FLOWSERVE

DECEMBER 2019

Application Solutions Guide

THE GLOBAL COMBINED CYCLE LANDSCAPE

Experience In Motion

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THE GLOBAL COMBINED CYCLE LANDSCAPE

The current era of combined cycle power generation began with the introduction of the third generation GE F-Class gas turbine in 1990. This was the first gas turbine to be specifically engineered to optimize performance in a combined cycle configuration. Since then the industry has grown steadily, and plants have become larger and more efficient.

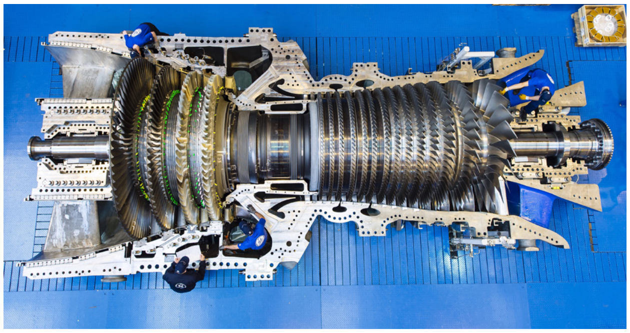
The gross thermal efficiency of the latest fourth generation H-Class combined cycle power plants is greater than 61% (based on the Lower Heating Value of the fuel) as compared to ultra-supercritical (USC) conventional steam power plants, with thermal efficiencies of only 47%. The USC plant takes 40 to 50 months to build, but a combined cycle plant can be built in 20 to 30 months. Thus, combined cycle plants can begin generating a return on investment two years earlier than a conventional steam plant of similar rating.

For all these reasons, conventional steam generation technology has been almost completely supplanted by combined cycle technology for gas-fired power generation applications. Integrated Gasification Combined Cycle (IGCC) plants, which convert coal or heavy oil to gas that can be used in a combined cycle plant, are already in operation and will eventually become competitive with conventional supercritical coal-fired plants. Combined cycle plants can also be integrated with Concentrated Solar Power (CSP) plants, significantly reducing the cost of the renewable energy generated by the CSP plant.

At the same time, gas-fired generation is increasingly being favored over coal because of its lower environmental impact. An ultra-supercritical coal fired plant emits more than 750 grams of CO_2 per kilowatt-hour generated, while a gas-fired combined cycle plant emits only 360 g/kWh. Pipeline natural gas has very low sulfur content; combined cycle plants do not require costly SOx scrubbing systems, which are needed in a coal-fired plant.

A Closer Look at Combined Cycle Power Technology

Basics



A gas turbine (GT) is a thermodynamic turbomachine based on the open Brayton Cycle where air is compressed in the gas turbine's compressor section, heated by the addition and combustion of a liquid or gaseous fuel in the combustion section, then expanded through the power turbine section to produce useful work. A Simple Cycle Gas Turbine (SCGT) power plant consists of a gas turbine driving an electric generator.

The relatively low thermal efficiency of a simple cycle gas turbine can be greatly increased by recovering the energy in its hot exhaust gases with a conventional steam/water Rankine Cycle. The hot exhaust gases are used to generate steam in a Heat Recovery Steam Generator (HRSG). The steam produced is expanded in a steam turbine, which provides additional power to drive the electrical generator before being condensed in the condenser. The condensate is pumped back to the feedwater tank to complete the closed cycle.

Because the operating temperatures in the gas turbine Brayton Cycle are much higher than in the water/steam Rankine Cycle, the former is referred to as the *topping cycle* and the latter as the *bottoming cycle*. Power plants based on the combined Brayton and Rankine Cycles are called Combined Cycle Gas Turbine (CCGT) power plants. Other acronyms used are GTCC and CCPP (Combined Cycle Power Plant).

In a CCGT plant, the gas turbine typically provides two-thirds of the total unit power output and the steam turbine provides the other one-third. The CCGT arrangement increases the overall thermal efficiency of the power plant from about 37% to 57–61%. This results in a dramatic reduction in fuel costs and emissions for a given power rating.

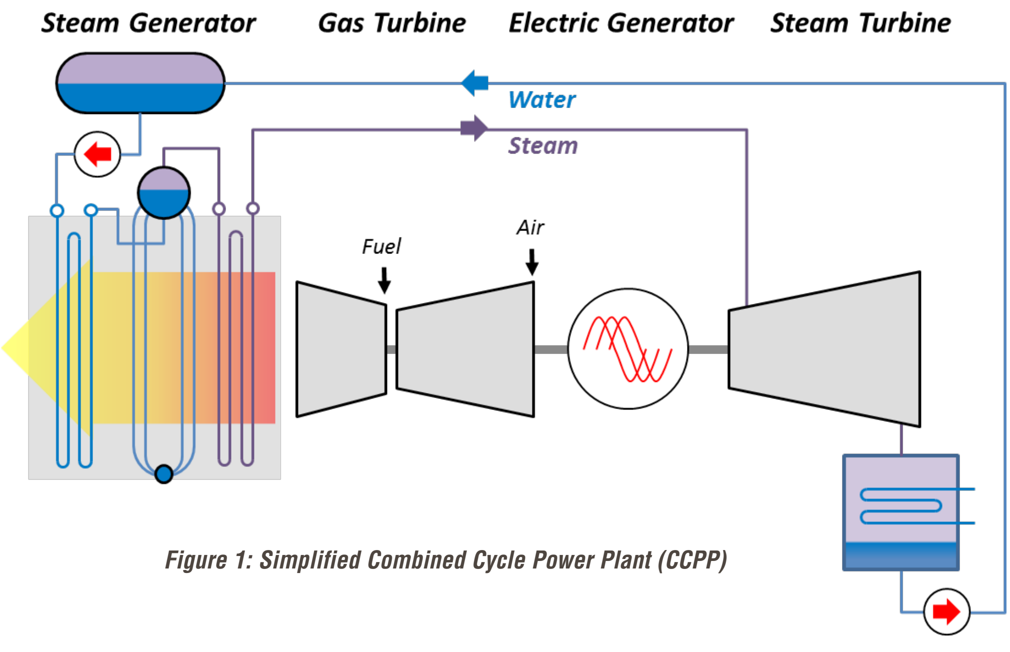


Figure 1: Simplified Combined Cycle Power Plant (CCPP)

Plant Configurations

The simplified CCGT plant depicted in Figure 1 has the steam turbine and gas turbine connected to the same electrical generator; this is called a *single-shaft configuration*. In a multi-shaft configuration, the gas turbine and steam turbine drive separate generators. Single-shaft units are generally less complex, less costly and have a smaller footprint, but multi-shaft units provide more flexibility in design and handle load variations more easily.

The single-shaft plant depicted in Figure 1 is called a *1x1x1 configuration* with one gas turbine, one HRSG and one steam turbine. Multi-shaft plants allow for other configurations such as 2x2x1 and 3x3x1. A 2x2x1 plant has two gas turbine/electrical generator sets, each with a dedicated HRSG, feeding steam to a single-steam turbine generator and condenser set. A 2x2x1 unit requires fewer auxiliaries (pumps, valves, etc.) than two (2) 1x1x1 units for a given power rating.

The simple CCGT plant illustrated in Figure 1 uses a single-pressure system, where steam is generated at only one pressure. State-of-the-art CCGT plants generate steam at three different pressures to feed low-, intermediate- and high-pressure sections of the steam turbine. This ensures that heat transfer between the steam/water and exhaust gas streams takes place at the lowest possible temperature difference as they pass in opposite directions through the HRSG, thus minimizing exergetic losses and maximizing efficiency. Reheat, wherein the exhaust steam from the high-pressure turbine is returned to the HRSG to be reheated before passing to the intermediate turbine, also improves plant efficiency.

Plant Sizes

Plant ratings are determined by available gas turbine sizes and, as already noted, gas turbines have been getting larger over the years. GE's first F-Class 1x1x1 installation in 1990 was rated at 214 MW in combined cycle; its latest GT-9H.02 turbines can generate 701 MW in the same configuration.

Siemens and MHI have also developed H-Class turbines of similar size to GE.

The turbines listed here are all industrial gas turbines developed specifically for land-based industrial applications. In addition, aero engine manufacturers have adapted their aircraft gas turbines for industrial applications in simple and combined cycle formats. These aeroderivative offerings are generally well less than 100 MW in combined cycle, though GE has recently introduced a package rated at 135 MW. Aeroderivative turbines account for less than 12% of globally installed gas turbines based on electrical generating capacity, but still present an opportunity for Flowserve. The main aeroderivative manufacturers are GE, Pratt & Whitney, and Rolls Royce.

GE, Siemens and MHI have localized gas turbine manufacturing of smaller earlier generation F-Class turbines in China, so the China domestic market is generally limited to smaller combined cycle blocks as follows:

- GE (Harbin Electric): 390 MW
- Siemens (Shanghai): 114, 266 and 456 MW
- MHI (Dongfang Electric): 270 and 397 MW

Of course, Chinese EPC's are involved in many international projects, which may be based on the latest gas turbine technology.

Lastly, it should be noted that supplementary firing or duct burning is frequently used to increase the power output of combined cycle plants. This involves burning natural gas directly after the gas turbine at the inlet to the HRSG. This is generally less efficient than burning the natural gas in the gas turbine, but provides added flexibility and is particularly useful in combined heat and power applications, which are discussed next.

Cogeneration and Combined Heat and Power (CHP)

Cogeneration is a term that is often confused with *Combined Cycle*, and the two are sometimes incorrectly used interchangeably. *Cogeneration* means the simultaneous production of electrical and thermal energy in the same power plant. Cogeneration can be implemented in any type of thermal power plant, including fossil and biomass conventional steam plants, geothermal plants, as well as in simple cycle or combined cycle gas turbine power plants. Cogeneration plants are also referred to as Combined Heat and Power plants (CHP).

The plant illustrated in Figure 2 is a combined cycle unit with cogeneration. Steam is extracted from intermediate points in the steam turbine to heat water for use in a district heating system providing heating to residential or commercial buildings. Other configurations include the use of the extraction steam directly in the district heating system. In some cases, the steam turbine is a back pressure non-condensing design where the turbine exhaust pressure is matched to the requirements of the heating system. Such a configuration has no condenser.

The heat may also be used in industrial process applications. Typically, all of the power and heat generated in these captive plants is used by the process facility.

Finally, a cogeneration plant may have an HRSG coupled to a simple cycle gas turbine generator without a steam turbine. In fact, such plants represent an intermediate step in the transition from simple cycle gas turbine power generation to combined cycle power generation and is the main reason why the meanings of *cogeneration* and *combined cycle* are sometimes confused.

While the extraction of steam from the steam turbine for heating reduces the amount of electricity that can be generated by the steam turbine, the overall fuel utilization (the percentage of energy in the fuel that is usefully used) is greatly increased. Fuel utilization in a CHP plant can be as high as 90%.

CHP plants provide additional pump and valve opportunities, especially for general service valves and industrial pump products.

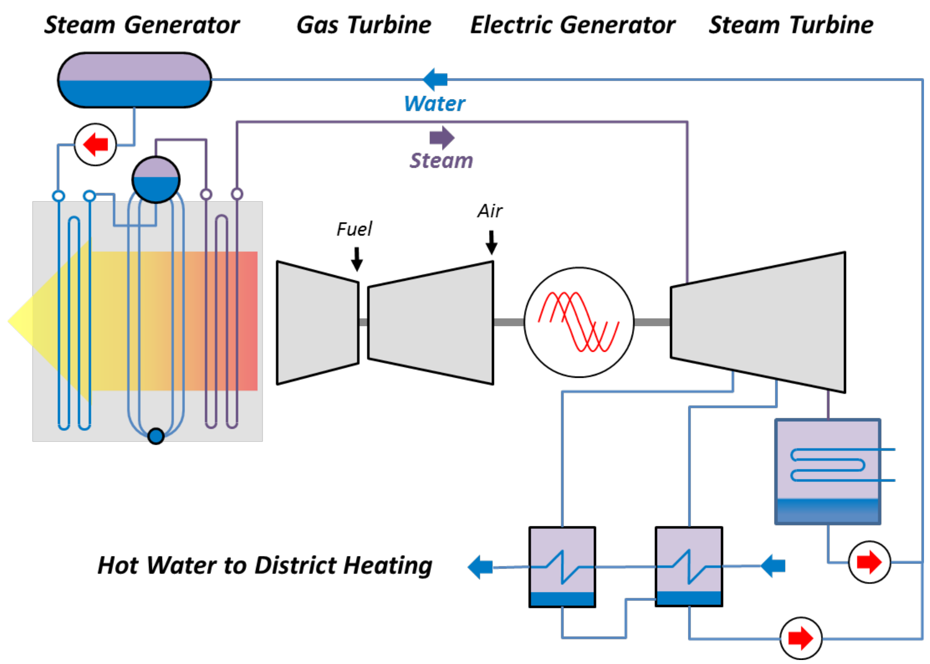


Figure 2: Simplified CCGT combined heat and power plant

Integrated Gasification Combined Cycle (IGCC)

Integrated Gasification Combined Cycle technology opens the way for the use of dirty liquid and solid fuels such as coal, refinery residue, biomass and wastes. This is accomplished by adding gasification, air separation and gas cleaning processes upstream of the CCGT plant.

Energy is consumed in the gasification of the coal, and the overall thermal efficiency of current IGCC plants is between 39 and 44%, while a USC plant is 47%.

This technology will become more important in the coming years as the cost per kW is reduced and present additional opportunities for Flowserve. Flowserve is currently participating in a major IGCC project called "Jazan" in Saudi Arabia.

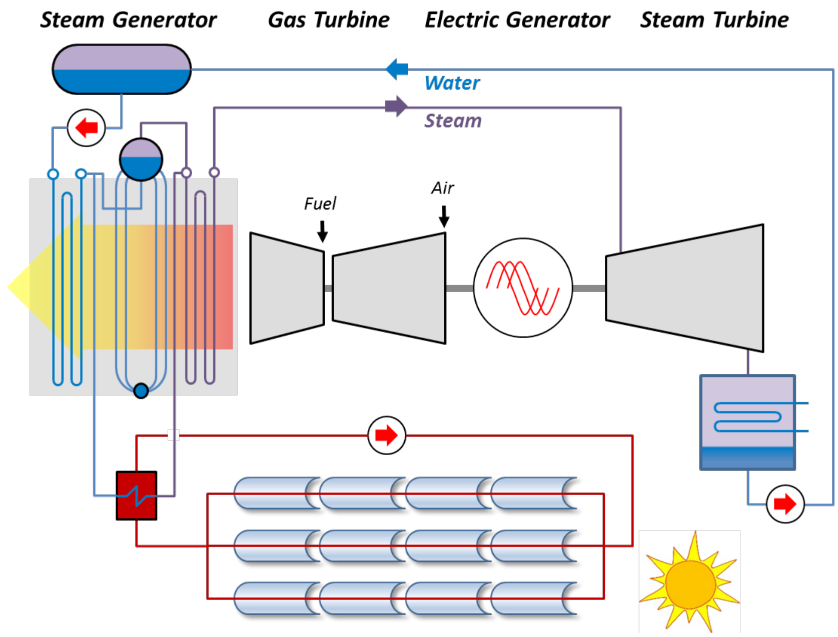
Integrated Solar Combined Cycle (ISCC)

Another developing application of combined cycle power involves its integration with a thermal concentrated solar power (CSP) plant.

There are several ways in which CCGT and CSP plants can be integrated, but Figure 4 shows a highly simplified illustration of perhaps the most common configuration. Heat transfer fluid (HTF) is circulated through the solar field and passed through a heat exchanger to generate saturated steam. The feedwater for this solar steam generator comes from the economizer section of the HRSG. The saturated steam produced by the CSP plant returns to the superheater section of the HRSG. In effect, there are two evaporator sections in the system operating in parallel: one using heat from the gas turbine exhaust gas and the other using the heat from the solar field. The two parallel heat sources use a common economizer and superheater, both located in the HRSG. An example of this type of plant is GE's facility in Dubai, Saudi Arabia, which is currently being built. The plant produces 650 MW in combined cycle plus another 50 MW from the solar field. Flowserve is a major supplier on this project.

One recent study concluded that integrating CSP with a CCGT plant can reduce the Levelized Cost of Electricity of the solar-generated electricity. This technology is ideally suited to the Middle East and parts of North Africa, where sun and natural gas are abundant.

Figure 3: Simplified integrated solar combined cycle plant



Combined Cycle Project Models

Combined cycle power plants are conceived and constructed under varying financial, regulatory and market circumstances. Understanding these can be vital to developing a successful sales strategy.

The ownership and operation of power plants take many different forms. First is the publicly owned utility that operates in a rate-based regulated market and is vertically integrated, owning not only the generation assets but also the transmission and retail distribution network. Many developing countries have national utilities of this type. In developed countries, this type of utility, if it exists at all, generally occurs at a state or municipal level. Regulated rate-based utilities can also be privately owned. This is a very common arrangement in many parts of the U.S. National-, regional- or state-based regulated utilities, whether publicly or privately owned, often have large experienced engineering, operations and maintenance organizations. These are much more likely to take an active part in the specification and evaluation of equipment proposed by project EPC's. Equipment specifications may have been developed over many years, and it can be very difficult to have any proposed deviations accepted. While EPC's generally work under lump sum/fixed price contracts, utilities can exercise important control on equipment purchased by them by including approved vendor lists in the bid specifications.

The situation with power plant owners in deregulated markets is somewhat different. One common project model is the Power Purchase Agreement (PPA) between an Independent Power Plant (IPP) developer and an offtaker or purchaser of the power. PPA's guarantee the quantity and price of the power to be purchased for an extended time period, and thus facilitate project financing. The offtaker is typically a public utility. These projects tend to be very sensitive to the overnight costs of the project because the PPA is often awarded on a competitive auction basis. IPP's are often owned by groups of investors who do not have an extensive portfolio of generating assets or a great deal of engineering and operating expertise. Thus, they may tend to take a more 'hands off' approach to selection of equipment on the project. However, PPA's often have penalties tied to plant availability and project completion dates, so developers are not indifferent to reliability and quality.

Another model is the merchant power plant. Merchant plants, by definition, do not have long-term PPA's and pre-identified customers. Financing projects with no guaranteed revenue stream can be difficult, and this type of arrangement is generally applicable to existing older power plant assets.

Power plant developers and owners typically hire a consulting engineering company or companies (also called *owner's engineer)* that will be involved in project planning, basic design, siting and permitting activities as well as the development of detailed project specifications for EPC bidding. The owner's engineer will not actually procure anything but may have substantial impact on the content of specifications, so it is important for Flowserve to be engaged with them by providing strong technical support on pumps and valves. In some cases, the owner's engineer may also be involved in the bid evaluation and purchase decision and provide technical advice to solve problems during manufacturing, startup and commissioning.

Most combined cycle projects are realized under lump sum turnkey engineer, procure and construct (EPC) contracts awarded to large EPC contractors by the project owners. The EPC contractor may be a pure EPC company or joint venture, or the OEM supplying the major equipment for the project (gas turbines, steam turbines and generators). In some cases, there may be more than one EPC contract, with each handling a specific part of the scope.

EPC's do business in a highly competitive market, and EPC contracts can involve substantial risk. The EPC contracts are fixed price, and the potential for cost overruns is high. EPC contracts typically include guarantees on plant performance and project milestones that are all subject to liquidated damages.

Thus, sub-vendors that provide competitively priced products and strong sales support at the contractor bidding phase as well as strong project and supply chain management during order execution, erection, commissioning and warranty are well placed to succeed in this market. The ability to source multiple packages from a single supplier can also reduce project management costs.

When major OEM's act as the EPC, they share many of the same concerns as pure EPC's as noted above, but other issues may factor into their decision-making process. For one thing, their reputation for supplying high-quality reliable gas turbines and steam turbines cannot be compromised by the failure of a pump or valve. They also may be more inclined to try to develop long-term agreements with fewer key equipment suppliers to enhance their overall equipment portfolio as they go to market. This would be particularly true the more standardized the component.

THE COMBINED CYCLE POWER – FLOWSERVE INTERFACE

Business Impact and Focus Areas

The Big Picture

According to the IEA World Energy Outlook 2016, global gas-fired generating capacity increased 7% in 2014 and 2015.

The IEA is forecasting that gas-fired capacity additions between 2016 and 2025 will be well behind renewables but ahead of coal. The regional distribution of these capacity additions is also worth noting. Almost 92% of all coal-fired capacity additions will occur in non-OECD Asia, with 62% of the total in China and India alone. Gas-fired capacity additions are more widely distributed, with China and India accounting for just less than 15%. The Americas, OECD Europe and the Middle East, which are long-served traditional markets for Flowserve, account for 47% or almost half of the market.

Some of the gas-fired capacity additions in the coming years (perhaps 10%) will be in the form of simple cycle gas turbine peaking installations, which require few pumps and valves. Some will also come from the conversion of existing coal-fired plants to natural gas (perhaps another 10%), but the major portion will come from combined cycle generation. This combined cycle capacity will come from new installations as well as the conversion of existing simple cycle installations.

[1] GW = 1000 megawatts (MW). One MW is enough to provide the electricity needs of 400 to 900 homes in the developed world.

Based on the GW figures provided by the IEA, total annual capex investment in pumps and valves for combined cycle plants could average between $700 million to $900 million per year for the next 10 years.

The Flowserve Fit in Combined Cycle

Flowserve has been a leader in the power generation industry for close to 100 years. Its reputation as a provider of engineered equipment is largely based on its participation in the power and oil & gas markets. Flowserve is a leading player in all sub-segments of the thermal power market, including conventional fossil-fired steam, nuclear, combined cycle, biomass concentrated solar power and geothermal.

Products for Combined Cycle – at a Glance

Combined cycle plants offer difficult challenges for pumps, valves and seals. High operating temperatures and pressures are characteristic of many applications. Combined cycle plants are also expected to handle rapid variations in load and may be required to start and stop frequently. Thus, pumps, valves and seals must be designed and selected to handle severe transient operating conditions. Flowserve has a portfolio of products up to this task.

Pumps

A typical combined cycle plant may have no more than 50–100 pumps. A few key services (main feedwater, condensate extraction and condenser cooling) account for a very high percentage:

- Multistage between bearings ring section pumps (WXH, WXM, WX, MS)
- Vertical wet-pit, single-stage pumps (VCT, VTP)
- Vertical canned multistage pumps (APKD, APKC, VPC)
- Horizontal single-stage axially split pumps (LNN, LR)
- High-capacity end suction overhung pumps (FRBH, Mark 3™ Gr 4)
- General service end suction pumps (Mark 3, ZLN, CBT)
- High-pressure and temperature end suction pumps (HPX)
- Sump pumps (CPXV, ESP3)
- Liquid ring vacuum pumps (LEH, LPH)

Valves

There can be up to 5000 valves in a combined cycle plant. A large share of these are small bore general service valves that are not discussed in this guide.

- Edward® gate, globe and check valves
- Valtek® globe control valves
- Valtek Valdisk™ double offset butterfly valves
- Limitorque® MX multi-turn, non-intrusive actuators

Seals

Flowserve pumps are sold into the combined cycle industry with Flowserve mechanical seals, unless the purchaser specifies otherwise. Virtually all applications can be handled with the following products:

- QB for main feedwater, boiler circulating water and condensate extraction applications
- PSS III split seal for condenser cooling, though packing is still the most popular solution
- ISC2-P pusher seals can be used for most other applications

Estimated Booking Values by Plant Size

In its *World Energy Investment Outlook* published in 2014, the IEA provided typical capital costs for construction of a combined cycle gas turbine plant in different regions.

The value of pumps and valves can also be fairly closely correlated with the plant rating.

It should be noted that almost all the pumps are completely associated with the steam bottoming cycle, which accounts for only one-third of the power generated in a combined cycle plant. Thus, the potential bookings value for pumps (and valves) in a combined cycle plant is much lower than it is in other types of thermal power plants.

Virtually all of the pump spend is through the EPC contractor. Fuel and NOx reduction pumps, when applicable, would typically be bought through the gas turbine OEM and the condenser vacuum pumps through the condenser OEM. HRSG recirculation pumps are in the scope of the HRSG vendor.

The pump spend is associated with the main feed, condensate extraction and condenser cooling water pumps.

It is estimated that only 35% of the valve spend is through the EPC. The rest comes through the HRSG, gas turbine and steam turbine OEM's.

Critical service valve applications are estimated to account for about 50–60% of the valve spend.

FLOWSERVE PRODUCTS IN COMBINED CYCLE POWER

In this section, you will find a detailed listing and description of the key products and capabilities Flowserve offers for combined cycle power plants.

Combined Cycle Applications Overview

The process flow diagram on the following two pages provides a somewhat simplified schematic of the main components of a triple-pressure combined cycle plant with reheat. The main pump and valve applications are identified.

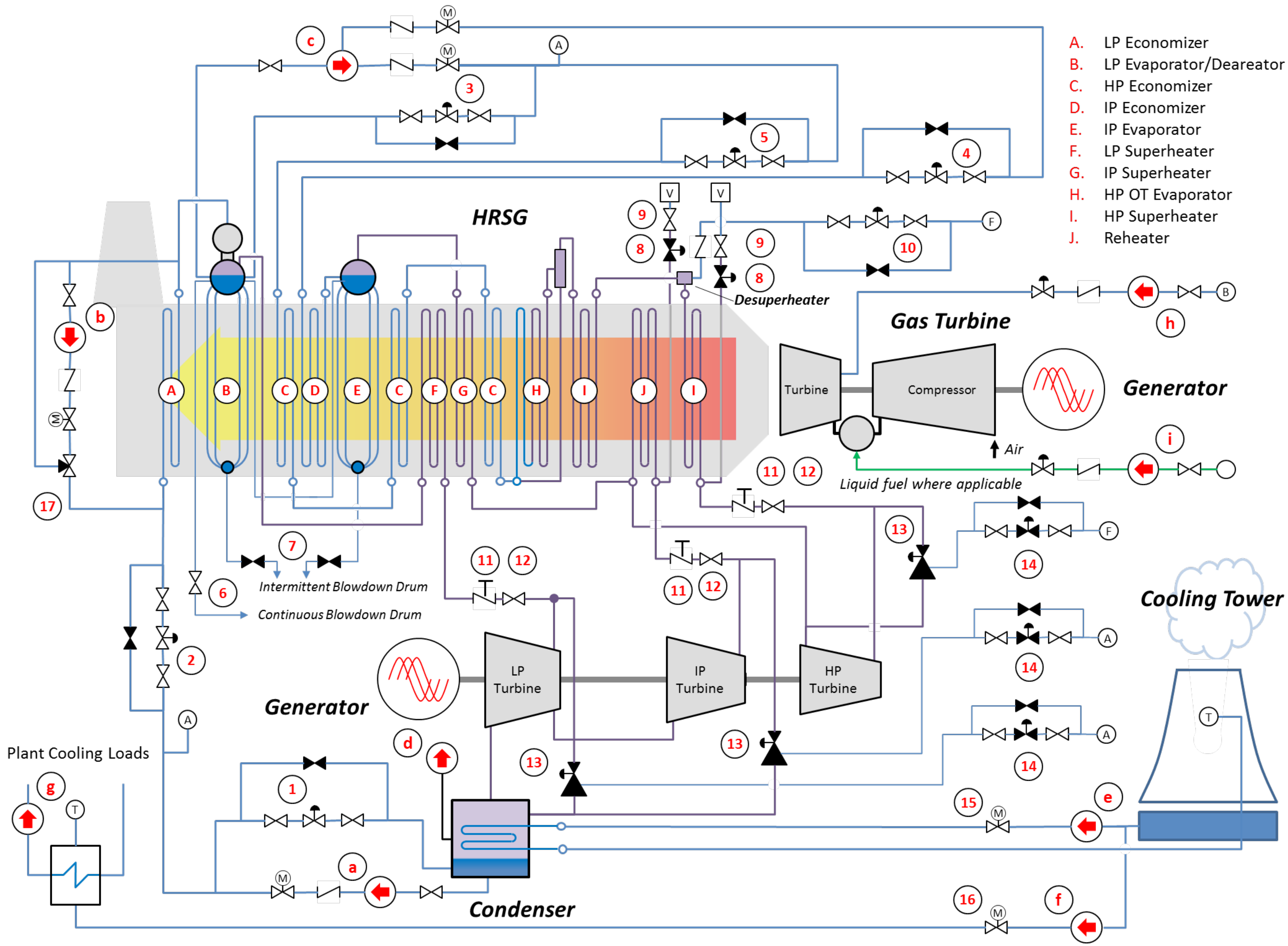
The easiest way to understand the layout is to start at the condenser in the lower middle of the diagram. The condensate in the condenser hot well is at vacuum of about 0.045 bar absolute (0.65 psia) and about 40°C. The condensate extraction pump (a) delivers the condensate to the cold end of the HRSG. The HRSG contains three separate steam generators producing superheated steam, each at a different pressure. Each of these steam generators consists of an economizer where the condensate is heated to the boiling point, an evaporator where the liquid condensate boils to produce saturated steam, and a superheater where the temperature of the saturated steam is raised to produce dry superheated steam. The three elements of each steam generator are arranged in an order from the cold end to the hot end of the HRSG that optimizes heat transfer between the exhaust gases and the water/steam.

The flow of the condensate extraction pump is regulated by a control valve (2) to maintain the desired water level in the low-pressure evaporator steam drum. It flows through the LP economizer (A) where it is heated to about 150°C before entering the combined LP evaporator drum and deaerator. Steam generated in the IP evaporator goes to the IP superheater, while feedwater is drawn off the bottom of the drum and sent to the suction of the main feed pump (c). This multistage feed pump has two separate discharges supplying feedwater at different pressures to the IP and HP economizers. The flow from each feed pump discharge is regulated by a control valve (4, 5) to maintain the correct flow. The IP evaporator is similar in design to the LP evaporator, but the HP evaporator is a ‘once through’ or ‘Benson’ design, which requires no steam drum. A separator is provided only for startup operation. The elimination of the large heavy-walled HP steam drum means that the plant can be ramped up and down much more quickly.

The superheated steam emerging from the LP, IP and HP superheaters is directed to the LP, IP and HP steam turbines and combines with the exhaust steam from the respective upstream turbine section. To improve the performance of the plant, the steam emerging from the exhaust of the HP turbine returns to the HRSG for reheating in the reheater (J) before combining with the steam from the IP superheater.

Other important systems to be noted in the diagram include the LP, IP and HP steam turbine bypass systems, including the bypass control valves (13) and associated bypass spray water control valves (14). Desuperheaters (or attemperators) are used to control steam temperature in the HP superheater and reheater by injecting water supplied from the attemperator spray valves (10).

Process flow diagram, letters and numbered pumps are described on the following pages in detail.



Pumps for Combined Cycle

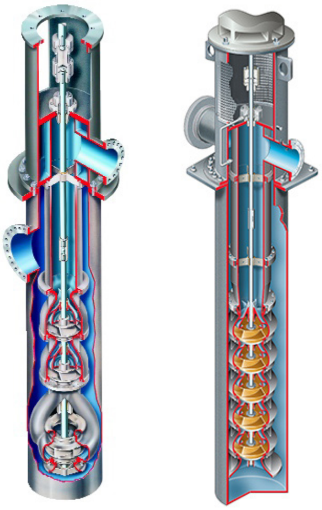
Condensate Extraction Pumps (a)

Condensate extraction pumps are used to pump the condensate in the hot well of the condenser to the inlet of the LP economizer of the HRSG. The condenser operates at a vacuum of approximately 0.045 bar absolute (0.65 psia). The condensate is at saturation conditions, with a typical temperature of 35–40°C. This means that the NPSH available at the liquid level in the condenser is zero. Thus, a canned vertical multistage pump is typically used for this application. The setting of the pump is selected to provide sufficient NPSHA to the first-stage impeller. Smaller CCGT plants use the Flowserve VPC (canned VTP) for this application. On larger plants, a double-suction, first-stage impeller can reduce the pump length substantially, so an APKD is recommended.

Condensate extraction pump sealing systems must prevent air from entering the pump when on standby under a vacuum. This is accomplished with API Plans 13 and 32.

The most common pump configurations are 2x100% or 3x50% per condenser (not per HRSG).

APKD VPC



Condensate Extraction

HRSG Recirculation Pumps (b)

HRSG's may be designed so that the gas flow is either horizontal or vertical. Horizontal HRSG's are also known as *natural circulation* HRSG's because circulation in the evaporator is achieved by gravity, since the tubes are vertical. Nevertheless, in some cases, forced circulation is provided in the LP economizer section.

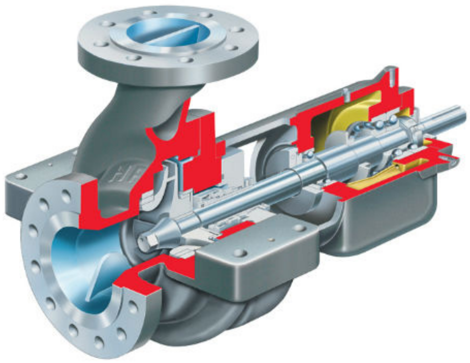
These pumps are required to operate at relatively high suction pressures and temperatures of 20 bar (290 psig) and 175°C (350°F). The maximum allowable working pressure (MAWP) takes account of the shutoff pressure of the upstream condensate extraction pump, pushing design pressures to more than 35 bar (500 psig).

The pumps need to be centerline mounted due to the high temperatures and must have a suitable pressure rating. Thus horizontal, single-stage, end-suction API 610 OH2 designs are the best selection.

Typical configurations are 1x100%, 2x100% or 3x50%, per HRSG.

Note that vertical HRSG's, which are more popular in Europe, are likely to require forced circulation because the tube bundles are horizontal. In such cases, pumps on the higher-pressure sections may be of sealless design, as supplied by vendors such as KSB, Torishima or Hayward-Tyler.

HPX



HRSG Recirculation

Main Feedwater Pumps (c)

The purpose of the main feed pump is to deliver feedwater from the LP drum to the economizer inlets of the IP and HP sections of the HRSG. The main feed pumps also supply spray water to the HP turbine bypass valves and the superheater and reheater attemperator spray valves.

Multistage in-line diffuser ring section pumps are most typically specified for main feedwater service in combined cycle plants. Occasionally, customers will specify a double-case design for this application. The Flowserve WXH ring section pump was specifically developed for combined cycle applications, and all of the hydraulics offered in the WXH can also be offered in the CSB double-case design. A 175 bar version of the WXH, the WXM, has also been developed. The WXM is well-suited to combined cycle conversions of existing simple cycle plants that are smaller and operate at lower pressures.

Channel rings, diffusers and impellers which see high fluid velocities must be provided in 13% chrome to avoid erosion-corrosion damage. The suction and discharge heads may be in carbon steel, though 13% chrome is available to meet customer specifications and/or increase the MAWP of the pump. Laser hardening and DLD at running fits can be offered to make the pump resilient to damage that may be caused by transient operation, including loss of suction pressure.

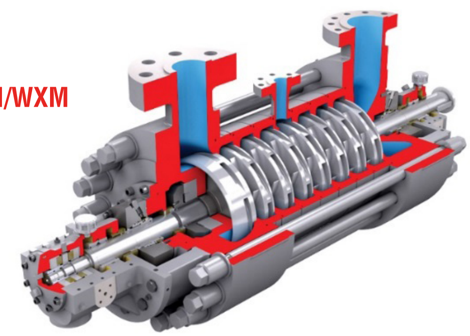
The WXH and CSB pumps are centerline mounted to maintain alignment under normal operating conditions of 150 to 175°C (300 to 350°F).

The pumps are provided with an intermediate takeoff connection to provide flow to the intermediate pressure section of the HRSG. Double-suction, first-stage impellers are available on larger sizes to provide better NPSH characteristics where needed.

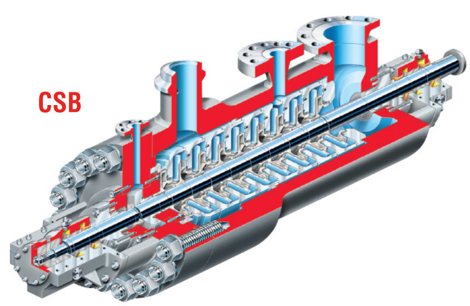
The feed pumps may be direct fixed or variable speed drive with the use of fluid couplings. The most common configurations are 2x100% or 3x50%, per HRSG.

The WX and MS may be suitable for feedwater applications on very small single-pressure plants, but this is a very limited part of the market.

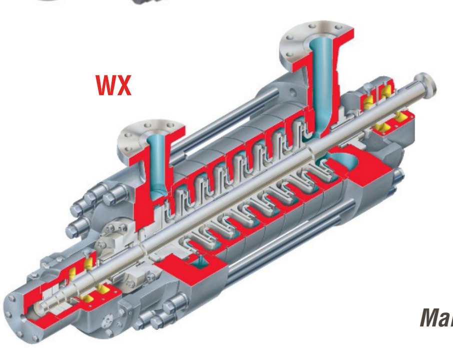
WXH/WXM



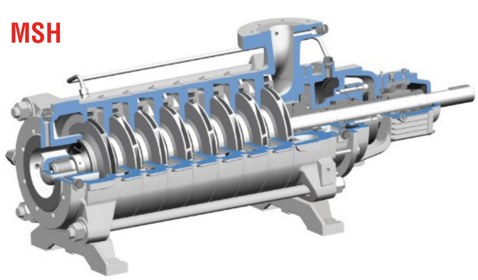
CSB



WX



MSH



Main Feedwater

TCA Cooler Pumps (WXH pump shown on previous page.)

Another important application for Flowserve on some plants using MHI gas turbines is the Turbine Cooling Air (TCA) cooler pumps. Modern gas turbines generally have air-cooled power turbine blades to cope with and allow very high firing temperatures. The air is provided from the compressor section of the gas turbine. Due to the high compression ratio of the compressor, the air is too hot to use directly for cooling and passes through a heat exchanger before entering the blade-cooling system. The cooling medium is feedwater from the LP drum. The TCA pump pumps feedwater from the LP drum through the TCA cooler and back to the HP evaporator. This low-, flow, high- head application is handled by WXH pumps with special hydraulics.

Condenser Air Evacuation Pumps (d)

Figure 4: Vacuum pumps for STOE, Netherlands CCGT

The condenser is an airtight vessel where the steam exhausted from the turbine is cooled and condensed. As a result of the condensation, a vacuum is formed in the condenser. The vacuum is determined by the temperature of the condenser cooling water (or the air temperature in case of an air-cooled condenser). The lower the cooling water temperature, the lower the vacuum. Typical condenser vacuums of 0.06 to 0.08 bar absolute (2.0 to 2.5 in Hg) are achieved in water-cooled condensers.

To maintain this low-pressure condition, it is essential that any air or other incondensable gases passing into the condenser with the steam be continuously removed. This is done with a single- or two-stage liquid ring vacuum pump. An ejector may also be used in series with the vacuum pump. Flowserve can provide complete systems for the application, including the ejector (as applicable), the liquid ring vacuum pump, a separator to separate the liquid from the gas, and a heat exchanger to cool the liquid returning to the vacuum pump.

The vacuum pumps are also used to create the initial vacuum in the condenser during startup. This operation is referred to as *hogging* as opposed to *holding* during normal operation. An important consideration in the selection of the pumps is the specified time to bring the condenser to full vacuum at startup. One arrangement is to have 2x100% pumps that are both operated during hogging. Another would be 3x50% pumps where only one operates during holding. It is also possible to have two differently sized pumps: one for holding and one for hogging.

Another vacuum pump application not specifically illustrated on the process flow diagram includes condenser water box priming. Condensers may be primed using the circulating water pumps, but some designers prefer to use a separate vacuum system to accomplish this task. Lastly, small SIHI® vacuum pumps can also be used in the deaeration of makeup boiler feedwater.

LEH (single-stage)

LPH (two-stage)

Condenser Air Evacuation

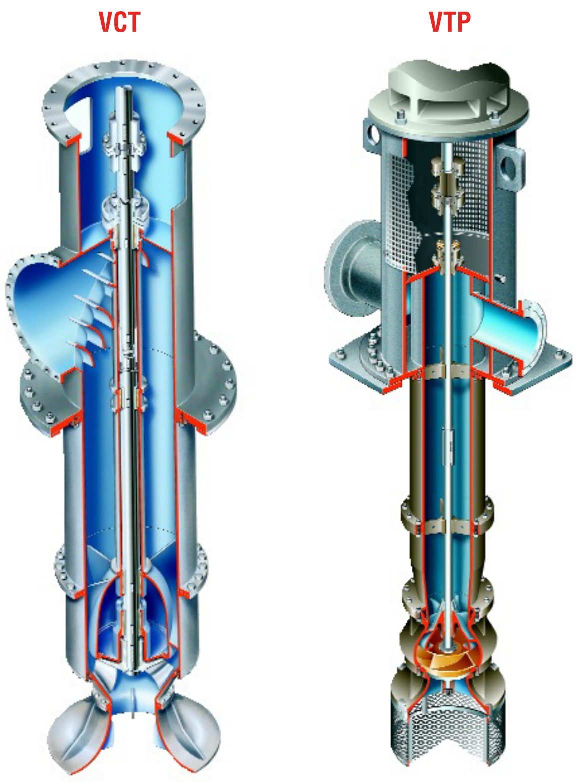
Condenser Cooling Water Pumps (e)

All thermal power plants reject large amounts of heat to the environment, and a combined cycle plant is no exception. A typical combined cycle plant with a 57% thermal efficiency will reject 43% of the heat input by the fuel. About 9% will go out the HRSG stack; the rest is removed by the cooling water pumped through the condenser.

Condensers have traditionally been cooled by water using either once through or closed (cooling tower) systems. The cooling water requirement of a typical combined cycle plant using a cooling tower can be estimated per MW based on a 10-degree Celsius temperature rise of the cooling water as it passes through the condenser. Thus, a 750 MW combined cycle plant will require a cooling water flow of about 45 000 m^3/h (200 000 US gpm). Once-through systems typically require more flow because the temperature rise is often limited to 7 degrees for environmental reasons.

Environmental legislation in many jurisdictions no longer allows once-through cooling from rivers or lakes. Even conventional wet-cooled cooling towers can be a problem, since water withdrawals are still needed to make up for blowdown, and evaporation and drift from the tower. Thus, air-cooled condensers have become a necessity in many cases, even though the initial capital cost is much higher and plant thermal efficiency may be reduced by as much as 3 or 4% in high ambient temperature locations.

The most frequent Flowserve offer for this application is the EPO VCT; however, small to medium combined cycle condenser cooling water needs may sometimes be fulfilled by the IPO VTP line.



Condenser Circulating Water, Service Water

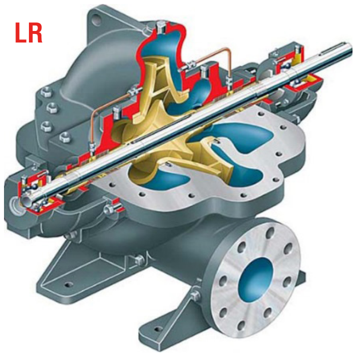
Closed Cooling Water Pumps (g)

Most of the service water provided by the service water pumps is for cooling the heat exchanger of the closed cooling water system. Service water is not used to directly cool the individual cooling loads in the plant because the service water is not of good enough quality to avoid deterioration and fouling of plant equipment. Rather, closed cooling water pumps circulate demineralized water through all of the cooling loads, and the heat is rejected in the closed cooling water cooler.

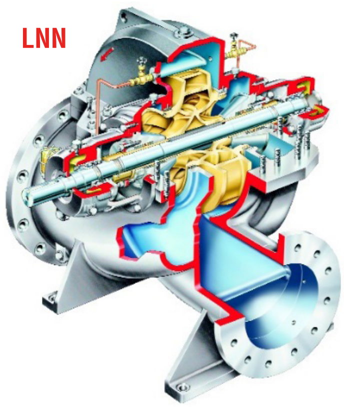
Closed cooling water pumps may be horizontal, axially split, double-suction pumps or high-capacity end suction pumps, depending on the plant flow requirements and the customer's preference. Many customers prefer the end suction design because it is less costly and the nozzle configuration offers advantages in plant design.

Since this is a low-temperature and low-pressure clean water application, the pumps are normally cast iron, with either carbon steel or 12% chrome impellers.

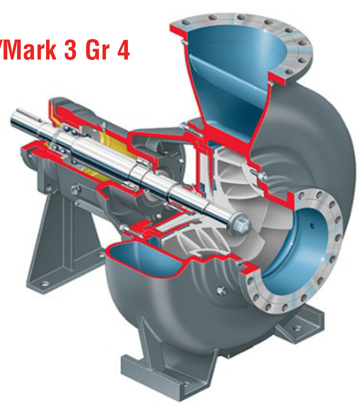
LR



LNN



FRBH/Mark 3 Gr 4



Closed Cooling Water

NOx Reduction Water Injection Pumps

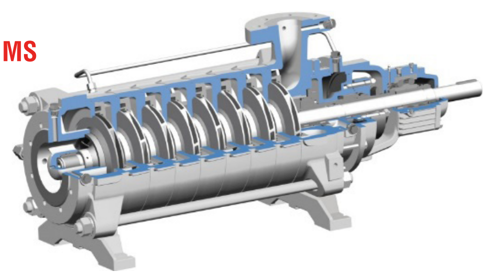
Liquid Fuel Pumps (not applicable to natural gas-fueled plants)

Gas turbines typically use water or steam injection into the combustors to reduce flame temperature and thus reduce NOx emissions. If the amount of water injected is roughly equal to the amount of fuel used, NOx emissions can be reduced without any injection.

While natural gas is the most common fuel used in combined cycle plants, some plants burn liquid fuels. In many cases, the liquid fuel is used only as a backup to natural gas. In these cases, pumps are needed to inject the fuel into the combustors, which operate at fairly high pressures. In many cases, positive displacement pumps are used, but centrifugal multistage ring section pumps can be used on the larger gas turbines.

Both of these applications are highly standardized, in the scope of the gas turbine vendor, and normally purchased under a long-term blanket agreement.

MS



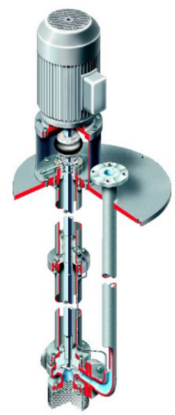
Gas Turbine NOx Water Injection, Gas Turbine Liquid Fuel

Miscellaneous Balance of Plant Pumps

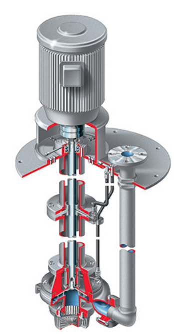
Combined cycle plants also have miscellaneous pump applications that can all be handled by various Flowserve IPO product lines. Most of these involve pumping cold clean water, so pumps are generally cast iron, with cast iron, carbon steel or 316 Series stainless impellers. Typical applications involve the handling of demineralized water in make-up systems, blowdown as well as drain sump applications.

Mark 3

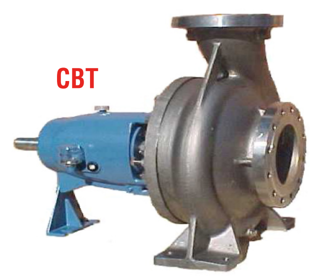
CPXV



ESP3



CBT



ZLN

Miscellaneous Applications

Valves for Combined Cycle

A typical combined cycle plant may have more than 5000 valves. The largest quantity of these are small bore general service valves that cannot be covered in detail in this guide. The following section attempts to describe the major critical service valve applications in a combined cycle plant. The item number after the application description refers to the location on the process flow diagram.

Condensate Extraction Pump Recirculation Valve (1)

This is a similar application as the main feed pump recirculation valve (see below), but the operating conditions are more moderate.

FLOWSERVE SOLUTION: Valtek Mark One™ or Mark 100 with ChannelStream or DiamondBack anti-cavitation trim.

LP Feedwater Control Valve (2)

The valve controls the water level in the LP steam drum. The valve is subject to cavitation at low flow during plant startup and must have high rangeability. It must provide accurate level control in the LP steam drum with low-pressure drop during normal full load operation. The process flow diagram shows the valve located upstream of the LP economizer, but it can also be located downstream to maintain the economizer at a higher pressure to avoid steaming at off-design conditions.

FLOWSERVE SOLUTION: Valtek Mark One or Mark 100 with CavControl anti-cavitation trim.

Main Feed Pump Recirculation Valve (3)

The feed pump recirculation valve is intended to ensure the required minimum flow through the feed pump to prevent excessive temperature rise, flow recirculation damage and hydraulic instability. Minimum flow requirements can vary, depending on the design and power of the pump. Each feed pump must have a dedicated recirculation valve. Earlier plants used an on/off valve for this application, but modulating control valves are now most common.

During normal operation, at full load the valve remains closed and must seal tightly against a differential pressure. Any leakage will result in energy losses and damage to the trim. Thus, these valves are equipped with hardened metal seating surfaces of Class V sealing trim.

These valves are usually equipped with sophisticated anti-cavitation trim to handle the high differential pressures when the valve is modulating. Thorough understanding of the application and various operating conditions is essential to proper sizing of the valve.

An alternative approach is the Automatic Recirculation Valve (ARV) offered by OEM's such as Schroeder, Shroedahl, Yarway and Hora. This is a self-actuated valve with an integral check valve. These valves have several disadvantages, including: higher-pressure losses; mechanical linkages in the flow path that wear; leakage during normal operation when the valve is closed; and flow cannot be monitored or flow settings altered during operation.

FLOWSERVE SOLUTION: Valtek Mark One or Mark 100 with ChannelStream and DiamondBack anti-cavitation trim.

IP and HP Feedwater Control Valves (4) (5)

These valves control the level of feedwater in the intermediate- and high-pressure steam drums. They operate at low flows and high-pressure drops during startup and are subject to cavitation. Under normal plant operation, the valves should have a low-pressure drop to minimize losses. Accurate control of feedwater flow at all operating conditions must be maintained. In some cases, a smaller startup valve is installed in parallel with the main valve.

FLOWSERVE SOLUTION: Valtek Mark One or Mark 100 with CavControl anti-cavitation trim.

Continuous Blowdown Valve (6)

Blowdown is the process of removing some of the feedwater from the HRSG system to avoid the concentration of dissolved impurities over time. The water lost through this process is made up by adding make-up demineralized water in the condenser. In the process flow diagram, the blowdown from the intermediate-pressure steam drum is cascaded back to the low-pressure steam drum, and the blowdown from the low-pressure steam drum is directed to a continuous blowdown flash tank. The valve may be manual or automated. Upstream conditions in this case would be about 5–7 bar/160–170°C.

Manual on-off valves are used for this application, but they still must be able to control flow. The trim must be designed to handle high velocities and pressure differentials. The valves must shut tightly and be resistant to some solids. Valves may also be automated.

FLOWSERVE SOLUTION: Edward angle pattern globe valves.

Intermittent Blowdown Valves (7)

These valves are used for intermittent blowdown from the bottom of the drum's type low- and intermediate-pressure evaporators to ensure that solids do not accumulate. These valves are subject to high-pressure drops and must seal tightly when closed in order to avoid wasting energy. The valves direct the flow to a blowdown drum.

FLOWSERVE SOLUTION: Edward Y-Pattern globe valve. Alternately, blowoff globe valves.

Start-up Vent (Sky Vent) Control Valve (8)

The gas turbine in a combined cycle plant can come up to full speed and load quickly, but the HRSG, steam turbine and condenser require more gradual loading to avoid thermal transients that could cause damage. The startup (or sky vent) system allows for controlled loading of the plant by venting steam to the atmosphere. Valves are normally provided on the HP superheater outlet and hot reheat line. These valves must be able to operate with minimum noise with high-pressure drops and ensure tight sealing when closed.

FLOWSERVE SOLUTION: Valtek Mark One and Mark 100 with MegaStream, TigerTooth or Stealth noise reduction trim.

Startup Vent (Sky Vent) Isolation Valve (9)

The startup vent isolation valve is installed downstream of the startup vent control valve and upstream of the vent silencer. It is normally left open, but can be closed in the event of any leakage from the upstream control valve. This valve may be subject to extreme thermal transients during startup and must provide tight closure.

FLOWSERVE SOLUTION: Edward Flite-Flow Y-Pattern globe valves.

Super Heater and Reheater Attemperator Spray Valves (10)

Attemperators are used to control the temperature of superheated steam going to the steam turbine by injecting feedwater or condensate through nozzles in the steam line. The attemperator nozzles are designed to ensure complete mixing and rapid vaporization of the spray water. Attemperators are normally located between the primary and secondary superheaters and at the inlet to the reheater (only the former is shown for clarity). Accurate control is essential to protect the turbine from overheating without impairing plant efficiency or allowing water droplets to form that might cause damage to turbine blades.

Attemperator spray valves control the flow of water to the attemperators. These valves require high rangeability, tight shutoff (Class V) and must provide long service life. Water is supplied from the discharge of the main feed pumps.

FLOWSERVE SOLUTION: Valtek Mark One with CavControl or SideWinder anti-cavitation trim.

Main Steam Non-return Valve (11) and Stop Valve (12)

These valves are provided on plants where two or more HRSG's feed a single steam turbine to prevent backflow of steam from one HRSG to another in the event a gas turbine is tripped. The valves are subject to high temperature and pressure as well as rapid thermal transients.

FLOWSERVE SOLUTION: Non-return valve: Edward Flite-Flow Y-Pattern globe valve. Stop valve: Edward Equiwedge gate valve.

HP, IP and LP Turbine Bypass Valves (13)

These valves are special steam conditioning valves used to bypass steam in the event of a steam turbine trip without having to shut down the gas turbine or HRSG. Flowserve does not have a product offering for this application, but can offer the associated turbine bypass spray valves (see below).

HP, IP and LP Turbine Bypass Spray Water Valves (14)

These spray water valves provide water to the steam conditioning bypass valves. The water for the HP bypass is provided by the main feedwater pump, while the supply for the IP and LP bypass is provided by the condensate extraction pump. The valves must provide accurate control and provide tight shutoff.

FLOWSERVE SOLUTION: Valtek Mark One with CavControl or SideWinder anti-cavitation trim.

Condenser Cooling Water Pump Butterfly Valve (15)

Generally, a quick opening double-offset butterfly valve is used for these applications. In seawater applications, the valves would need to be made of duplex or super-duplex.

FLOWSERVE SOLUTION: Valdisk double-offset BX butterfly valves.

Service Water Pump Butterfly Valve (16)

Service water may be provided by dedicated service water pumps or from a takeoff line from the discharge of the main condenser cooling water pumps. The valve construction would be similar to what is provided for the condenser cooling pumps, but would have a much smaller diameter.

FLOWSERVE SOLUTION: Valdisk double-offset BX butterfly valves.

Equipment Block and Bypass Valves, Check Valves

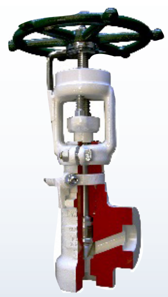
Most of the control valves indicated in the process flow diagram and discussed above are equipped with upstream and downstream isolation or a block valve as well as a bypass valve. These valves require tight shutoff. The isolation valves, which are normally open, need to allow full flow with minimum pressure drop; gate valves are the preferred option for these applications.

FLOWSERVE SOLUTION: Edward Equiwedge gate valves, Edward Flite-Flow globe valves and Edward tilting disc check valves.

The following Flowserve products handle most of the on-off applications discussed here.

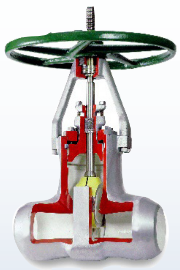
EDWARD BLOWOFF Y-PATTERN GLOBE VALVES

EDWARD ANGLE PATTERN GLOBE VALVES



EDWARD Y-PATTERN FLITE-FLOW GLOBE VALVES

EDWARD EQUIWEDGE GATE VALVES

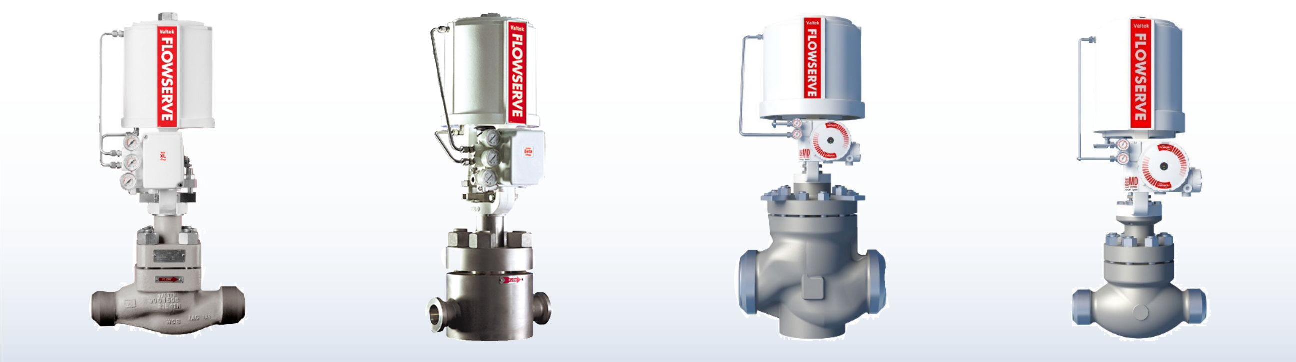


EDWARD TILTING DISC CHECK VALVES

VALDISK BX DOUBLE-OFFSET BUTTERFLY VALVES

The following Flowserve products handle most control valve applications:

VALTEK MARK ONE	VALTEK MARK TWO	VALTEK MARK 100	VALTEK MARK 200



Actuators for Combined Cycle

Many of the Edward multi-turn globe and gate valves and their related applications as described herein would use electrical instead of manual actuation, as pictured. Flowserve offers an extensive range of electrical actuators for these applications, e.g., the Limitorque MX non-intrusive, multi-turn actuator. These provide a comprehensive network option portfolio to users, including Foundation Fieldbus, HART and DeviceNet.

The QX quarter-turn actuator would be used for any quarter-turn applications (e.g., ball valves).

On new projects, the actuators are normally purchased with the valves and not directly by the EPC or OEM.

Limitorque MX

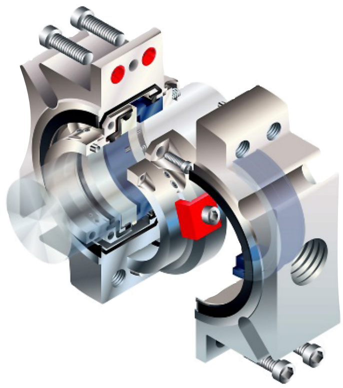
Non-intrusive Electric Actuators

Seals for Combined Cycle

Flowserve has a full range of seal products to cover all pump applications in a combined cycle power plant. The most challenging applications are main boiler feed, HRSG recirculation and condensate extraction. These applications are handled by the QB Series of balanced pusher seals.

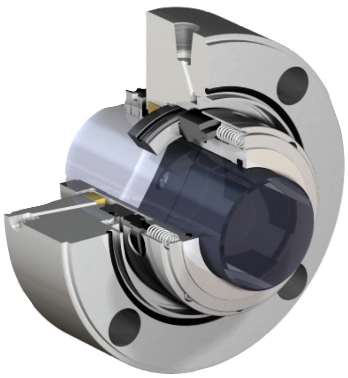
Condenser cooling water and service water pumps typically use packing, but the PSS III split seal is an ideal mechanical sealing option.

Most other applications in the combined cycle plant can be handled with the ISC2 family of products.



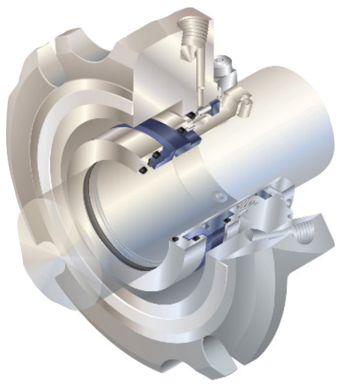
PSS III Split Seal for CCW and Service Water

Vertical wet-pit condenser circulating water and service water pumps with packing can be easily upgraded with this split-seal design.



QB Series Balanced Pusher Seals for HRSG Feed, HRSG Recirculation and Condensate Extraction

Boiler feed and recirculation applications are typically provided with Plan 23 seal flush systems. Condensate extraction applications are provided with Plan 13 and 32.



ISC2-PX Standard Cartridge Pusher Seals for General Service Applications

The ISC2 is the first choice for miscellaneous sealing applications such as closed cooling water, demineralized water, etc.

COMMUNICATING OUR VALUE

Flowserve Value Proposition in Combined Cycle

FLOWSERVE	PROPOSITION	CUSTOMER BENEFIT
Ethical business practices	Flowserve sets the highest standards in business integrity in its dealings with suppliers and customers.	A trustworthy partner with more than a century of experience to work toward their project success
Quality	Flowserve manufactures to the most rigorous quality standards to provide reliable products.	Satisfaction in supplier choice, on-time commissioning and project startup
Engineering excellence	The Flowserve depth of engineering experience is unparalleled in combined cycle.	Optimized product and material selection for each application ensures reliable operation.
Experience	Flowserve has been a leader in combined cycle power generation since the process was commercialized on a large scale.	Lessons learnt have been built into today's products, increasing reliability, maintainability and product life.
Broad product range	Flowserve comprises a list of world-renowned heritage brands and a wide portfolio of products and services.	A product for every service designed by specialists in their respective fields ensures low-cost, high-efficiency solutions.
Project management	Dedicated project managers certified by IPMA	Professional team to handle documentation and ensure on-time delivery
After-sales support	Dedicated after-sales support engineers	Implanted within project management, with the sole objective to resolve support issues quickly and painlessly
Local Quick Response Centers (QRCs)	Fully equipped Quick Response Centers in the region	Skilled team to handle upgrades and repairs; localized to reduce downtime, full access to Flowserve component drawings, procedures and standards
Aftermarket solutions	Long-term maintenance	Specialist group capable of maintaining, servicing and upgrading equipment to meet operating goals throughput
Safety	Considerable experience and pioneer in power industry; with product designs considering industry standards and low-risk design factors and maintainability	Maximize MTBF, ease of monitoring equipment

Innovative Ways Flowserve Addresses Customer Challenges

EXPERTISE AND EXPERIENCE	• Flowserve has more than 80 years of experience in the power industry and has been a key supplier of pumps, valves and seals for combined cycle power plants since the beginning of the combined cycle era. • Flowserve has one of the largest installed bases of pumps and valves in critical combined cycle applications around the world. • Specialist "Virtual Centers of Excellence" ensure that expertise acquired over multiple products and manufacturing sites is shared across the global Flowserve organization.
SINGLE-SOURCE PROVIDER	• Flowserve offers a full range of pumps, valves and seals for the combined cycle market, simplifying the procurement process for our customers. • Global Commercial Operations organization ensures knowledgeable and professional review and response to customer RFQ's, including those with the most complicated technical requirements.
STREAMLINED EXECUTION	• Each of the Flowserve factories has efficient and professional project management organizations to ensure on-time completion of projects to customer requirements. • Where projects involve multiple Flowserve manufacturing locations, global project managers can be provided to coordinate order fulfillment. This ensures less errors and delays and simplifies communications between Flowserve and the customer.
LOCAL SUPPORT WORLDWIDE	• A large field service organization ensures technicians are available for installation, commissioning and troubleshooting without delay. • Service and maintenance contracts for highest availability and continuous efficiency optimization can be tailored to customer needs. • A global network of Flowserve Quick Response Centers means that local service and repair are always available. • Product upgrades are continuously being introduced to improve the performance and reliability of Flowserve products in the field. • Full operation and maintenance training are available to end users. • Equipment monitoring programs are also available.
OPTIMIZED EFFICIENCY	• The Flowserve close involvement with the combined cycle market has provided the industry feedback needed to develop the range of hydraulics best suited to customer requirements, ensuring the best and most efficient selections are always available. • As one of the largest engineered pump manufacturers in the world, the Flowserve hydraulic engineering capabilities and resources are second to none. Flowserve is able to provide pumping equipment that consumes the least amount of power.

APPENDIX

Glossary of Key Terms, Abbreviations and Acronyms

Terminology

Attemperator: a device for reducing the temperature of superheated steam by spraying water through nozzles into the steam line.

Availability: the percentage of the hours in the year that the plant was operating or available to operate.

Benson boiler: an evaporator design that does not require a steam drum. Feedwater enters one end of the boiler and steam comes out the other end without any separation or recirculation. Originally a license of Siemens.

Capacity factor: The total kWh generated in a year divided by the plant nameplate net rating in kW times 8760 hours.

Gigawatt (GW): 1000 megawatts.

Kilowatt (kW): a unit of power (work done per unit time). A kilowatt is 1000 watts.

Megawatt (MW): 1000 kilowatts. One megawatt is sufficient to provide the electricity needs of 600 to 900 homes in the developed world. Plants are typically rated in MW.

Overnight cost: the cost of a construction project if no interest was incurred during construction, as if the project was completed "overnight."

Repowering: converting an existing conventional steam power plant to combined cycle. The steam boilers are typically replaced with new HRSG's, but the existing steam turbine is used.

Acronyms

ARV: Automated Recirculating Valve

BFP: Boiler Feedwater Pump

CCGT: Combined Cycle Gas Turbine (also written as GTCC)

CCPP: Combined Cycle Power Plant

CCS: Carbon Capture and Storage

CCW: Condenser Cooling Water, as in CCW pump

CEP: Condensate Extraction Pump

CHP: Combined Heat and Power

CSP: Concentrated Solar Power

EPC: Engineer, Procure and Construct

GT: Gas Turbine

HRSG: Heat Recovery Steam Generator

HTF: Heat Transfer Fluid

IGCC: Integrated Gasification Combined Cycle

IPP: Independent Power Plant

ISCC: Integrated Solar Combined Cycle

LCOE: Levelised Cost of Electricity

MCR: Maximum Continuous Rating

MWe: Megawatt electric (the electrical power output of the generator)

MWt: Megawatt thermal (the thermal power output of the boiler)

PPA: Purchase Power Agreement

QRC: Quick Response Center

SCGT: Simple Cycle Gas Turbine (also written as GTSC)

TCA: Turbine Cooling Air

T-G Set: Turbine Generator Set

USC: Ultra-supercritical

North America

Latin America

Europe

Middle East

Africa

Asia-Pacific

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Experience In Motion