press
23. Gao Xiuhua, Guo Jianhua (2006) Internal combustion engines. Chemical Industry Press
24. Qian Guozhu, Zhou Zengxin, Yan Shan Qing (1987) Steam machine principle and design. National Defense Industry Press
25. Mao Zongqiang, et al (2005) The fuel cell. Chemical Industry Press, p 4
26. Wang Linshan, Li ying (2005) Fuel cells. Metallurgical Industry Press, p 8
27. Li Xiaotang, Hou lingyun, Yang min (2006) Modern gas turbine technology. The Aviation Industry Press
28. Jin Hongguang, Lin Rumou (2008) Cascade utilization of energy and gas turbine total energy system. Science Press
29. Sun Jianguo, Feng Zhibing (2006) Cold hot electric installations, system development and prospect. Gas turbine technology 19(2):11–17
30. Li Sheng, Wu Jingyi, Wang Ruzhu (2008) Cold and hot research focus in the electrical installations, systems overview. Refrigeration and air-conditioning 8(6):1–9
31. Wu DW, Wang RZ (2006) Combined cooling, heating and power: a review. Prog Energy Combust Sci 32(5–6):459–495
32. New York State Energy Research and Development Authority (2002) Combined heat and power market potential for New York State final report
33. COGEN Europe (The European Association for the Promotion of Cogeneration) (2001) The European educational tool on cogeneration, 2nd ed. www.cogen.org
34. WADE (World Alliance of Decentralized Energy) (2002) Guide to decentralized energy technologies. www.localpower.org
35. COGEN (2002) Europe (www.cogen.org). Decentralized generation technologies—potentials, success factors and impacts in the liberalized EU energy markets. Final report
36. Alanne K, Saari A (2004) Sustainable small-scale CHP technologies for buildings: the basis for multi-perspective decision-making. Renew Sust Energ Rev 8(5):401–431
37. Najjar YSH (1996) Enhancement of performance of gas turbine engines by inlet air cooling and cogeneration system. Appl Therm Eng 16(2):163–173
38. Zhao Changxing (2007) Steam turbine technical manual. China Electric Power Press
39. Alhazmy MM, Jassim RK, Zaki GM (2006) Performance enhancement of gas turbines by inlet air-cooling in hot and humid climates. Int J Energy Res 30(10):777–797
40. Al-Madani H (2009) Effects of thermodynamic and mechanical irreversibilities on gas turbine performance enhancement by intake air cooling. International Journal of Exergy 6(2):166–180
41. Xu Jiaoyun (2003) Economic efficiency of gas turbine inlet evaporative cooling device. Gas turbine technology 16(1):29–32
42. Lv Tai, Sun Rui, Zhang Xuerong (2006) 350 mw class gas – steam combined cycle unit design. China electric power 39(3):14–17
43. Gong Qi, Lu Jun (2005) About the exploration of the development of small gas turbine cogeneration. Energy saving. Technology 23(2):146–149
44. Han Xiaoping (2002) Small gas turbine cogeneration – the best choice of the west-east gas market. Energy saving and environmental protection 2:8–12
45. Shen Digang (2000) Gas turbine development route and direction abroad. Aircraft engine 1:43–48
46. Weng Yiwu, Su Ming, Weng Shilie (2003) Characteristics and application prospects of advanced micro gas turbine. Thermal power engineering 18(2):111–116
47. Zhao Shihang A (2001) new concept of the development of the micro gas turbine. Gas turbine technology 14(2):8–13
48. Diao Zhenggang (2000) The micro gas turbine toward commercialization. Gas turbine technology 13(4):13–16
49. Xiao Li, Zeng Chengbi, Li Jicai (2008) With the core of the micro gas turbine distributed energy supply system solutions. Sichuan electric power technology 31(2):78–81

50. Yang Ce, Liu Hongwei, Li Xiao, et al (2003) The micro gas turbine technology. Thermal power engineering 18(1):1–4
51. Wei Bing, Wang Zhiwei, Li Li, et al (2006) The micro gas turbine cold hot electrical installations, systems and its development status in abroad. Power demand side management 8(6):62–64
52. Du Jianyi, Wang Yun, Xu Jianzhong (2004) Development and application of distributed energy system and micro-gas turbine. J Eng Thermophys 25(5):786–788
53. Liu Aiguo, ZHANG Shijie, XIAO Yunhan (2009) Comparison of application of micro-combustion engine and small combustion engine in distributed distribution system in South China. Gas Turbine Technology 22(3):1–9
54. Gillette SF (2004) Market development of microturbine combined heat and power applications. Cogeneration and Distributed Generation Journal 19(2):46–59
55. Gamon S, Yokoyama R, Ito K (2005) Parametric study on economic feasibility of microturbine cogeneration systems by an optimization approach. J Eng Gas Turbines Power 127(2):389–396
56. Campanari S, Macchi E (2004) Technical and tariff scenarios effect on microturbine tri-generative applications. J Eng Gas Turbines Power 126(3):581–589
57. Li HW, Nalim R, Haldi PA (2006) Thermal-economic optimization of a distributed multi-generation energy system – a case study of Beijing. Appl Therm Eng 26(7):709–719
58. Khaliq A, Choudhary K (2007) Combined first and second-law analysis of gas turbine cogeneration system with inlet air cooling and evaporative aftercooling of the compressor discharge. J Eng Gas Turbines Power 129(4):1004–1011
59. Yilmaz T, Bayraktar S, Tasci F (2008) Efficiency optimization of gas turbine based cogeneration cycle. J Energy Inst 81(2):110–113
60. Kurt H, Recebli Z, Gedik E (2009) Performance analysis of open cycle gas turbines. Int J Energy Res 33(3):285–294
61. Chen L, Zhang W, Sun F (2009) Parametric analysis of a gas turbine cycle coupled to a Brayton refrigeration cycle. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 223(5):497–503
62. Liu AG, Weng Y (2010) Performance analysis of a pressurized molten carbonate fuel cell/micro-gas turbine hybrid system. J Power Sources 195(1):204–213
63. Xiaoli H, Guoqiang Z (2005) Summary of the construction of cold and heat and power system. Gas and heat 25(5):67–73
64. Zhu Xinding (2000) China internal engine engineer handbook. Shanghai Science and Technology Press
65. Zhang Wankun. Configuration of BCHP and its optimal operation analysis. Master's Thesis from Shanghai Jiaotong University
66. Wang Cuncheng (1993) Industrial power system and energy conservation principles handbook. Department of Thermal Engineering, Tsinghua University
67. Tu Shan, Mao Jingru, Sun Bi (2000) China's gas-steam cycle power generation technology prospects. Thermal Power. Engineering 15(4):336–338
68. Jiao Shujian (1997) When will the gas turbine industry in China start. Gas Turbine Technology 10(1):1–8
69. Yang Song, Li Shikui (2005) Overview of gas-steam combined cycle waste heat boiler. Power Station Systems Engineering 21(4):43–44
70. Fan Lulu, Zeng Hong (2001) Discussion on several technical and economic problems of "Gas-Steam Combined Cycle". Shanghai Steam Turbine 2:19–26
71. Wang Zhenhua (2003) Analysis of world gas turbine electricity market order from June 2001 to May 2002. Gas Turbine Technology 16(1):71–72
72. Jiao Shijian (2001) Discussion on the development of gas turbine in China in the first half of the 21st century. Gas Turbine Technology 14(1):10–13
73. Jiao Shijian (2009) Review and prospect of IGCC technology development. Power Construction 30(1):1–7

74. Commentary on the current development and trend of IGCC in the world (2004) Gas Turbine Technology 17(3):1–5
75. Harry J (2007) CO2 cloud looms large over IGCC and gasification plant development. Gas Turbine World 37(6):16–24
76. Jiao Shijian (2008) Reconsideration on the development of IGCC technology in China. Huadian Technology 30(4):1–9
77. Bai Huifeng, Xu Yue (2009) The development and key technologies of IGCC and poly-generation system. Gas Turbine Technology 22(4):1–3
78. Lin Rumou, Wang Yingshi dangerous division (1997) The development prospect of IGCC technology in China – a review based on the report of Chinese and American experts. Gas Turbine Technology 10(3):1–7
79. Cai Ningsheng, Zhang Mingyao (2002) Progress and innovation of PFBC-CC power generation technology. Journal of Southeast University (Natural Science Edition) 32(3):437–442
80. Cai Ningsheng (2001) Consideration of PFBC-CC technology in China. Gas Turbine Technology 14(1):29–36
81. Chen Xiaoping, Zhao Chang Sui, Duan Yufeng, et al (2002) Design and test results of pressurized fluidized bed boiler for 15MWePFBC-CC pilot plant CHEN Xiao-ping, ZHAO Chang-sui, DUAN Yu-feng, et al. Power Engineering 22(6):2072–2077
82. Miao Xuelong, Huang Zhen (2006) Summary of combustion technology of internal combustion engine. Modern Vehicle Power 2:6–11
83. Zhu Bangrong (2008) Stirling's optimization design and simulation study. North China Electric Power University (Beijing) Master's Thesis
84. Zhu Chenyuan, Xue Fei, Wang Hai Gui (2006) Research and Application of Hot Air Machine in Landfill Gas Combustion Power Generation ZHU Chen-yuan, XUE Fei, WANG Hai-gui. Study on Energy Generation in Landfill Gas Combustion Power Generation 27(5):216–219
85. Yao Rui, Wu Keqi (2001) Application of stirling engine in space solar power generation. Journal of Solar Energy 22(1):111–114
86. Mills D (2004) Advances in Solar Thermal Electricity technology. Sol Energy 76(1–3):19–31
87. Kongtragool B, Wongwises S (2003) A review of solar-powered stirling engines and low temperature differential stirling engines. Renew Sust Energ Rev 7(2):131–154
88. Zhu Chenyuan, PAN Wei-ming (2009) Progress of solar thermal power generation technology for hot air heaters. Shanghai Energy Conservation 8:23–29
89. Deng He (2002) Status and future of hot air power generation devices. Journal of Shanghai University of Electric Power 18(3):75–77
90. Yi Baolian (1998) Fuel cell status and future. Power technology 22(5):216–221
91. Zhang Chun, Mao Zongqiang (1996) Development, Status and Prospect of Phosphoric Acid Fuel Cell (PAFC) power plant technology. Power Technology 20(5):216–221
92. Feng Yucheng, Yang Ying (1999) Fuel cell is the main force of the 21st century power industry. China Energy 11:21–24
93. Lu Dehong (2003) Fuel cell and its application in the hot and cold power supply system. HVAC 33(1):91–93
94. Xu Shisen, Zhu Baotian (2001) Discussed the technical route of China’s power system development of fuel cell power generation. China Electric Power 34(7):9–12
95. Emmerich SJ, McGrattan KB (1998) Application of a large eddy simulation model to study room airflow. ASHRAE Trans 104(1):1128–1140
96. Chen Binjian, Fang Zhaoxiang (2004) Development status of fuel cell technology. Energy Conservation and Environmental Protection 8:36–40
97. Gigliucci G, Petruzzi L, Cerellic E et al (2004) Demonstration of a residential CHP system based on PEM fuel cells. J Power Sources 131(1):62–68
98. Yu Zeting, Han Yitian (2004) Application of fuel cell in the family. Energy saving and environmental protection 9:14–16
99. International Electric Power Editing Department (2001) Fuel cell power generation system and its demonstration project. International Electric Power 4:23–26

100. Lan Li, Yin Yingde, Gu Dengfeng (2005) Fuel cell and cogeneration system. Refrigeration and air conditioning 3:58–63
101. V. Hartkopf, Pan Yijun, Wu Gang, et al (2003) Application of solid oxide fuel cells in building CCHP. HVAC 33(1):47–53
102. Jiang billion, Xue Zhifeng, Zeng Jianlong, et al (2004) Tsinghua University ultra-low energy consumption demonstration building. HVAC 34(6):64–66
103. Zhao Xi-ling, Zhang Xing-mei, Duan Chang-gui, et al (2007) Research and application of fuel cell distributed hot and cold power supply technology. HVAC 37(9):74–78
104. Silveira J, Leal EM, Ragonha LF (2001) Analysis of a molten carbonate fuel cell: cogeneration to produce electricity and cold water. Energy 26(10):891–904
105. Weber C, Marechal F, Favrat D et al (2006) Optimization of an SOFC based decentralized polygeneration system for providing energy services in an office building in Tokyo. Appl Therm Eng 26(13):1409–1419
106. Jing S, Hongliang H, Hongyou C (2004) Research status of fuel cell in China. Power Technology 28(2):125–128
107. Allan CC, Stenhen EV (2001) Siemens fuel cell system demonstration project. China Electric Power 34(9):61–62
108. Daozhi B (2000) The development of fuel cell in China. Power supply technology 24(2):103–107
109. Yu Tao, Zhang Cuizhen (2006) Review on inlet air cooling technology for gas turbine. Journal of Refrigeration 27(4):50-53