Contemporary Cogeneration Technologies

Most cogeneration systems can be characterised either as *topping systems* or as *bottoming systems*. In topping systems, a high temperature fluid (exhaust gases, steam) drives an engine to produce electricity, while low temperature heat is used for thermal processes or space heating (or cooling).

In bottoming systems, high temperature heat is first produced for a process (e.g. in a furnace of a steel mill or of glass-works, in a cement kiln) and after the process hot gases are used either directly to drive a gas-turbine generator, if their pressure is adequate, or indirectly to produce steam in a heat recovery boiler, which drives a steam-turbine generator.

Indicative temperature ranges for the two types of systems are given in below:

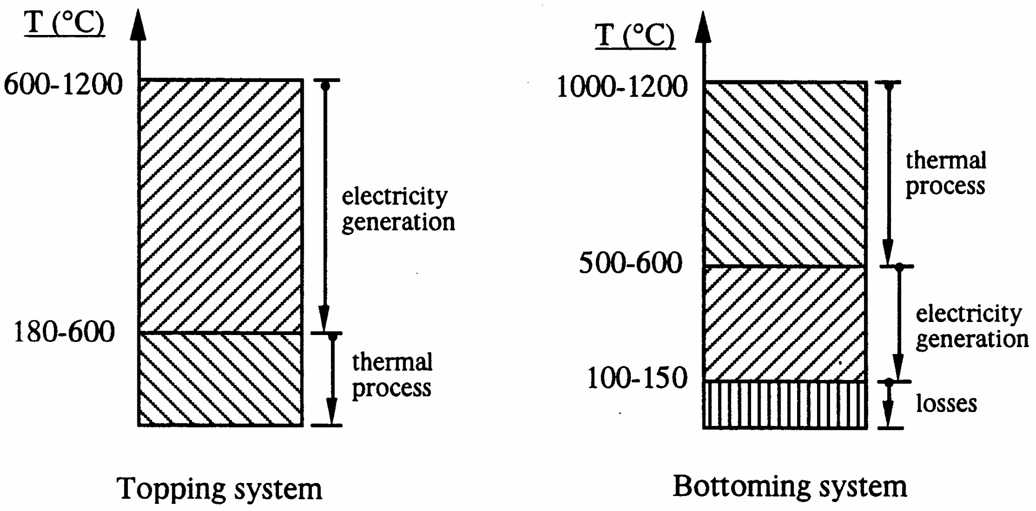


Figure: Indicative temperature ranges for topping and bottoming cogeneration systems

1. Steam Turbine Cogeneration Systems

A system based on steam turbine consists of three major components: a heat source, a steam turbine and a heat sink. The system operates on the Rankine cycle, either in its basic form or in its improved versions with steam reheating and regenerative water preheating. Most of the generation capacity installed since the early 1900's is based on systems of this type.

The most common heat source is a boiler, which can burn any type of fuel or certain combinations of fuels, and produces superheated steam. In place of a boiler, nuclear reactors can be used. On the other hand, the system can use renewable energy such as biomass or concentrated solar radiation. Even waste by-products can be burned, provided the boiler is equipped with proper pollution abatement units.

The operating conditions can vary in a wide range. For cogeneration applications, steam pressure can range from a few bars to about 100 bar; in the utility sector, higher pressures can also be used. Steam temperature can range from a few degrees of superheat to about 450^{O}C, and, in the utility sector, to about 540^{O}C. The power output is usually in the range of 0.5-100 MW, even though higher power is also possible.

Steam turbine systems have a high reliability, which can reach 95%, high availability (90-95%) and long life cycle (25-35 years). The installation period is rather long: 12-18 months for small units, up to three years for large systems.

1.1 Main Configurations of Steam Turbine Cogeneration systems

There are several configurations of steam turbine cogeneration systems, which are described below. The flow diagrams are simplified in order to depict the basic configurations without details; thus, steam reheating, if any, regenerative water preheating and auxiliary equipment are not drawn.

- ***Back-pressure steam turbine systems***

It is the simplest configuration. Steam exits the turbine at a pressure higher or at least equal to the atmospheric pressure, which depends on the needs of the thermal load. This is why the term "back-pressure" is used. It is also possible to extract steam from intermediate stages of the steam turbine, at a pressure and temperature appropriate for the thermal load (figure below). After the exit from the turbine, the steam is fed to the load, where it releases heat and is condensed. The condensate returns to the system with a flow rate which can be lower than the steam flow rate, if steam mass is used in the process or if there are losses along the piping. Make-up water retains the mass balance.

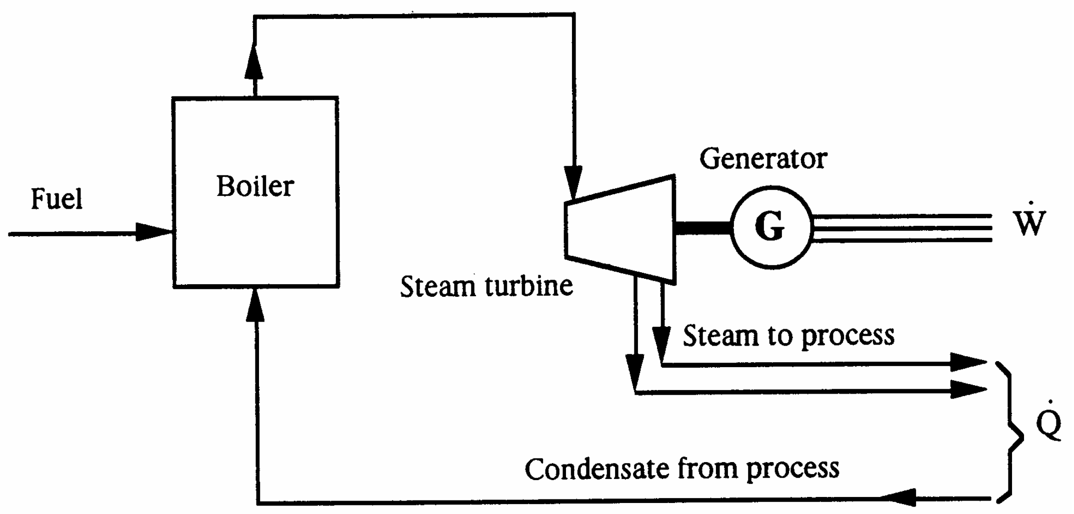


Figure: Cogeneration system with back-pressure steam turbine

The back-pressure system has the following advantages:

- Simple configuration with few components.
- The costs of expensive low pressure stages of the turbine are avoided.
- Low capital cost.
- Reduced or even no need of cooling water.
- High total efficiency, because there is no heat rejection to the environment through a condenser.

However, it has certain disadvantages:

- The steam turbine is larger for the same power output, because it operates under lower enthalpy difference of steam.
- The steam mass flow rate through the turbine depends on the thermal load. Consequently, the electricity generated by the steam is controlled by the thermal load, which results in little or no flexibility in directly matching electrical output to electrical load. Therefore, there is need of a two-way connection to the grid for purchasing supplemental electricity or selling excess electricity generated. Increased electricity production is possible by venting steam directly to the atmosphere, but this is very inefficient, it results in waste of treated boiler water and, most likely, in poor economic as well as energetic performances.

A way to reach some flexibility is to extract steam from the turbine for regenerative feed-water heating. The thermal output is then reduced with all the heat of condensation of the extracted steam, while the mechanical output is less reduced, because extracted steam still delivers work through its incomplete expansion. The total efficiency remains nearly unchanged.

Condensing steam turbine systems

In such a system, steam for the thermal load is obtained by extraction from one or more intermediate stages at the appropriate pressure and temperature (figure below). The remaining steam is exhausted to the pressure of the condenser, which can be as low as 0.05 bar with corresponding condensing temperature of about 33°C. It is rather improbable for such a low temperature heat to find a useful application and consequently it is rejected to the environment.

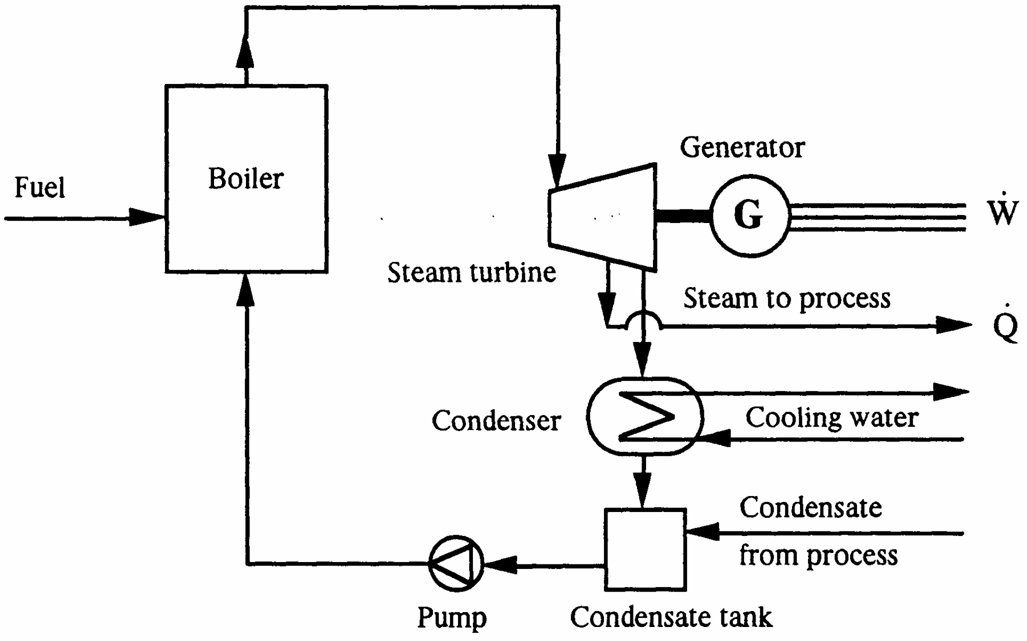


Figure: Cogeneration system with condensing steam turbine

Extracted steam can also be used for regenerative feedwater heating, which improves the Rankine cycle efficiency, and for driving auxiliary equipment.

In comparison to the back-pressure system, the condensing one has a higher capital cost and, in general, a lower total efficiency. However, it can control the electrical power independently, to a certain extent, of the thermal load by proper regulation of the steam flow rate through the turbine.

Bottoming cycle steam turbine systems

Many industrial processes (e.g. in steel mills, glass-works, ceramic factories, cement mills, oil refineries) operate with high temperature exhaust gases (1000-1200°C). After the process, the gases are still at high temperature (500-600°C). Instead of releasing them directly into the atmosphere, they can pass through a heat recovery steam generator (HRSG) producing steam, which then drives a steam turbine. Thus, the energy of fuel is first used to cover a thermal load and then to produce electricity by a steam turbine system in a bottoming cycle (figure below).

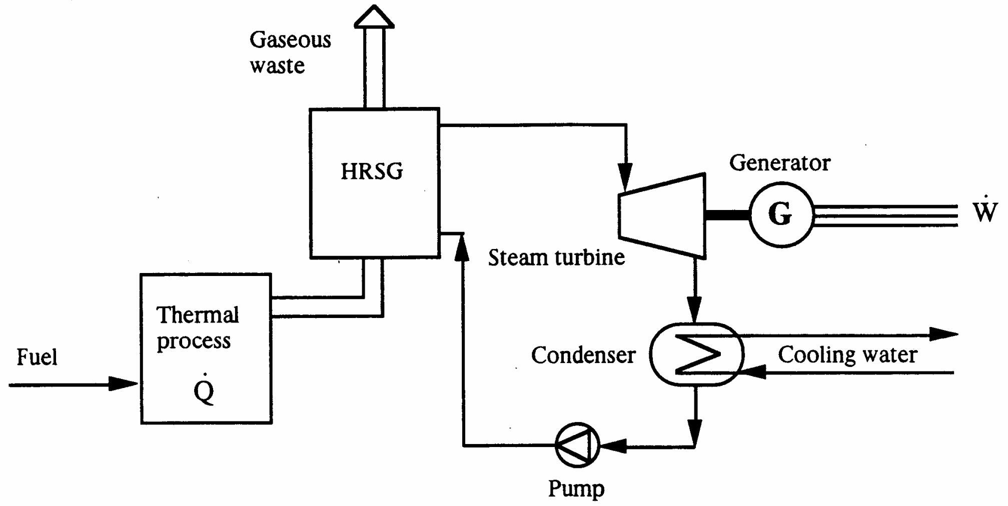


Figure: Bottoming cycle cogeneration system with condensing steam turbine

In

Figure, a condensing steam turbine is shown. Alternatively, a back-pressure turbine can be used, if conditions make it preferable. Of course with either the condensing or the backpressure turbine extraction can be applied, if needed.

Bottoming Rankine cycle systems with organic fluids

These systems are usually referred to as organic Rankine cycles (ORC).

In the bottoming cycle, water is the working fluid, which evaporates by heat recovery at high temperature (500°C or higher). However, when heat is available at relatively low temperatures (80-300°C), organic fluids with low evaporation temperatures can be used, such as toluene, improving the heat recovery and the performance of the system. ORC's can be effective also in geothermal applications, where only low temperature heat is available. In certain cases, the working fluid can be a mixture of two different fluids such as water and ammonia, which increases the cycle efficiency.

Organic fluids have two major disadvantages in comparison to water. (i) They are more expensive than water, and losses of the fluid can result in significant costs. (ii) Fluids such as toluene are considered hazardous materials and must be handled accordingly. Safety and materials-handling systems can also increase ORC system cost. (iii) Thermal stability of some organic fluids appears to be limited. (iv) Their lower heat of vaporisation as compared with water leads to higher mass flow rates and higher pumping power, resulting in some lowering of the efficiency.

Some advantages of organic fluids have to be recognised: (i) Their higher molecular weight leads to a lower number of stages and consequently to lower turbine costs. (ii) For most organic fluids, the absolute value of the slope of the line of separation between liquid-vapour and pure vapour-domains in a (t,s) diagram is larger than for water. As a consequence, the rate of condensation inside the turbine is lower.

The electric power output of these systems is in the range 2 kW–10 MW. The electric efficiency is low, 10–30%, but of importance is the fact that such a system produces additional power with no fuel consumption.

The installation time of small units (up to 50 kW), and especially those appropriate for applications in the commercial-residential sector, are 4-8 months, while for larger systems it is 1–2 years. There are no statistical data available regarding the reliability of ORC systems. It is estimated that their annual average availability is 80–90%. The expected life cycle is about 20 years.

1.2 Thermodynamic Performance of Steam Turbine Cogeneration Systems

Efficiency and PHR of steam turbine systems

The total energy efficiency is relatively high (60–85%) and decreases only slightly at partial load. However, the electrical efficiency is low (values in the range 15–20% are not seldom), which results in low power to heat ratio (PHR = 0.1–0.5). In general, the higher the temperature required for process steam is, the lower the electrical efficiency is. The electrical efficiency can be increased to a certain extent by increasing the pressure and temperature of steam at the turbine inlet.

Back-pressure steam turbine systems

When all the thermal energy of steam is utilised and the condensate returns from the processes with no supplementary cooling and no heat rejected to the environment, the total efficiency may reach 85%. Since the generated electrical power is proportional to the steam flow rate towards the process, the value of the power to heat ratio, PHR, remains approximately constant during load changes.

Condensing steam turbine systems

The heat rejected through the condenser results in a lower total efficiency. Main advantage of these systems is the capability to change the electrical and thermal power independently, inside certain limits, and consequently to change the value of PHR.

Bottoming cycle steam turbine systems

The electrical efficiency is typically in the range 5–15%. This is a low value, but it is important that electricity is produced from thermal energy, which otherwise would be rejected to the environment.

Partial load operation of steam turbines

Optimum performance of a steam turbine typically occurs at approximately 95% of the rated power. Since most turbines used in cogeneration systems are multistage devices designed for a specific application, often having both condensing and extraction capabilities, the part-load characteristics are unique to each turbine. The turbine manufacturer will provide a performance map such as the one illustrated below. The map has been developed for a condensing/extracting turbine and relates throttle flow (flow rate of steam at the turbine inlet) to turbine electrical and thermal power output; the latter is determined by the extraction flow rate, which appears in the map.

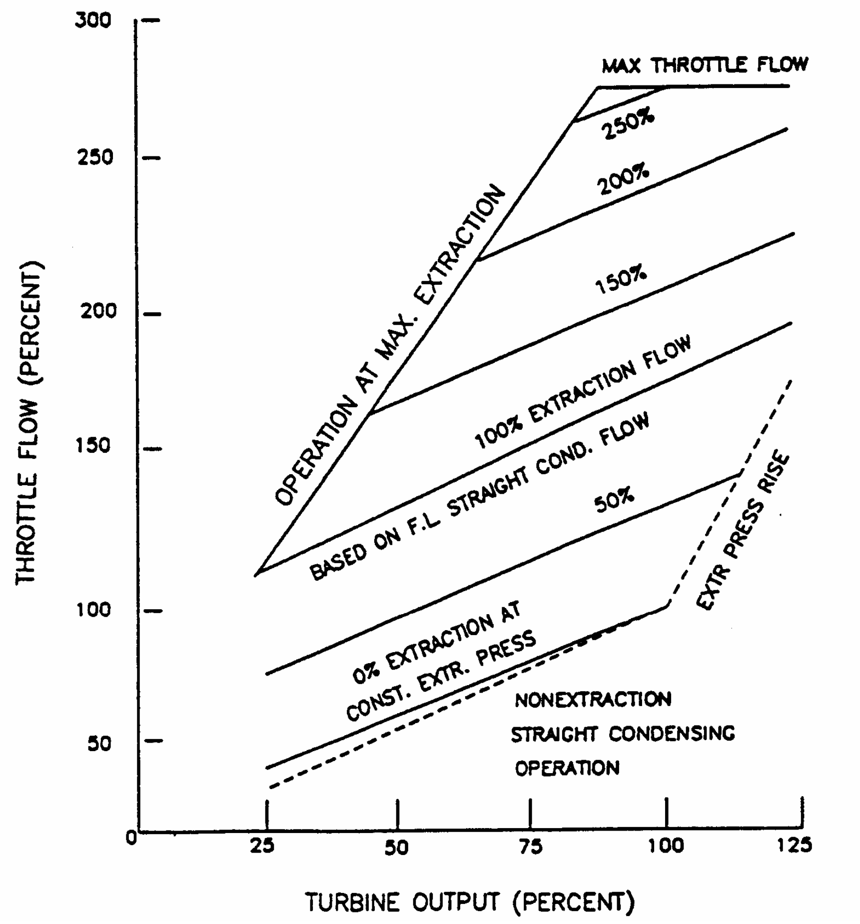


Figure: Steam Turbine performance map (Orlando 1996)

1.3 Gas Turbine Cogeneration Systems

Gas turbines either in a simple cycle or in a combined cycle are the most frequently used technology in recent cogeneration systems of medium to high power. Their electric power output ranges from a few hundred kilowatts to several hundred megawatts. On the other side of the spectrum, recent research and development aims at the construction of micro turbines, which have a power output of a few kilowatts.

Gas turbines have been developed as either heavy-duty units for industrial and utility applications, or as lightweight, compact and efficient aircraft engines. These engines are modified for stationery applications, in which case they are called “aeroderivative turbines”. In general, they are capable of faster start-ups and rapid response to changing load. Both gas turbine designs have been successfully used for cogeneration having as main advantages low initial cost, high availability, fast and low-cost maintenance, fuel-switching capabilities, high quality heat which can easily be recovered, and high efficiencies in larger sizes. In addition, the commercial availability of packaged units helped in their widespread applications.

Gas Turbine Cycles

A gas turbine can operate either in open cycle or in a closed cycle.

Open-cycle gas turbine cogeneration systems

Most of the currently available gas turbine systems in any sector of applications operate on the open Brayton (also called Joule cycle when irreversibilities are ignored): a compressor takes in air from the atmosphere and derives it at increased pressure to the combustor. The air temperature is also increased due to compression. Older and smaller units operate at a pressure ratio in the range of 15:1, while the newer and larger units operate at pressure ratios approaching 30:1.

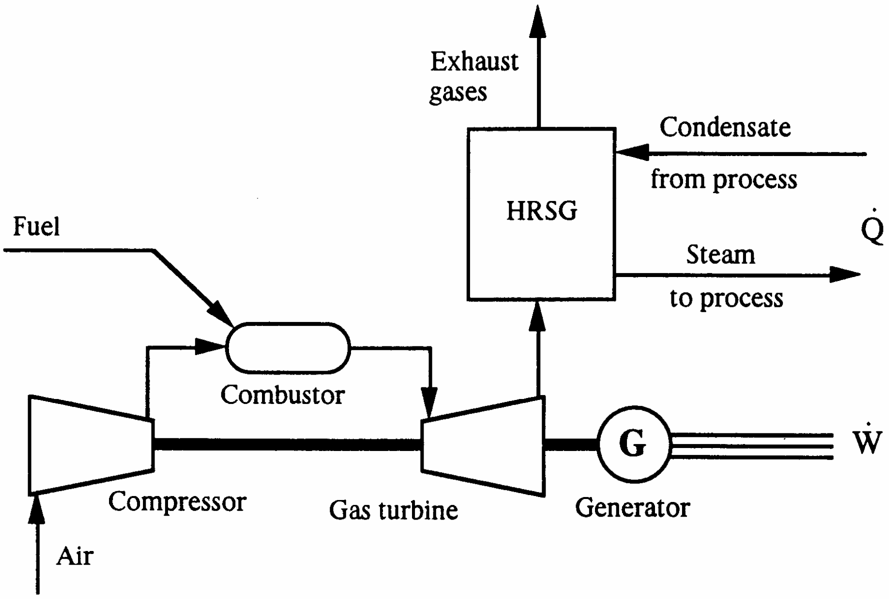


Figure: Cogeneration system with open-cycle gas turbine

The compressed air is delivered through a diffuser to a constant-pressure combustion chamber, where fuel is injected and burned. The diffuser reduces the air velocity to values acceptable in the combustor. There is a pressure drop across the combustor in the range of 1–2%. Combustion takes place with high excess air. The exhaust gases exit the combustor at high temperature and with oxygen concentrations of up to 15–16%. The highest temperature of the cycle appears at this point; the higher this temperature is, the higher the cycle efficiency is. The upper limit is placed by the temperature the materials of the gas turbine can withstand, as well as by the efficiency of the cooling blades; with the current technology it is about 1300°C.

The high pressure and temperature exhaust gases enter the gas turbine producing mechanical work to drive the compressor and the load (e.g. electric generator). The exhaust gases leave the turbine at a considerable temperature (450-600°C), which makes high-temperature heat recovery ideal. This is effected by a heat recovery boiler of single-pressure or double-pressure, for more efficient recovery of heat. Triple-pressure is also possible but not very usual, because it makes the system more complex and expensive, which is not always justified.

The steam produced can have high quality (i.e. high pressure and temperature), which makes it appropriate not only for thermal processes but also for driving a steam turbine thus producing additional power. In the latter case a combined cycle system is obtained.

Instead of producing steam, the exhaust gases after the turbine can be used directly in certain thermal processes, such as high-temperature heating and drying.

In any of the aforementioned applications, it is possible to increase the energy content and temperature of the exhaust gases by supplementary firing. For this purpose, burners are installed in the exhaust gas boiler, which use additional fuel. Usually there is no need of additional air, since the oxygen content in the exhaust gases is significant, as mentioned above.

Cogeneration systems with open cycle gas turbines have an electrical power output usually in the range 100 kW–100 MW, not excluding values outside this range. A variety of fuels can be used: natural gas, light petroleum distillates (e.g. gas oil, Diesel oil), products of coal gasification. The use of heavier petroleum distillates (fuel oil) in mixtures with light ones is under investigation and it may prove successful. Also, non-commercial fuel gases, produced during the catalytic cracking of hydrocarbons in petroleum refineries, are used as fuels in gas turbines. However, attention has to be paid to the fact that the turbine blades are directly exposed to the exhaust gases. Consequently, the combustion products must not contain constituents causing corrosion (such as chemical compounds of sodium (Na), potassium (K), calcium (Ca), vanadium (Va), sulfur (S)) or erosion (solid particles larger than a certain size). In order to prevent these effects, there may be need of fuel treatment or exhaust gas treatment before they enter the turbine.

The installation time for gas turbine cogeneration systems of up to 7 MW_e is about 9–14 months, and it may reach two years for larger systems. The reliability and annual average availability of gas turbine systems burning natural gas are comparable to those of steam turbine systems. Systems burning liquid fuels or gaseous by-products of chemical processes may require more frequent inspection and maintenance, which results in lower availability. The life cycle is 15–20 years and it may be critically affected by a low quality fuel or poor maintenance.

Closed-cycle gas turbine cogeneration systems

In the closed-cycle system, the working fluid (usually helium or air) circulates in a closed circuit. It is heated in a heat exchanger before entering the turbine, and it is cooled down after the exit of the turbine releasing useful heat. Thus, the working fluid remains clean and it does not cause corrosion or erosion.

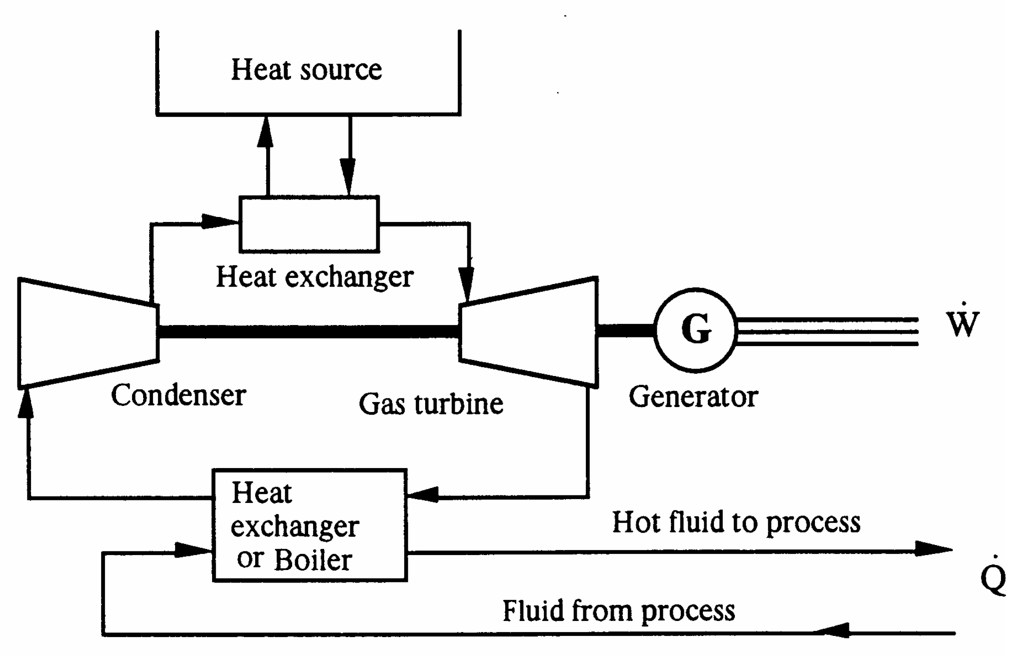


Figure: Cogeneration system with closed-cycle gas turbine

Source of heat can be the external combustion of any fuel, even city or industrial wastes. Also, nuclear energy or solar energy can be used.

Systems of this type with a power output of 2–50 MW_e operate in Europe and Japan, but their number is rather small.

After accumulation of experience, the reliability of closed-cycle systems is expected to be at least equal to that of open-cycle systems, while the availability is expected to be higher thanks to the clean working fluid.

1.4 Thermodynamic Performance of Gas Turbine Cogeneration Systems

Efficiency and PHR at rated power

The nominal electric efficiency (i.e. the efficiency at rated power) of small to medium gas turbine systems is usually in the range of 25–35%. Larger systems built recently have reached electric efficiencies of 40–42% by means of high temperature of exhaust gases at the turbine inlet (1200-1400°C). The total efficiency is typically in the range of 60–80%. The power to heat ratio (PHR) is in the range 0.5–0.8.

A significant portion of the turbine power output, often exceeding 50%, is consumed to drive the compressor, thus resulting in a relatively low electric efficiency (e.g. in comparison to a reciprocating engine of similar power). In cases of high pressure ratios, intercooling of the air at an intermediate stage of compression can be applied, which reduces the work required for compression. A significant increase in electric efficiency is also achieved by regenerative air preheating, i.e. preheating of air with exhaust gases. In such a case the recoverable heat from the exhaust gases after the regenerative heat exchanger decreases and the value of PHR increases. In the case of cogeneration, as well as for combined gas-steam cycles, the addition of a regenerative air preheater is not justified.

The maximum recoverable heat depends on the minimum temperature acceptable in the exhaust gases. If the fuel contains sulphur, the exhaust gas temperature can not be lower than 140-165°C, in order to avoid the sulphuric acid dew point. If the fuel is practically free of sulphur, as is the case with natural gas, the exhaust gas temperature can be as low as 90-100°C.

Effect of ambient conditions and partial load on power output and efficiency of gas turbine systems

Air enters the compressor at ambient conditions. This initial temperature and density of air dictate the amount of work required for compression, the fuel that can be burned, the fuel required to achieve a specified turbine inlet temperature. As a result, the net power output, the efficiency, the exhaust gas flow rate and temperature at the turbine exit (consequently the recoverable heat) are functions of the ambient conditions, which are far from weak.

Manufacturers normally specify the capacity (power output) and performance of a gas turbine at ISO standard conditions: 15°C, 60% relative humidity, at sea level. In addition, the performance is typically specified without pressure losses in the inlet and exhaust ducts. The effect of these losses for typical single-shaft turbines is illustrated in Figure below:

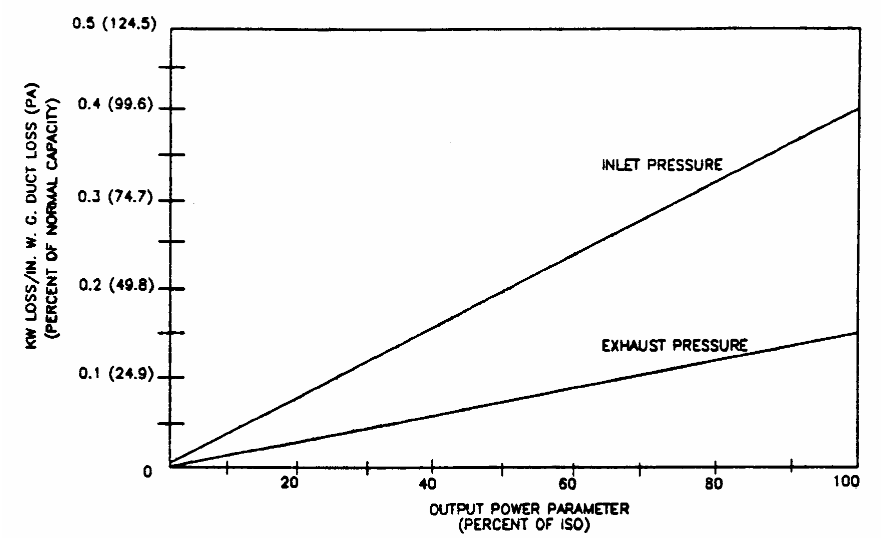


Figure: Effect of inlet and exhaust duct pressure losses on gas turbine capacity

The capacity of the turbine decreases as ambient temperature or altitude increases. The capacity may decrease by about 2–4% for each 300 m increase in altitude. Partial load has a strong effect on efficiency: decreasing load causes a decrease in electrical efficiency. As with the steam turbines, it is necessary to consult the manufacturer for performance maps or graphs of each particular gas turbine.

If a gas turbine system is to operate over long periods of time in an environment of high temperature, precooling of the inlet air may be economically feasible. Mechanical, evaporative or absorption chillers may be used; the final choice will be dictated by a feasibility study. It is interesting to note that absorption chillers may operate with turbine exhaust gas heat as the main source of energy.

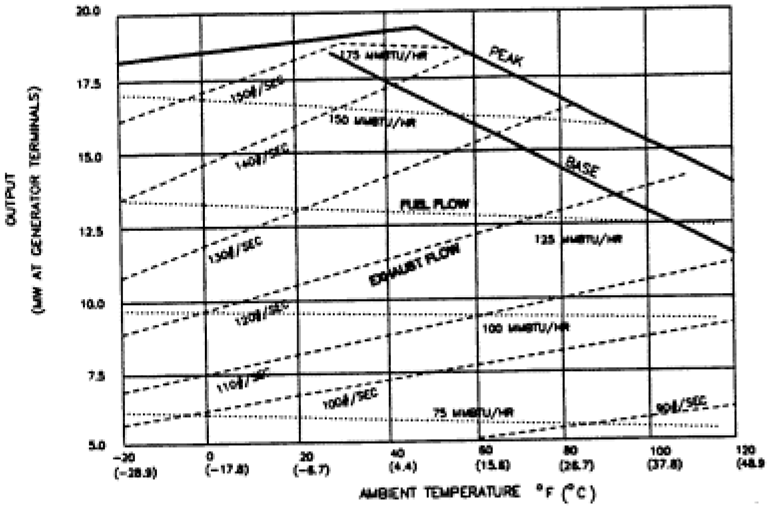


Figure: Gas turbine performance map

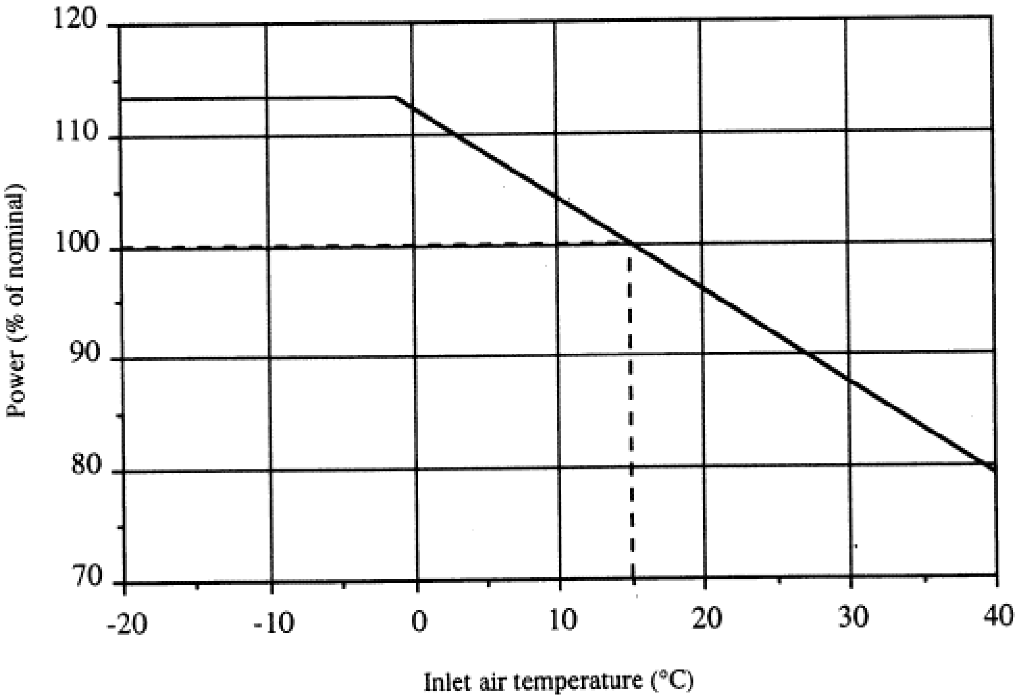


Figure: Effect of inlet air temperature on the power output of a gas turbine

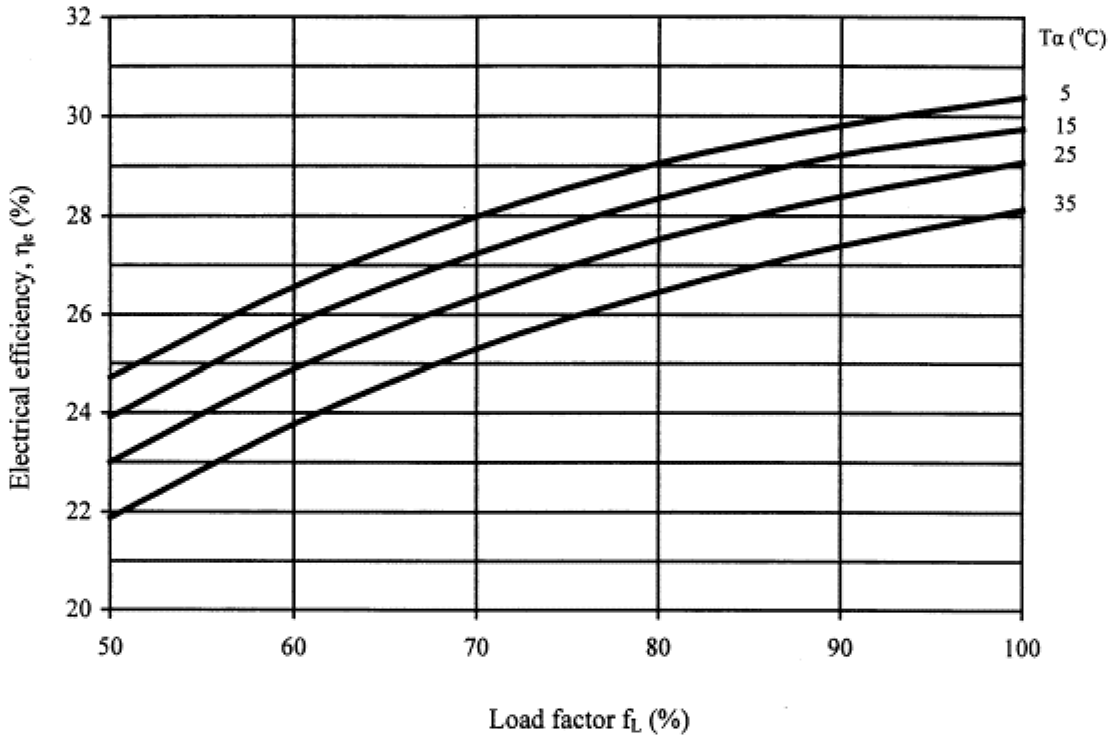


Figure: Effect of load and inlet air temperature on the electric efficiency of a gas turbine system

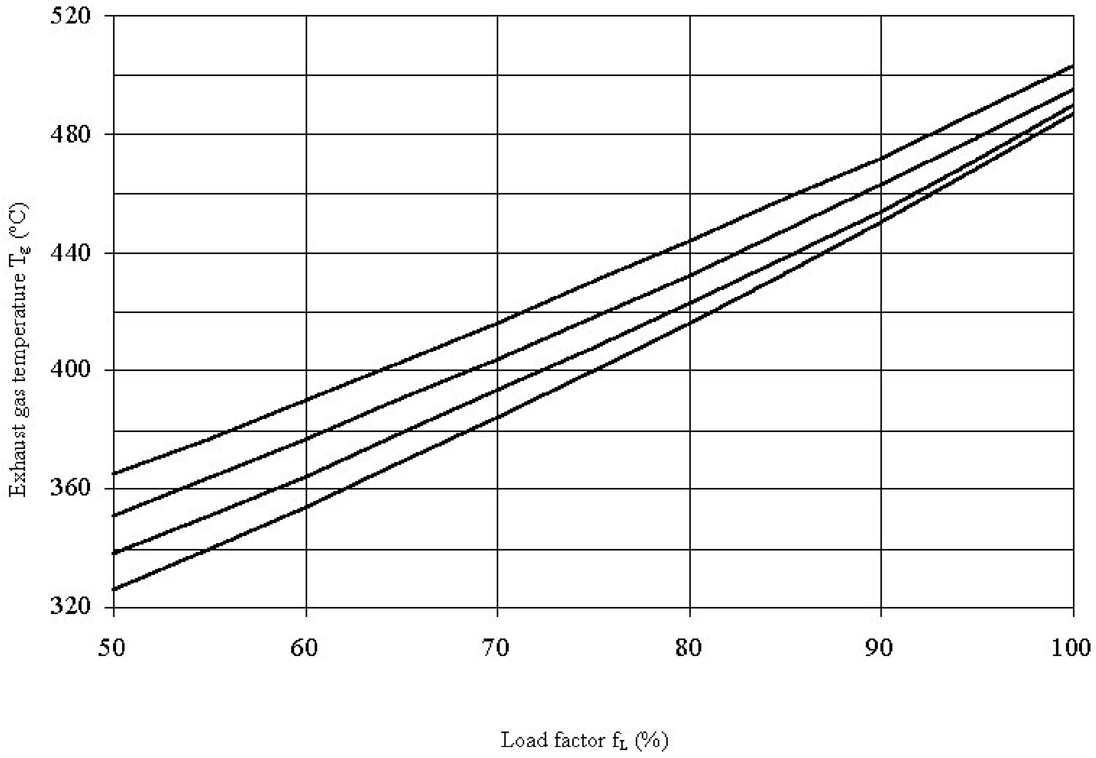


Figure: Effect of load and inlet air temperature on gas turbine exhaust gas temperature.

1.5 RECIPROCATING INTERNAL COMBUSTION ENGINE COGENERATION SYSTEMS

Reciprocating internal combustion engines have high efficiencies, even in small sizes. They are available in a variety of sizes in a broad range (75 kW–50 MW). They can use a broad variety of gaseous and liquid fuels, and have good availability (80–90%). These characteristics have made them the first choice, up to now, for cogeneration applications in the institutional, commercial and residential sector, as well as in the industrial sector when low to medium voltage is required.

Types of Reciprocating Internal Combustion Engine Cogeneration Systems

One way to classify the systems is based on the internal combustion engine cycle: Otto cycle and Diesel cycle. In an Otto engine, a mixture of air and fuel is compressed in each cylinder and the ignition is caused by an externally supplied spark. In a Diesel engine, only air is compressed in the cylinder and the fuel, which is injected in the cylinder towards the end of the compression stroke, ignites spontaneously due to the high temperature of the compressed air.

Otto engines can operate on a broad range of fuels such as gasoline, natural gas, propane, sewage plant gas, landfill methane. They are often called “gas engines”, if they use gaseous fuel. Diesel engines operate on higher pressure and temperature levels, and for this reason heavier fuels are used: Diesel oil, fuel oil and, in large two-stroke engines, residual fuel oil.

Another classification of the cogeneration system is based on the size of the engine:

a) Small units with a gas engine (15–1000 kW) or Diesel engine (75–1000 kW).

b) Medium power systems (1–6 MW) with gas engine or Diesel engine.

c) High power systems (higher than 6 MW) with Diesel engine.

Gas engines of the following types are commercially available.

a) Gasoline engines of cars, converted to gas engines. Usually, they are small engines (15–30kW), light, with high power to weight ratio. The conversion has a rather small effect on efficiency, but it decreases the power output by about 18%. Mass production results in low cost of the engines, but their life cycle is relatively short (10000–30000 hours).

b) Diesel engines of cars, converted to gas engines. Their power is up to about 200 kW. Conversion is necessary on pistons, cylinder heads and valve mechanism, which are imposed by the fact that ignition will be effected not by compression only but by a spark. Conversion usually does not cause power reduction, because it is possible to adjust the excess air properly.

c) Stationary engines converted to gas engines or originally designed and built as gas engines. They are heavy duty engines manufactured for industrial or marine applications. The power output reaches 3000 kW. Their robustness increases the initial cost, but reduces maintenance needs and prolongs the life cycle (15–20 years). They are capable of running continuously at high load.

d) Dual-fuel stationary engines. They are Diesel engines with a power output of up to 6000 kW. Natural gas is the main fuel, which is ignited not by a spark, but by injection of Diesel oil towards the end of the compression stroke. Of the total fuel energy required, about 90% is provided by the natural gas and 10% by the Diesel oil. They also can have the capability to operate either with the aforementioned dual fuel or with Diesel oil only, which, of course, increases the capital and maintenance cost.

Regarding fuels of gas engines, landfill gas and sewage gas are of particular importance as a means not only of resource utilisation but also of environmental protection. Both landfill gas and sewage gas are very well suited for the operation of gas engines, since the knock-resistant methane and the high content in CO_2 permit a methane number of over 130. Another opportunity to utilise the energy potential of waste is through the process of pyrolysis (decomposition of substances by heat). The resultant pyrolysis gas can be used in a gas engine.

One of the most important properties regarding the use of gas in a gas engine is its knock resistance. This is rated according to the methane number. Highly knock-resistant methane has a methane number of 100. In contrast to this, butane has a methane number of 10 and hydrogen with a methane number of 0 lies at the bottom of the scale (

Table: Methane number of gaseous fuels

Fuel		**Methane** number
Name	Composition	
Hydrogen	H_2	0
Methane	CH_4	100
Ethylene	C_2H_4	15
Ethane	C_2H_6	43.7
Propylene	C_3H_6	18.6
Propane	C_3H_5	33
Butane	C_4H_{10}	10
Carbon monoxide	CO	75
Natural gas (Typical)	CH_4 88.5 % C_2H_6 4.7 % C_3H_6 1.6 % C_4H_{10} 0.2 % N_2 5.0 %	72-98
Sewage gas	CH_4 65 % CO_2 35 %	134
Landfill gas	CH_4 50 % CO_2 40 % N_2 10 %	136

Diesel engines are classified as high-speed, medium-speed and low-speed engines. Table gives the speed and power ranges for each type; the limits are not meant to be absolutely strict.

Table: Speed and power range of Diesel engines.

Type	Speed (RPM)	Power (kW)
High-speed	1200 – 3600	75 – 1500
Medium-speed	500 – 1200	500 – 15000
Low-speed	100 – 180	2000 – 50000

As with the gas turbines, exhaust gases of reciprocating internal combustion engines can be used either directly in thermal processes or indirectly, e.g. through a heat recovery boiler. Their temperature is in the range of 300-400°C, i.e. significantly lower than that of gas turbines. This is why additional heating may more often be necessary with these engines. It can be obtained either by supplementary firing in the exhaust gas boiler (supply of air is necessary, because there is no significant oxygen content in the exhaust gases) or by an auxiliary boiler. Large engines may make the combined cycle economically feasible.

The engine drives the generator. Four heat exchangers recover heat from fluids necessary for the operation of the engine: lubricating oil cooler, jacket water cooler (closed circuit of the engine), charge air cooler, and exhaust gas heat exchanger (or boiler). The recovered heat produces hot water and steam, or it may be used for other thermal processes. In small engines, the available heat may not be sufficient to make steam production feasible; in such a case only hot water is delivered. On the other hand, in a naturally aspirated engine there is no charge air cooler.

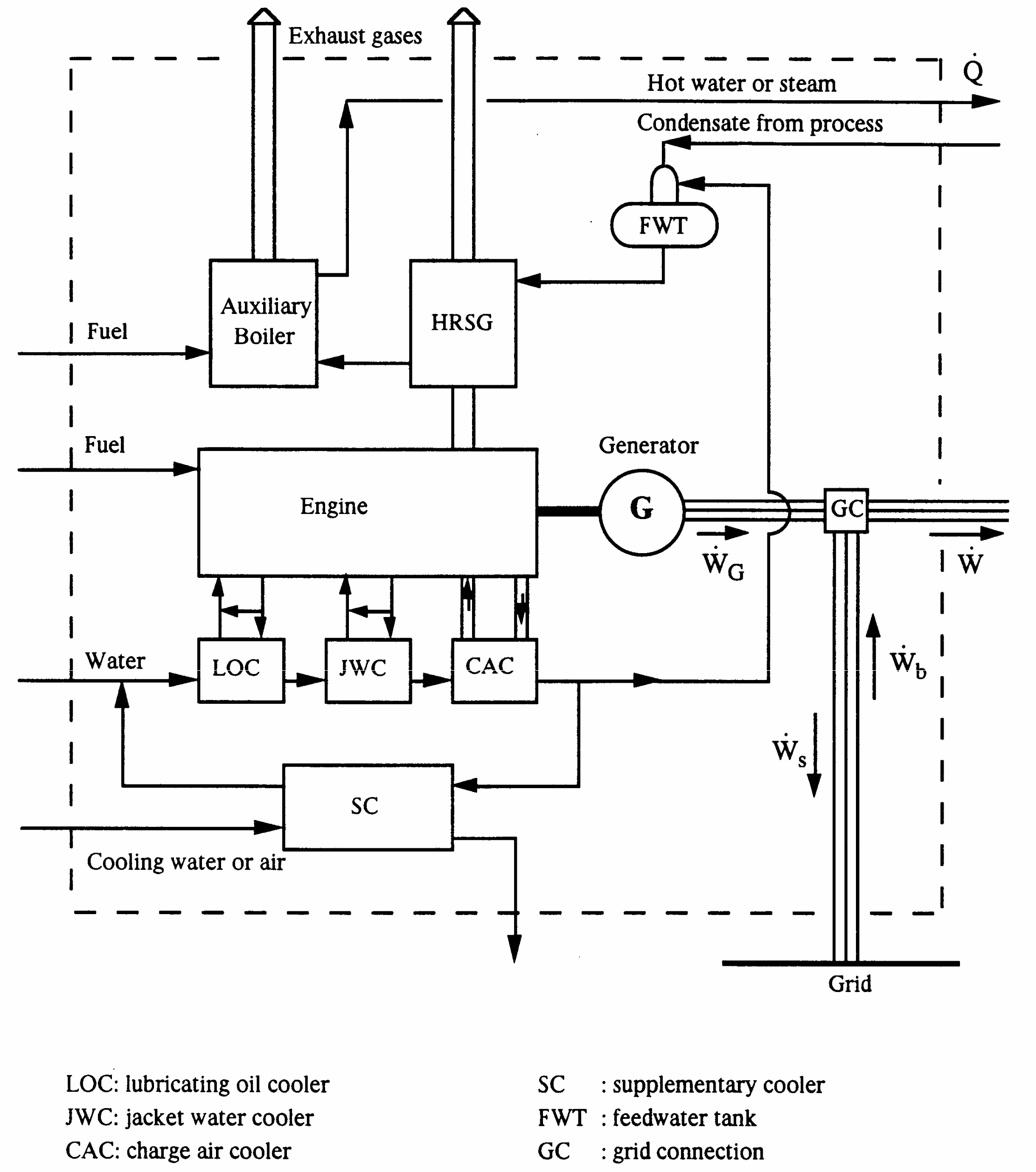
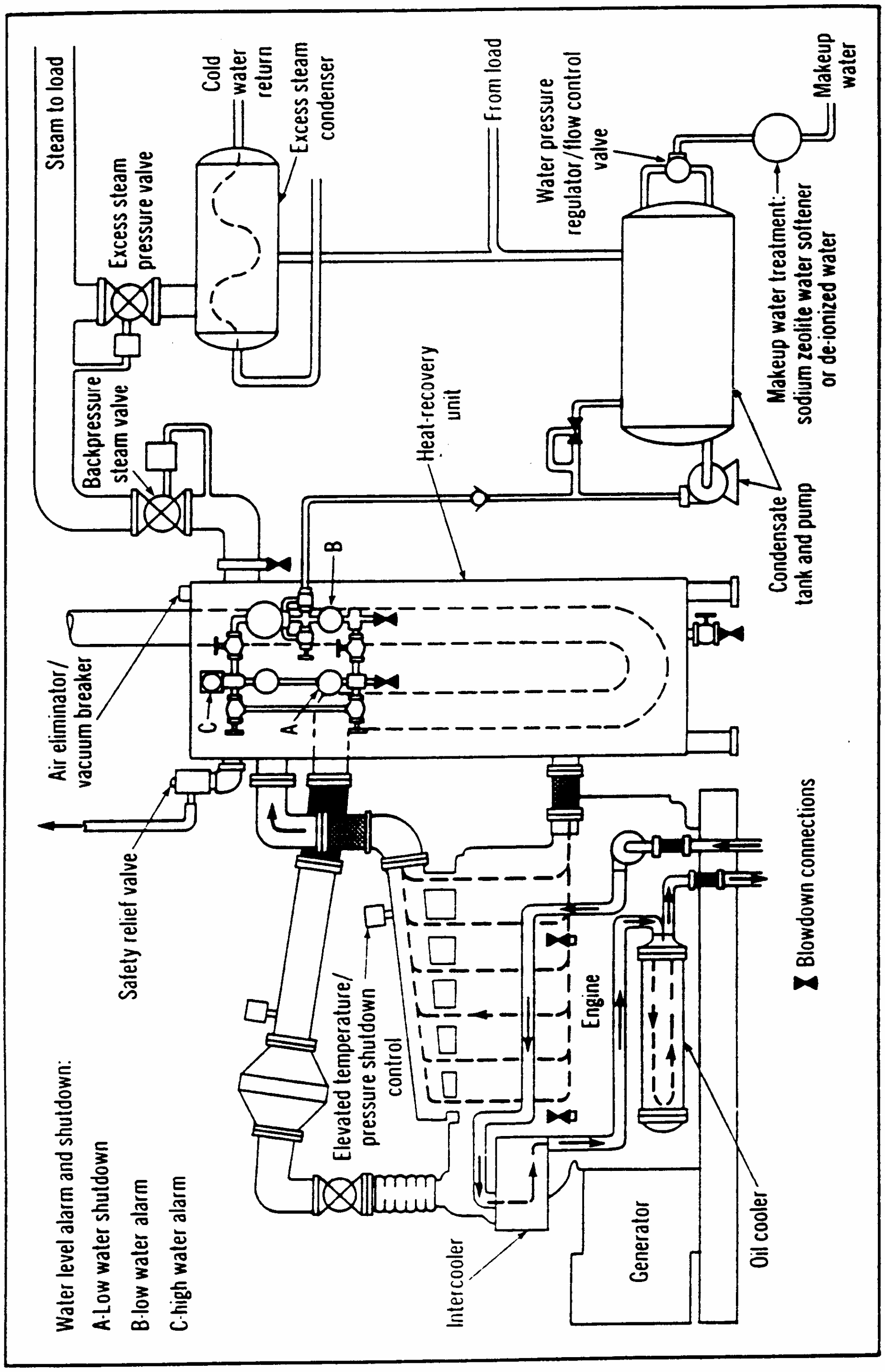


Figure: Flow diagram of a cogeneration system with reciprocating internal combustion engine

With heat recovery from the three coolers, water is heated up to 75-80°C. The pre-heated water enters the exhaust gas heat exchanger where it is heated up to 85-95°C, or it is evaporated. Medium size engines usually produce saturated steam of 180-200°C, while large units can deliver superheated steam at pressure 15–20 bar and temperature 250-350°C. The minimum exhaust gas temperature at the exit of the heat exchanger is 160- 170°C for fuels containing sulphur, like Diesel oil, or 90-100°C for sulphur-free fuels like natural gas.



Heat-recovery system of an ebulliently cooled engine supplies low-pressure steam.

Courtesy of Waukesha Engine Div., Dresser Industries, Inc.

Figure: Cogeneration with ebulliently cooled engine (courtesy from Waukesha)

A particular type of cylinder cooling is the ebullient cooling. In an ebulliently cooled engine, the coolant (e.g. water) enters the engine as a pressurised liquid at its boiling point. It absorbs heat from the engine and changes phase (evaporates). Not all of the coolant changes phase. Therefore, heat transfer from the engine to the coolant occurs at a constant temperature, which causes lower thermal stress to the engine. The coolant in the engine, which is a mixture of liquid and vapour, has a lower density than the coolant that enters the engine, and consequently it rises to the top of the engine. After exiting the engine, the mixture enters a steam separator, where steam is separated from the mixture to serve the thermal process. As an alternative to ebullient cooling, a forced-circulation system operating at higher than usual pressure and temperature in the range of 120-130°C can produce low-pressure steam.

Supercharging increases the power output for the same size of engine. Usually supercharging is effected by a turbocharger (there may be more than one in large engines): a gas turbine operates by the exhaust gases of the engine and drives an air compressor. The air temperature at the exit of the compressor is high (120-140°C) and its density low. In order to increase the mass of air in the cylinder (and consequently the mass of fuel and the power of the engine) it is necessary to cool the air before its entrance to the cylinders. There are two typical levels of air temperature at the exit of the cooler: low temperature (about 45°C), and high temperature (about 90°C).

Low temperature results in higher power output, but the recovered heat is of restricted use, because the water temperature at the cooler exit is low (30-35°C). Such a temperature level can be selected if there is need of preheating feedwater coming at a temperature of 10-25°C. However, if water enters the system at a temperature of 60-70°C, as is the case with central heating networks of buildings, then the high temperature level may be preferable, because it increases the total efficiency of the cogeneration system by 3–5%. The temperature level also affects the positioning of the air cooler relative to the other coolers along the water path.

1.6 Thermodynamic Performance of Cogeneration Systems with Reciprocating Internal Combustion Engine

Efficiency and PHR at rated power

Small and medium size engines have an electric efficiency of 35–45%, while modern large engines (tens of megawatts) achieve efficiencies at the order of 50%. The total efficiency of the cogeneration system is in the range of 70–85%. The power to heat ratio is in the range of 0.8–2.4, the highest of the three systems examined up to this point.

Effect of ambient conditions, quality of fuel and partial load on the performance of the systems

Reciprocating internal combustion engines are less sensitive than gas turbines in changes of ambient conditions or load.

Naturally aspirated engine power decreases by about 3% for each 300 m increase in altitude. For turbocharged engines, the effect of altitude depends on the individual manufacturer’s design. In some cases a decrease of power by about 2% for each 300 m increase in altitude is reported, but in other cases no decrease is noticeable at altitudes up to 1500 m.

The power output decreases by about 1% per 5.5°C increase in ambient temperature. The use of heated air should be avoided.

Engine specifications are given for a certain type and heating value of fuel. For the same type of fuel, the power output is, to a first approximation, proportional to the fuel heating value.

Reciprocating internal combustion engines maintain their efficiency over a wide range of operating loads. Manufacturers give partial load performance in the form of either tables or graphs. Examples are given in Tableand the following figures.

Table: Examples of partial load performance of gas-engine cogeneration units.

Nominal shaft power	kW	827			1500		
Load	%	100	75	50	100	75	50
Electric power	$\mathrm{kW_e}$	803	601	398	1464	1092	724
Thermal power	$\mathrm{kW_{th}}$	1018	800	578	1536	1245	935
Heat sources:							
Supercharging air cooler	%	5.9	3.2	0.2	7.4	5.1	2.7
Lubricating oil cooler	%	4.4	4.9	6.0	5.2	6.0	7.6
Jacket water cooler	%	13.8	17.3	21.0	8.8	10.9	12.7
Exhaust gases	%	25.0	24.6	24.2	22.2	23.4	24.7
Thermal efficiency	%	49.1	50.0	51.4	43.6	45.4	47.7
Electrical efficiency	%	37.6	37.6	35.3	41.5	39.8	36.9
Total efficiency	%	86.7	87.6	86.7	85.1	85.2	84.6
Water temperature:							
supply	°C	90	87	83	90	86	82

return	°C	70	70	70	70	70	70
Data are valid under the following conditions: Fuel: natural gas with lower heating value H_u=34.200 kJ/Nm^3 Maximum jacket water temperature 90°C Cooling of exhaust gases down to 120°C Useful heat supplied in the form of hot water. Uncertainty in values of thermal power ±8%.							

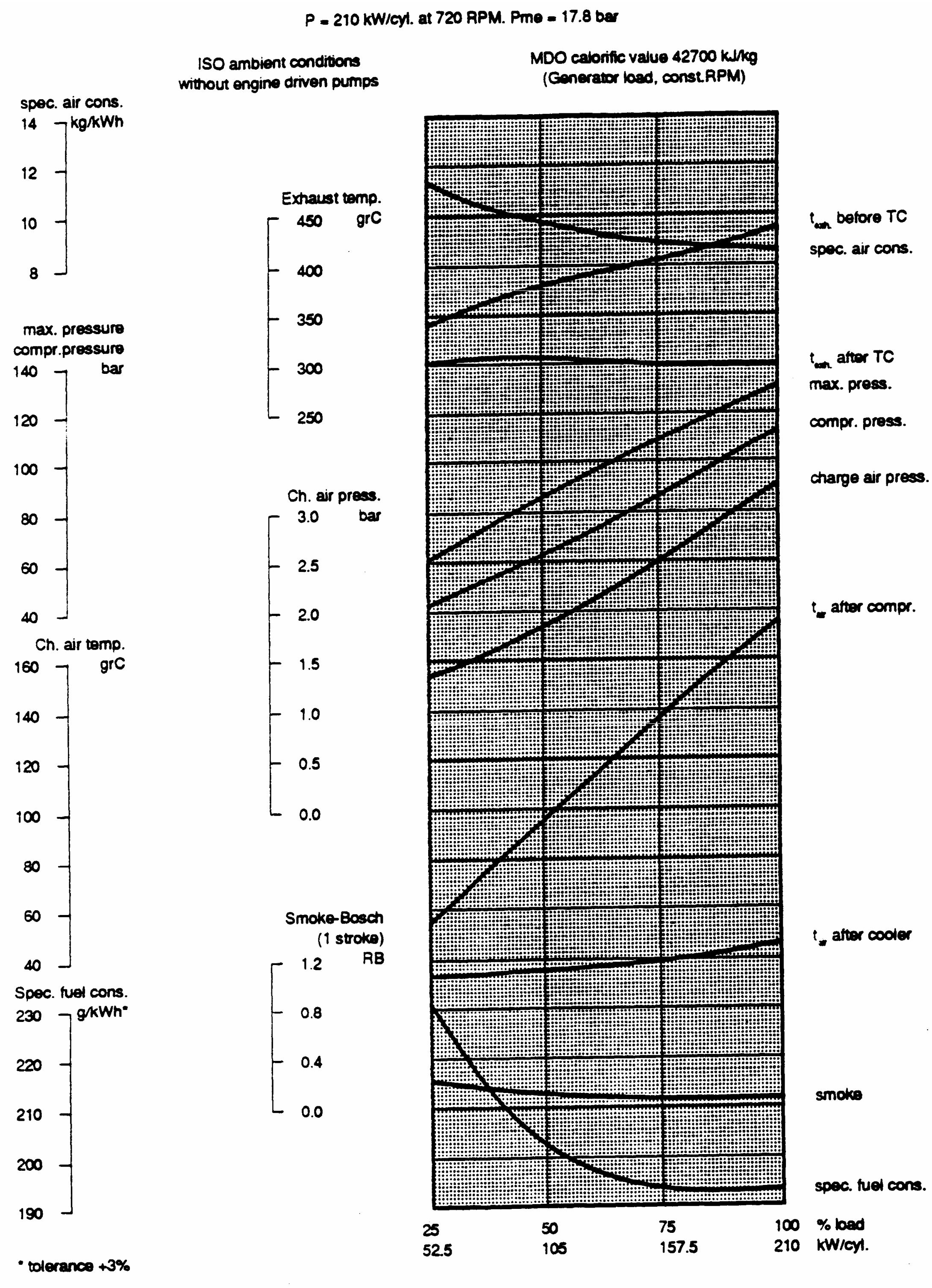


Figure: Performance curve of reciprocating internal combustion engine

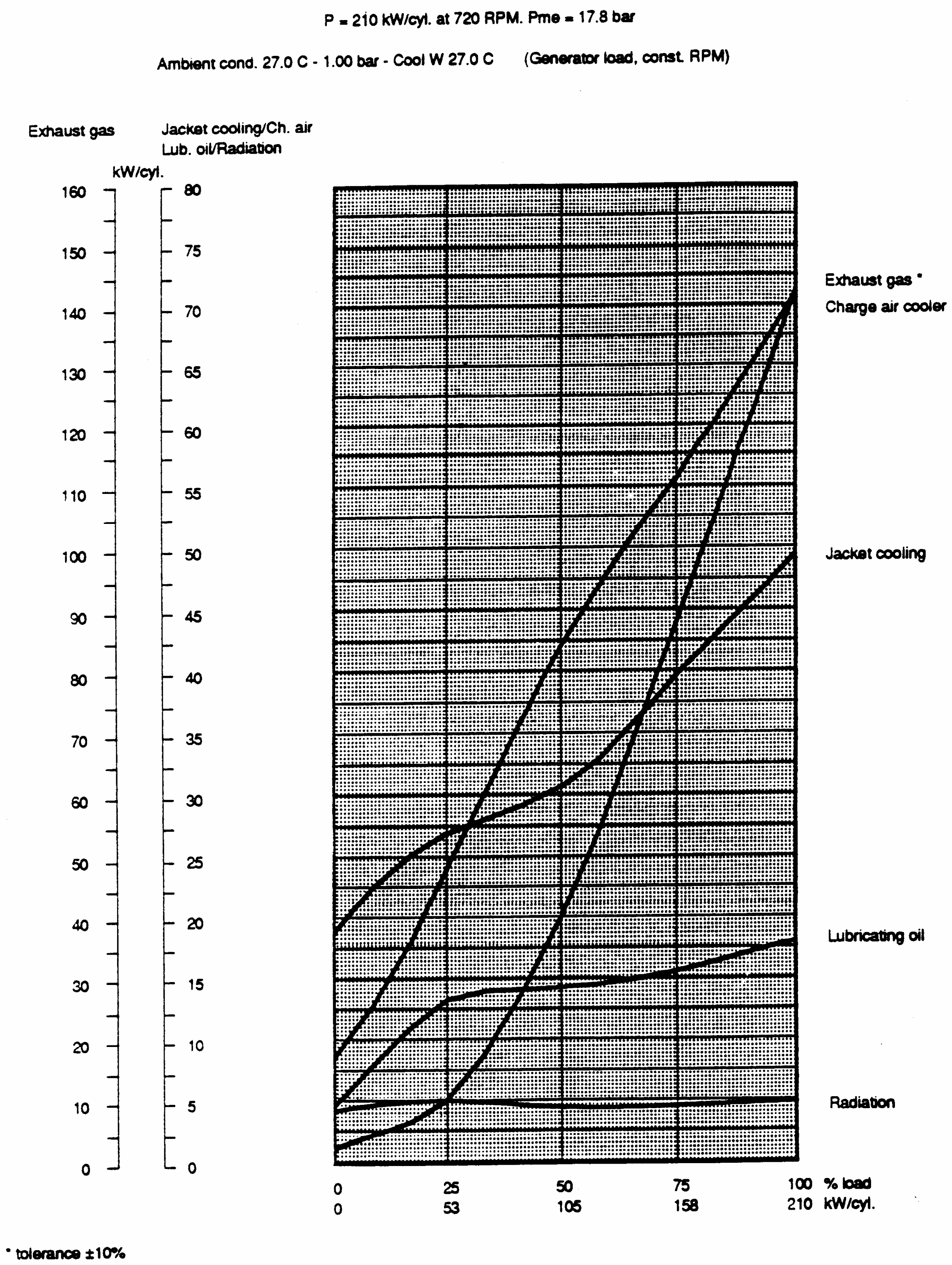


Figure: Heat balance of reciprocating internal combustion engine

1.7 Combined Cycle Cogeneration Systems

The term “combined cycle” is used for systems consisting of two thermodynamic cycles, which are connected with a working fluid and operate at different temperature levels. The high temperature cycle (topping cycle) rejects heat, which is recovered and used by the low temperature cycle (bottoming cycle) to produce additional electrical (or mechanical) energy, thus increasing the electrical efficiency.

Combined Joule – Rankine Cycle Systems

The most widely used combined cycle systems are those of gas turbine – steam turbine (combined Joule – Rankine cycle). They so much outnumber other combined cycles that the term “combined cycle”, if nothing else is specified, means combined Joule – Rankine cycle. Double- or triple-pressure steam boilers enhance the heat recovery and increase the efficiency, but make the system more complex; they are used in large systems.

The steam turbine is a backpressure one. Of course this is not the only configuration. Condensing turbine is also possible, while extraction can also be used with either the backpressure or the condensing turbine.

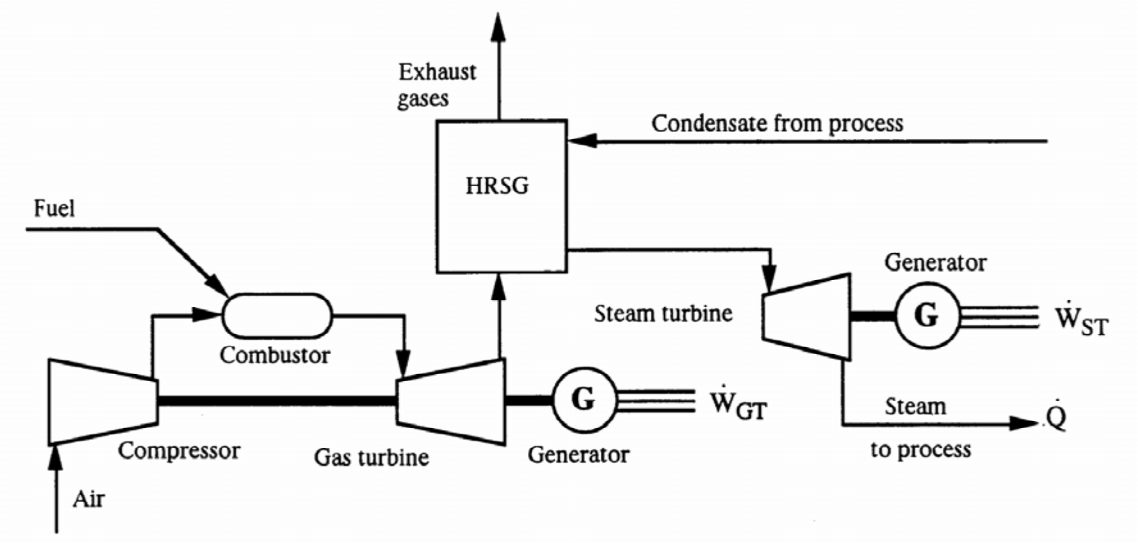


Figure: Joule-Rankine combined cycle cogeneration system with back pressure steam turbine

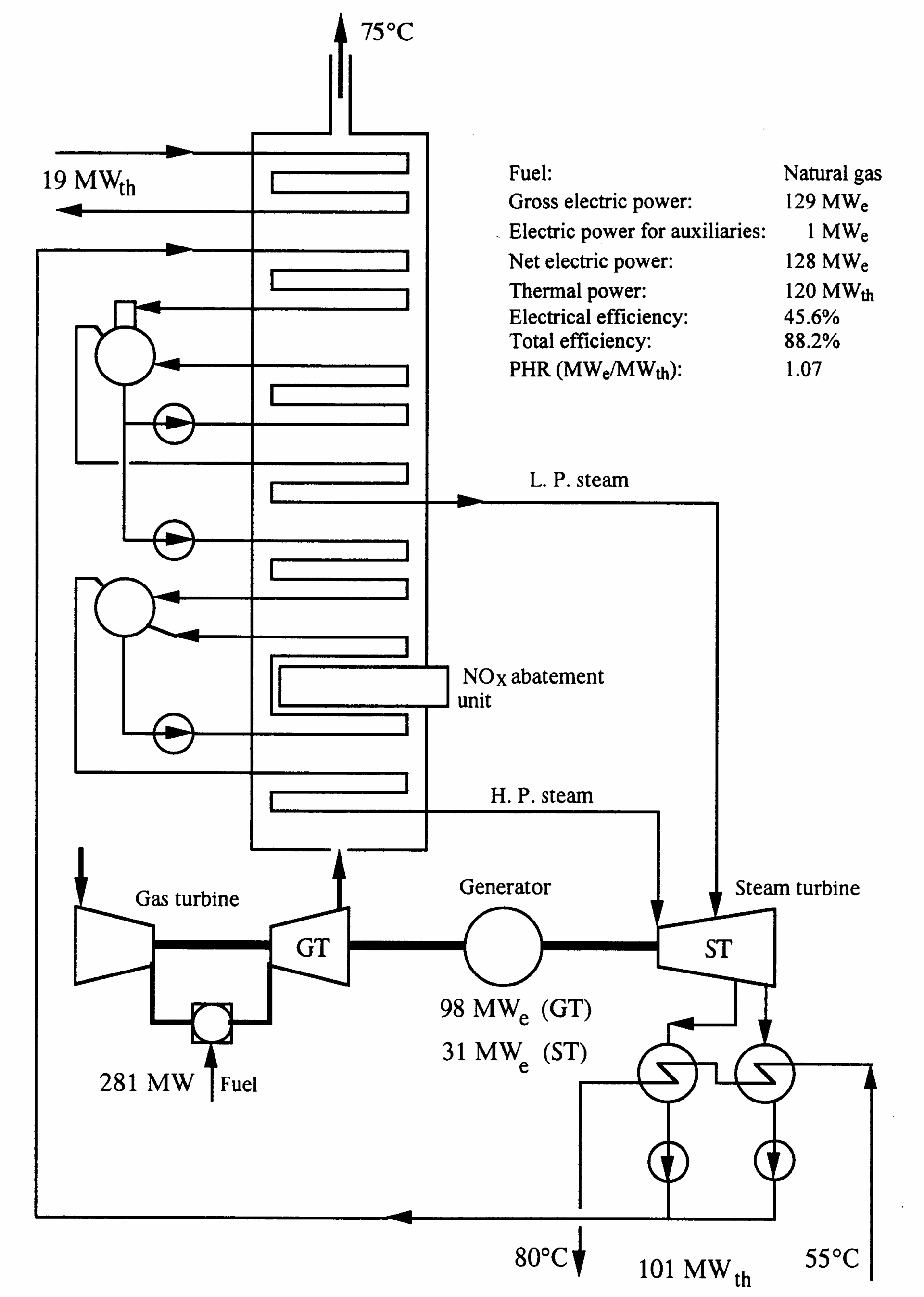


Figure: ASEA STAL combined cycle system with extraction / condensing steam turbine

The maximum possible steam temperature with no supplementary firing is by 25-40°C lower than the exhaust gas temperature at the exit of the gas turbine, while the steam pressure can reach 80 bar. If higher temperature and pressure is required, then an exhaust gas boiler with burner(s) is used for firing supplementary fuel. Usually there is no need of supplementary air, because the exhaust gases contain oxygen at a concentration of 15–16%. With supplementary firing, steam temperature can approach 540°C and pressure can exceed 100 bar. Supplementary firing not only increases the capacity of the system but also improves its partial load efficiency.

Initially, combined cycle systems were constructed with medium and high power output (20–400 MW). During the last years, also smaller systems (4–15 MW) have started being constructed, while there is a tendency to further decrease the power limit. The power concentration (i.e. power per unit volume) of the combined cycle systems is higher than the one of the simple gas turbine (Joule) or steam turbine (Rankine) cycle. Regarding the fuels used, those mentioned for gas turbines are valid also here.

The installation time is 2–3 years. It is important to note that the installation can be completed in two phases: the gas turbine subsystem is installed first, which can be ready for operation in 12–18 months. While this is in operation, the steam subsystem is installed.

The reliability of (Joule – Rankine) combined cycle systems is 80–85%, the annual average availability is 77–85% and the economic life cycle is 15–25 years.

The electric efficiency is in the range 35–45%, the total efficiency is 70-88% and the power to heat ratio is 0.6–2.0. The electric efficiency can be increased further; in fact, contemporary combined cycle systems producing electric power only (no heat to process) can have efficiencies approaching 60%. However, these systems do not qualify as cogeneration systems.

Combined Diesel – Rankine Cycle Systems

It is also possible to combine Diesel cycle with Rankine cycle. The arrangement is similar the difference that the gas turbine unit (compressor – combustor – gas turbine) is replaced by a Diesel engine. Medium to high power engines may make the addition of the Rankine cycle economically feasible.

Supplementary firing in the exhaust gas boiler is also possible. Since the oxygen content in the exhaust gases of a Diesel engine is low, supply of additional air for the combustor in the boiler is necessary.

1.8 Fuel Cell Cogeneration Systems

A fuel cell is an electrochemical device, which converts the chemical energy of fuel into electricity directly, without intermediate stages of combustion and production of mechanical work.

The direct conversion of chemical energy of a fuel to electrical energy by a hydrogen-oxygen fuel cell was achieved for the first time in 1839 by Sir William Grove, in London. Since that time, the development of fuel cells has been one of the most difficult technological problems. Systematic research during the last 30–40 years has been fruitful and several pilot plants have been built and operated successfully. Certain types of fuel cells are available, although at high cost. Fuel cells are still considered as an emerging technology and very promising both for electricity generation and for cogeneration. Since it is not widely known yet, it is useful to present the basic principle here in brief.

Basic Operation Principle of Fuel Cells

In its basic form a fuel cell operates as follows: hydrogen reacts with oxygen in the presence of an electrolyte and produces water, while at the same time an electrochemical potential is developed, which causes the flow of an electric current in the external circuit (load). The following electrochemical reactions take place on the two electrodes:

Anode: $$H_2 \rightarrow 2H^+ + 2e^- \tag{3.1}$$

Cathode: $$2H^+ + \frac{1}{2}O_2 + 2e^- \rightarrow H_2O \tag{3.2}$$

Thus, the total reaction is: $$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{3.3}$$

At the anode, ions and free electrons are produced. Ions move towards the cathode through the electrolyte. Electrons move towards the cathode through the external circuit, which includes the load (external resistance). The reaction is exothermic. The released heat can be used in thermal processes.

The required hydrogen is usually produced from hydrocarbons, most frequently natural gas, by a process known as *reforming*, which can be either external or internal to the fuel cell unit, depending on the type of the fuel cell. Also, it can be produced by electrolysis of water. In certain types of fuel cells, carbon monoxide can be used as fuel, instead of hydrogen.

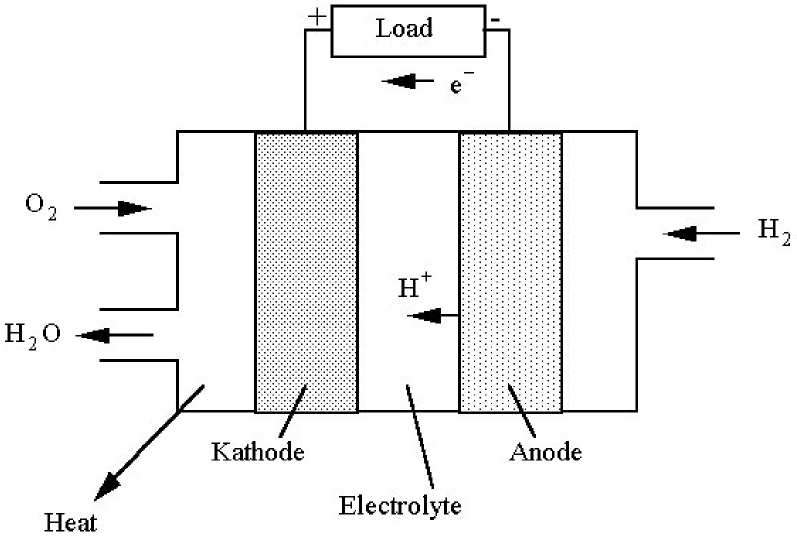


Figure: Basic principle of a hydrogen – oxygen fuel cell

A single cell develops an electric voltage slightly lower than 1 Volt. The proper number of cells connected in series produce the required voltage, while with parallel connection the required power is produced. Thus, a stack of cells is created. A direct current is produced; a (usually static) inverter is used to transform the direct current to alternating current of the appropriate voltage and frequency.

1.9 Types of Fuel Cells

Several classifications of fuel cells have appeared in the literature throughout the years. The most prevailing one is based on the type of the electrolyte.

Alkaline fuel cells (AFC)

Potassium hydroxide (KOH), which is the most conducting of all alkaline hydroxides, is the electrolyte, at a concentration around 30%. Pure hydrogen is the fuel and pure oxygen or air is the oxidiser. Alkaline fuel cells operate at a temperature 60-80°C. This is why they are characterised as low temperature fuel cells. The operating pressure in some cases is a few atmospheres, but most often it has been the atmospheric pressure.

Alkaline fuel cells have been used in NASA’s Apollo mission. Today they are still used in space applications. Also they are one of the most attractive systems for transportation applications. Units with a power up to 100 kW have been constructed.

Polymer electrolyte fuel cells (PEFC)

They are also known with the initials PEM (Polymer Electrolyte Membranes). The electrolyte consists of a solid polymeric membrane, which is sandwiched between two platinum-catalysed porous electrodes. The operating temperature is around 80ºC and the operating pressure 1-8 atm. PEFC units with a power output up to 100 kW have been constructed.

Phosphoric acid fuel cells (PAFC)

PAFC is at the moment the most advanced fuel cell technology for terrestrial applications. Packaged units of 200-250 kW_e are already commercially available for electricity generation or cogeneration, while demonstration systems of 25 kW–11 MW have been constructed in Europe, USA and Japan.

Phosphoric acid (H_3PO_4) is the electrolyte. Hydrogen is produced by an external reformer from fuels such as natural gas or methanol. Air is the oxidiser. The operating temperature is around 200ºC, which makes PEFC’s attractive for cogeneration applications, in particular in the tertiary sector.

Molten carbonate fuel cells (MCFC)

Molten alkali carbonate mixture, retained in a porous lithium aluminate matrix, is used as the electrolyte. The eutectic mixture consists of 68% Li_2CO_3 and 32% K_2CO_3, which at the operating temperature of 600-700ºC is at liquid phase. The fuel consists of a gaseous mixture of H_2, CO and CO_2, which is obtained with reforming of hydrocarbons such as natural gas, or with coal gasification. The high operating temperature makes internal reforming possible. For this purpose, the heat released by the fuel cell itself is used. The following reactions occur:

Anode:
$$H_2 + CO_3^{--} \rightarrow H_2O + CO_2 + 2e^- \tag{3.4}$$

$$CO + CO_3^{--} \rightarrow 2CO_2 + 2e^- \tag{3.5}$$

Cathode:
$$CO_2 + \frac{1}{2}O_2 + 2e^- \rightarrow CO_3^{--} \tag{3.6}$$

Total reaction:
$$H_2 + CO + O_2 \rightarrow H_2O + CO_2 \tag{3.7}$$

Carbonate ions are transferred through the electrolyte. In order to sustain the flow of ions, carbon dioxide is supplied continuously with air at a molar fraction of O_2/CO_2 equal to ½. This need increases the complexity of the system and the processes. However, there is no need of an external reformer: when, for example, natural gas is the fuel, catalysts are inserted in the pipes supplying the gas, which reform the preheated (with heat released by the system) fuel.

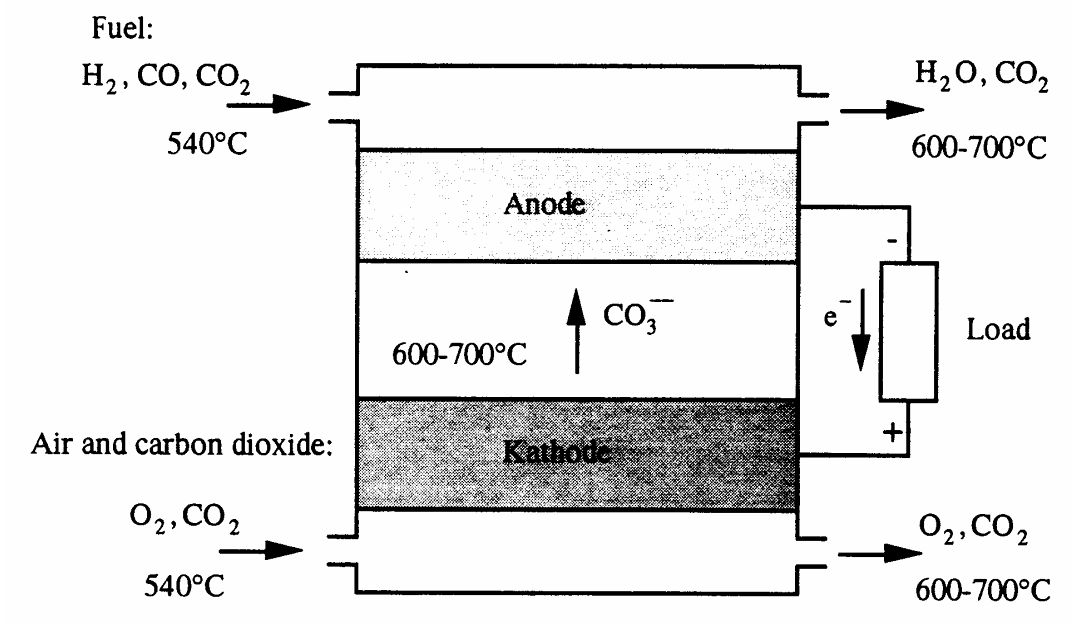


Figure : Basic principle of a molten carbonate fuel cell

MCFC's have good prospects for utility and industrial applications of medium to large size (at the order of MW). Efficiencies higher than 50% are expected. The high temperature available heat can be used either for thermal processes (cogeneration) or in a bottoming cycle for additional power production. Experimental units have been constructed, but the MCFC technology is still at the development phase.

Solid oxide fuel cells (SOFC)

The solid oxide fuel cell is an all-solid-state power system, which uses yttria-stabilised zirconia (Y_2O_3-ZrO_2), a ceramic material, as the electrolyte layer. It operates at temperatures of 950-1000 ºC. Pure hydrogen or a mixture of H_2 and CO is used as fuel, which is produced with internal reforming of hydrocarbons or with coal gasification.

In the case of SOFC, CO_2 does not re-circulate from the anode to the cathode.

SOFC's also have good prospects for utility and industrial applications of medium to large size (at the order of MW) with efficiencies higher than 50%. The system provides high quality waste heat, which is ideal for cogeneration or for additional power production by a bottoming cycle. It is envisaged that units at the order of tens of megawatts can be combined with a gas turbine – steam turbine combined cycle: hot gases exiting the cell stack will drive a gas turbine. After the exit from the gas turbine they will pass through an exhaust gas boiler producing steam for thermal processes or for additional power production by a steam turbine.

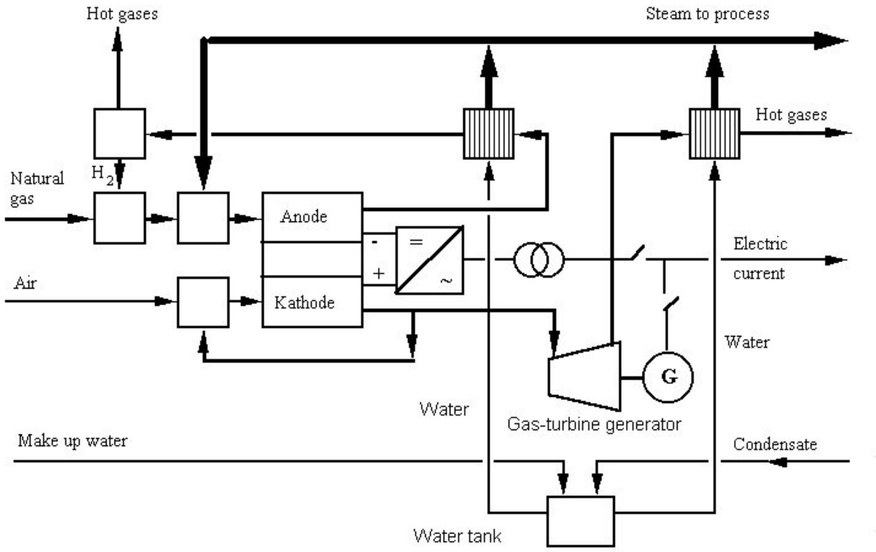


Figure: Cogeneration system with solid oxide fuel cell for applications in the tertiary sector

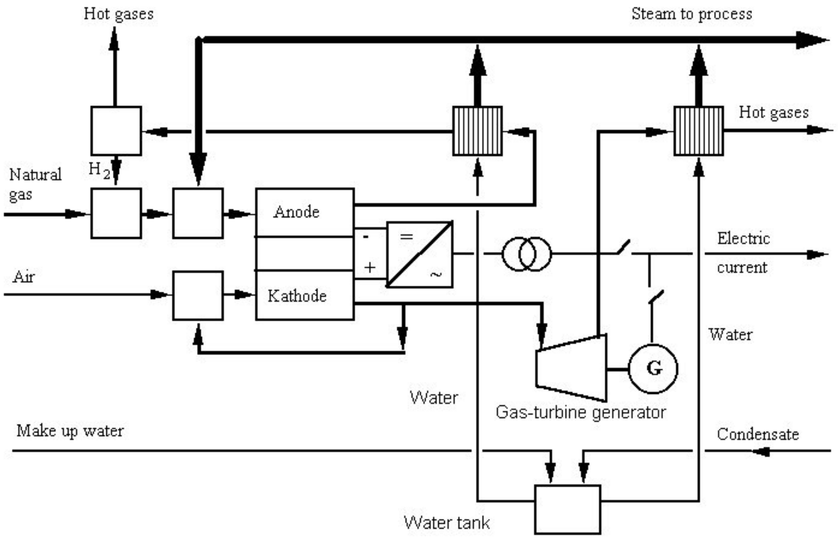


Figure: Cogeneration system with solid oxide fuel cell for applications in the industrial sector.

Thermodynamic Performance of Fuel Cells

The efficiency of power plants operating on a thermodynamic cycle has an upper limit, which is equal to the Carnot efficiency. For example, this limit for a Rankine cycle operating with maximum steam temperature of 540°C at an environment with temperature 25°C is 63.3%. Fuel cells convert the chemical energy of the fuel to electricity directly, with no intervention of a power cycle. Consequently, Carnot efficiency is not applicable for fuel cells and their efficiency theoretically can reach 100%.

In practice, several losses in the various components of a fuel cell system, which consists of the fuel reformer, the cell stack, the inverter and the auxiliary equipment, result in efficiencies much lower than 100%. Thus, the electric efficiency of phosphoric acid fuel cell units, which are commercially available, is in the range of 37-45%, and it depends on the quality of fuel and the operating temperature. At a 50% load, the efficiency is equal to and sometimes higher than the efficiency of full load. The total efficiency of a cogeneration system reaches 85-90%, while the power to heat ratio is in the range 0.8-1.0.

As the technology develops further, and in particular for the molten carbonate and solid oxide fuel cells, electric efficiencies higher than 50% are expected. Integrated with gas- and steam-turbine combined cycles, systems based on molten carbonate fuel cells are expected to have electric efficiency of 55-60%, while for systems based on solid oxide fuel cells the expected electric efficiency is 60-65%.

Fuel Cell Perspective

The great promise of fuel cells as a mean of efficient production of electric energy from the oxidation of fuel was recognised nearly from the beginning. Their main advantages are the following:

- High efficiency, which remains high and fairly constant over a wide range of load conditions.
- Modular construction, which makes it easy to build units with the desired power output.
- Low emission level.
- Very low noise level, since there are no major rotating equipment.

The very low emission and noise level make the fuel cell units particularly appropriate for applications in the residential and tertiary sector (house, office buildings, hospitals, hotels, etc.). The main drawbacks are their high capital cost and the relatively short lifetime. Research and development to solve certain technological problems is continued. On the other hand, the use of less expensive material and mass production is expected to decrease the capital cost.

1.9 Stirling Engine Cogeneration Systems

Cogeneration is also possible with Stirling engines. This technology is not fully developed yet and there is no wide-spread application, but there is an increasing interest because of certain advantages: prospect of high efficiency, good performance at partial load, fuel flexibility, low emission level, low vibration and noise level.

Perhaps the technology is not widely known, therefore it is helpful to present the basic principle first.

Basic Principle of Stirling Engines

A patent for the first Stirling engine was granted to Robert Stirling, a Scottish minister, in 1816. It was one of the most amazing inventions of its kind, being well in advance of all pertinent scientific knowledge of its time. In this respect, it is worth recalling that Sadi Carnot published his *“Reflections on the motive power of fire”* in 1824, while Joule established the mechanical equivalent of heat, and thus laid the foundations for the First Law of Thermodynamics, in 1849.

The ideal Stirling cycle, which is reversible. The positions of the pistons are shown at the four extreme state points of the cycle as seen in the pressure-volume and temperature-entropy diagrams. Process 1-2 is an isothermal compression process, during which the heat is removed from the engine at the cold sink temperature. Process 3-4 is an isothermal expansion process, during which heat is added to the engine at the hot source temperature. Processes 2-3 and 4-1 are constant-volume displacement processes, in which the working gas (usually air, helium or air) is passed through the regenerator. During the process 4-1 the gas gives its heat up to the regenerator matrix, to be recovered subsequently during the process 2-3. The regenerator substantially improves the efficiency of the cycle. It comprises a matrix of fine wires, porous metal, or sometimes simply the metal wall surfaces enclosing an annular gap.

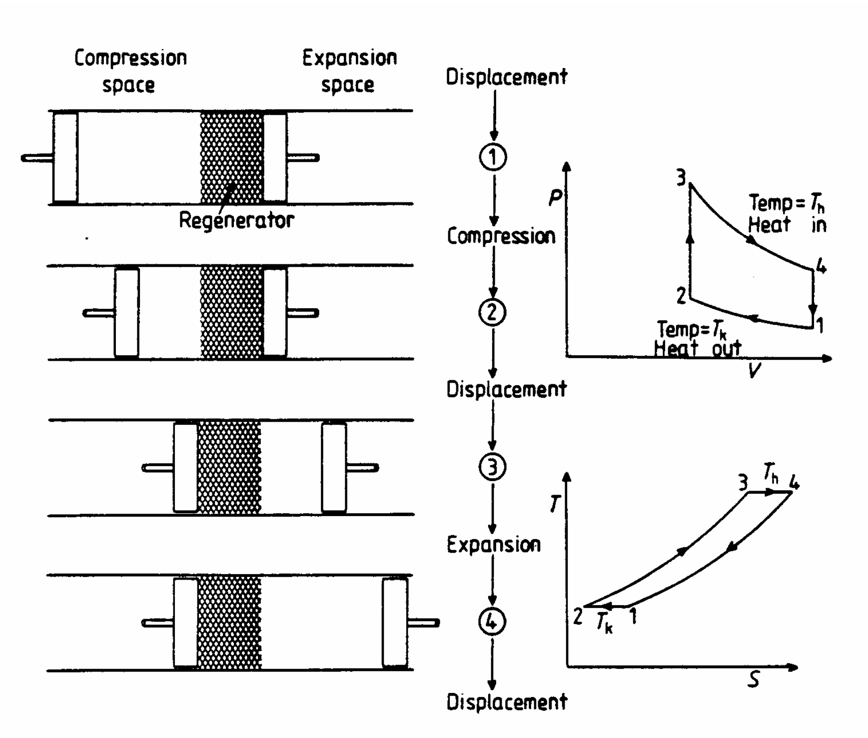


Figure: The ideal Stirling cycle (Urieli and Berchowitz 1984)

The external combustion allows for use a variety of fuels: liquid or gaseous fuels, coal, products of coal liquefaction or gasification, biomass, urban wastes, etc. It is possible to change fuels during operation, with no need to stop or make adjustments on the engine. Nuclear or solar energy may also be the source of heat.

Stirling Engine Configurations

The configurations of Stirling engines are generally divided into three groups, known as Alpha, Beta and Gamma arrangements. Alpha engines have two pistons in separate cylinders, which are connected in series by a heater, regenerator and cooler. Both Beta and Gamma engines use displacer-piston arrangements, the Beta engine having both the displacer and the piston in the same cylinder, whilst the Gamma engine uses separate

Drive methods may be broadly divided into two groups: the cinematic and the free-piston drives. Cinematic drives may be defined as a series of mechanical elements such as cranks, connecting rods and flywheels, which move together so as to vary the working spaces in a prescribed manner. They are considered as the conventional design. On the other hand, free-piston drives use the working gas pressure variations to move the reciprocating elements, work being removed by a device such as a linear alternator.

Alpha configurations have been mainly pursued for automotive applications. Their main advantage is the simple way in which it can be compounded in compact multi-cylinder configurations, enabling an extremely high specific power output.

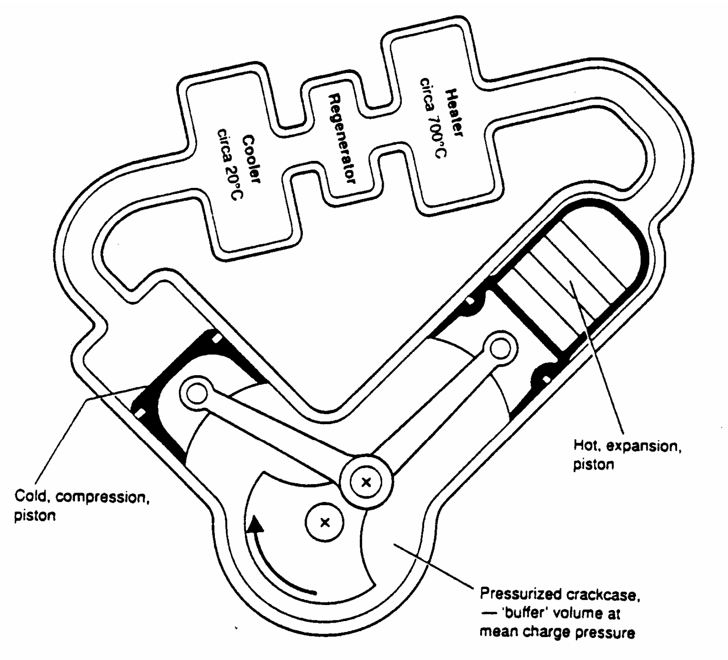


Figure: Alpha-type Stirling engine

Beta configuration is the classic Stirling engine configuration and it is the original Stirling's engine arrangement. The free-piston engines invented and developed by William Beale at Ohio University in the late 1960's are of the Beta type [Lane and Beale, 1996].

Gamma engines tend to have somewhat larger dead (or unswept) volumes than either the Alpha or Beta engines. This often leads to a reduction in specific power. Therefore, they are used when the advantages of having separate cylinders outweigh the power disadvantage.

Developments in Stirling Engine Technology

Initially, research and development was aiming at car engines of power 3-100 kW. Then, the effort was reoriented towards engines of power 1-1.5 MW with an expected lifetime of 20 years. Since the technology is still at the development phase, there are no statistical data for reliability and availability, but it is expected that they will be comparable to those of Diesel engines. The working gas operates on a closed path and it does not participate in the combustion. Thus, the moving parts of the engine are not exposed to combustion products; as a result, their wear is reduced as compared to an internal combustion engine. However, special sealings are needed to avoid leakage of the high pressure working gas and its loss to the environment, as well as passing of the lubricating oil from the crankcase to the internal side of the cylinder. One of technical difficulties encountered up to now is the construction of effective sealings with long lifetime.

The free-piston engine mentioned above has evolved as a solution to the sealing problems. The free piston with an attached linear alternator can be hermetically sealed so as to contain the working gas for extended periods and the working gas itself serves as lubricant. The piston performs an harmonic oscillation, which causes the compression-expansion of the gas, while a displacer serves to move the gas between hot and cold heat exchangers. At present, the power of these engines is restricted to several tens of kilowatts. Their characteristics are well suited for micro-cogeneration applications.

Performance of Stirling Engine Cogeneration Systems

The Stirling cycle has the capability of efficiencies higher than those of the Rankine or Joule cycles, because it more closely approaches the Carnot cycle. Currently, the electric efficiency is at the order of 40%, and an increase to the level of 50% is expected. In particular, the free-piston engines for micro-cogeneration have electric efficiencies of 30-35%. The total efficiency of Stirling engine cogeneration systems is in the range of 65-85% and the power to heat ratio is 1.2-1.7.

Properly designed Stirling engines have two power pulses per revolution; in addition, the combustion is continuous. These features make them running very smoothly, with vibration level lower than that of reciprocating internal combustion engines. The continuous combustion results also in lower emissions and noise level.

Table: Technical characteristics of cogeneration systems

System	Electric power	Annual average availability	Electric efficiency %		Total efficiency	Power to heat ratio
	MW	%	Load 100%	Load 50%	%	—
Steam turbine	0.5-100*	90-95	14-35	12-28	60-85	0.1-0.5
Open cycle gas turbine	0.1-100	90-95	25-40	18-30	60-80	0.5-0.8
Closed cycle gas turbine	0.5-100	90-95	30-35	30-35	60-80	0.5-0.8
Joule-Rankine combined cycle	4-100*	77-85	35-45	25-35	70-88	0.6-2.0
Diesel engine	0.07-50	80-90	35-45	32-40	60-85	0.8-2.4
Reciprocating internal combustion engine package	0.015-2	80-85	27-40	25-35	60-80	0.5-0.7
Fuel cells	0.04-50	90-92	37-45	37-45	85-90	0.8-1.0
Stirling engines	0.003-1.5	85-90 (expected)	35-50	34-49	60-80	1.2-1.7

* The value 100 MW is a usual upper limit for industrial applications. Systems of this type can have higher capacities too.

Reference:

www.cogen.org