SUPERCRITICAL & ULTRASUPERCRITICAL TECHNOLOGY

Continuing efforts to increase efficiencies and reduce emissions from large conventional thermal power plant have seen a corresponding trend to ever-higher steam conditions and advanced turbine technology.

The oldest of all power generation technologies, the basic water/steam cycle has been in common use for more than 110 years is as old as the commercial production of electrical power itself.

During early 20th century coal fired power plants were producing 1.0–5.0MW per unit with live steam pressure of 1.0–1.4MPa (145-203psi) and temperatures around 200-260°C (392-500°F) reaching net plant efficiency (heat rate) no greater than 8% to 12% (42,650-28,435Btu/kWh).

At the beginning of world war I, 1914-15 military and commercial cargo ships have been driven by 6.0MW/3000rpm – 20.0MW/1000rpm STs with live steam pressure between 1.0 and 1.6MPa (145-232psi) and temperatures in the range of 300-350°C (572-662°F).

By the end of the Second World War, continuing improvements in both boiler and steam turbine technologies saw the introduction and commercial utilization of the single reheat cycle with operating pressure of 16.5MPa (2,400psi) and live steam temperatures in the region of 538°C (1000°F), resulting in improved net efficiency (heat rate) in the range of 28% to 30% (12,185-11,375Btu/kWh).

Over the next 20 years, evolving technology and still-higher steam conditions offered further improvements in overall plant efficiency. With the introduction of super critical technology on large thermal base load power plant during the 1980s with typical steam temperatures of some 550°C, thermal efficiencies were boosted to around 48%.

THERMAL EFFICIENCIES

Today, operating at ultra-supercritical steam conditions with live steam of above 30 MPa and reheat steam temperatures of about 600°C, large thermal power plants are now reaching overall thermal efficiencies in excess of 50%.

Major steam turbine manufacturers (e.g. Siemens PG, MHI, Toshiba, Alstom, GE, Hitachi and other not named companies) are currently producing turbines capable of operating at these advanced steam conditions, with maximum main steam parameters of 25.0 – 30.0MPa/560-600°C and 580-620°C reheat steam.

This provides a gross water/steam cycle efficiency of above 50 – 52% giving a net efficiency of above 46 – 48%.

Continuing development effort over the next decade will see a steam turbine under test, operating at temperatures of some 700°C, giving a net thermal efficiency of above 52%.

Compared to the development costs of R&D investment levels in ultra-supercritical steam turbines are regarded as being relatively modest, but result in significant improvements in both fuel efficiency and stack emissions.

STEAM TURBINES

For example the design of a typical Siemens' advanced steam turbine for ultra-supercritical 1,000MW-class applications, takes the form of a modular, tandem-compound, four-cylinder arrangement with a single crossover pipe.

The steam enters the HP turbine through two closely connected main steam valves. The barrel--type HP turbine has full arc admission and is designed for the highest steam conditions. Exhaust steam from the HP stage is reheated and fed to the double-flow IP turbine, being fed subsequently to the two LP turbines via a single crossover pipe, giving a four-flow exhaust arrangement into the condenser.

The last-stage blade length for full-speed applications is typically 45inches (1,140mm) for steel and 56 inches (1,420mm) for titanium.

In a typical Siemens PG barrel-type HP turbine module, the split outer casing consists of two halves with a vertically flanged joint, the design eliminating the mass concentration of a horizontal flange.

The inner casing is split horizontally and functions either as a blade carrier - taking no pressure, or as an inner casing design - taking a proportion of the pressure drop. The design reduces radial deformation and radial clearances to increase efficiency, while total heat-mass is also reduced leading to faster start-up times. A special ‘U’-type seal allows for differential expansion between different materials.

The turbine is a single-flow type with full arc admission and can operate at steam conditions up to 30.0MPa/600°C without any external cooling. The single-flow extraction from the HP blade-path allows steam parameters to be adjusted to optimize main feed-heating line temperatures and the overall heat balance.

Reheated steam is fed to the IP turbine, a double-flow, double-shell design with full arc admission and horizontally-jointed outer and inner casings, designed for steam conditions up to 620°C without any external cooling.

The reheat valve is flanged on the lower half of the outer casing, allowing the IP rotor to be removed during major overhauls without cutting the reheat steam line. A diagonal inlet stage combined with vortex cooling results in a 15°C decrease in rotor surface temperature in the inlet area, enabling the rotating high temperature elements to operate below the maximum inlet steam temperature.

The materials used for high temperature components such as the rotor and inner casing include 9 per cent to 10 per cent chrome steel alloyed with boron and cobalt, providing high creep resistance and reduced oxidation.

Inner casing deformation is reduced by the use of integral ribs at top and bottom which counteract the mass concentration of the horizontal flange. The outer casing is not subjected to exhaust temperatures greater than 400°C and is constructed from nodular cast iron.

The LP turbine uses a double-flow, double-shell design, the inner casing being either a casting or welded fabrication according to specific customer requirements.

The maximum height of the last stage blades is around 45 inches (1,100mm) for steel and 56 inches (1,400mm) for titanium, which together with a four-flow exhaust configuration allows compatibility with all condenser conditions.

The inner casings of the LP turbines are rigidly connected by push rods to minimize axial clearances by transmitting axial deformation in parallel to the rotor expansion. The arrangement allows a larger number of fin-type seals to be installed, reducing leakage and raising turbine efficiency.

STEAM GENERATORS

Steam Generators (Boilers) for power generation are either "drum" or "OT" types, referring to how water is circulated to cool the tubing.

In drum-type units, the steam-flow rate is controlled by the fuel-firing rate only. Superheated steam temperature is determined by properly sizing the superheater heat-transfer surface, and is controlled by spray water.

In OT type boiler, the steam-flow rate is established by the boiler feedwater pump and the superheated steam temperature is controlled by the fuel-firing rate.

Two types of SC/USC OT boiler designs are currently in use, those that operate with a constant pressure in the furnace tubes and those that vary pressure with load.

The latter is the popular design for SC/USC boilers today because it is not only more efficient at lower loads, but in combination with a circulation pump, it can also be cycled on and off much more rapidly.

Since the OT boiler does not rely on the density difference between steam and water to provide proper circulation and cooling of the furnace enclosure tubes, it can be operated at SC/USC pressures, in other words:-

-*Considering elevated steam conditions, OT boiler is the answer; only OT boiler can generate SC/USC pressure steam*-.

With about 1000 units built, the Benson boiler is by far the most widespread OT boiler (around 60% of all OT boilers).

The variable evaporation endpoint in Benson boilers enables achievement of high live steam temperatures over a large output range independent of operating conditions (i.e. also the load). This results in higher process efficiency for the power plant over a wide load range.

ADVANCED MATERIALS

Future development of high efficiency advanced steam turbine and boiler at advanced USC conditions is largely dependent on the parallel development of advanced materials and super-alloys capable of withstanding the extreme working environments both in terms of corrosion resistance and their creep rupture strength.

However, the extra costs of using advanced materials can be partly compensated by reduction in the amount of material, because of thinner pipe walls in the boilers and smaller dimensions of machinery.

This in turn demands major investments in a range of metallurgical technologies, from chemical composition, smelting and heat treatment, to manufacturing processes. The optimum design figure for creep resistance after 100,000 hours as a function of temperature for steam turbine components is 100MPa.

Within these parameters, the upper temperature limit for chromium steel alloys with between 9% and 11% Cr is 620°C, although research is currently being carried out under the EU-sponsored COST 501 programme to extend the application range up to 650°C.

However, at steam temperatures up to 700°C even high chrome steels have insufficient creep rupture strength, making it necessary to replace them with nickel and cobalt-based 'super-alloys'.

Siemens PG is currently heavily involved in developing this leading-edge materials technology within European COST 522 and Thermie materials programmes, looking to the introduction of a 700°C turbine by 2015.

With regard to sealing technology developments, the main thrust is towards reduced leak-age flows and increased operational reliability, with the introduction of abradable coatings and brush seals.

Abradable coatings provide an additional surface layer in the sealing area which reduces clearances, but without causing damage to the seal fins due to physical rubbing-contact in the event of zero clearances between seal fin and layer. The use of abradable seal-coatings results in a reduction in leakage flow of around 30%.

Designed for eventual installation in steam gland and blade path areas, brush-type seals result in a reduction of 70% in leakage flow, raising the output of a typical 700MW unit by between 10 and 15MW.

Siemens has gained extensive practical experience in the use of both abradable and brush seals in industrial gas and steam turbines, where operating temperatures are in the same range as in advanced steam turbines.

New developments in last-stage steam turbine blade technology include the introduction of a titanium blade with curved fir-tree root, interlocked design and a profile length of 56 inches (1,400mm) for an exhaust cross section of 16m^2.

Due to the relatively poor vibrational damping characteristics of titanium, an integral shroud and a mid-snubber have been added to provide dynamic stability. In addition to the new blades, the entire LP blade path is also being optimized, improving overall steam flow in all stages of the LP turbine.

CONCLUSION

The coal is the most abundant and widely spread fossil energy resource worldwide and pulverized coal fired power plants currently account for more than 40% of electrical power produced in the world.

In view of the coal long range reserves', increasing importance is to be attached to improve their worldwide utilization.

To achieve an economically optimized pulverized coal-fired power plant, the cycle conditions under which such plant shall operate need to be carefully evaluated taking into account miscellaneous important parameters as the live steam conditions, feed water arrangement as well as number of reheats employed.

To open up further efficiency potentials, the electricity supply industries are developing even more advanced power plant concepts using advanced materials for boiler and steam turbine.

The assurance of long-term prospects for coal in the industrialized countries constitutes a decisive precondition necessary to develop the advanced technologies there and also apply them in the developing and threshold countries as required by the envisaged sustainable development.

Overall outlook for pulverized coal-fired SC/USC power plant technology is promising and its further growth lies ahead.

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