The paper deals with the development of supercritical technology with its salient features and points out necessity of some revisions in Indian Boiler Regulations.
SUPERCritical steam generator technology

ABSTRACT

In the fossil fuel fired power plants successful operation of once through steam generator technology and drive to achieve higher thermal efficiencies made possible for the development of supercritical steam generators. Systematic development of materials to withstand higher steam temperatures gave an impetus in the power industry to adopt higher steam parameters in supercritical power plants. Both constant pressure and sliding pressure steam generator technologies are matured and can be adopted to meet the specific operational requirements. Globally, sliding pressure steam generators have become popular for recent thermal plants to achieve higher plant efficiency, reduction in auxiliary power consumption, and to provide faster response of unit to load changing conditions. Key factors to the success of supercritical technology include use of sliding pressure operation, application of high strength materials, use of oxygenated treatment (OT) in the condensate / feed water system and highly automated operation. The paper deals with the development of supercritical technology with its salient features and points out necessity of some revisions in Indian Boiler Regulations.

INTRODUCTION

The Indian economy is growing in recent times at an average rate of 8.5% and a growth rate of about 8 to 10% is being forecast for the coming years, against a growth rate of about 5 to 7% in the past years. To sustain the economic growth on continuous basis, reliable supply of electricity and availability of infrastructure shall be made available which are the key contributors. To augment the power demand, large capacity power generating units are being installed. Advantage of supercritical technology lies in the fact that it offers higher efficiencies than subcritical technology which results in lower fuel consumption and lower particulate and gaseous pollutant emissions per unit of electricity generated. The technology is matured through advancements in design and materials and is available in the higher capacity range. Coal being available abundantly at reasonable price pulverized coal fired boiler with supercritical technology has gained worldwide popularity. By process, the supercritical technology shall employ once through flow boiler. Developments are under way to extend the supercritical technology to fluidised bed combustion boilers (FBCs), and also to heat recovery steam generators (HRSGs) for combined-cycle gas turbine (CCGT) plant.

CURRENT POWER GENERATION TRENDS IN INDIA

The present total installed capacity in India as on March 2010 is about 159400 MW excluding captive power generation as on March 2010. Coal based thermal power plants contribute to about 53% of the installed capacity and all power stations are based on subcritical technology with the largest unit being 500 MW capacity. The 500 MW units have been operating at 167 bar/ 538°C/538°C at turbine inlet with the exception of Trombay Unit VI (Tata Power) which has a reheat temperature of 565°C. The once through technology has been introduced in the Talcher 500 MW power station with subcritical steaming conditions. Once through boilers operating in the subcritical range,
have an ability to take larger load change rates without causing adverse effect on the plant operations, when compared to drum type boilers. All these generating units have been operating at an efficiency level in the range of 35-37%.

Indian utilities are on the threshold of adopting supercritical technology and several utilities both private and public sector viz., NTPC, Tata Power, Reliance, JSW, Essar. First supercritical unit is under execution by NTPC, 3 x 660 MW at Sipat, Chhattisgarh. Ultra Mega power plants (UMPP) of 4000 MW are being installed at different locations identified by the Government of India. These power plants would have 660 / 800 MW coal fired units with supercritical technology. The first of these UMPP is under execution by Tata Power in Mundra, Gujarat.

STEAM GENERATOR - TYPES

Rankine cycle is the basic steam cycle employed in power plant. Raising the steam pressure or steam temperature improves the cycle efficiency. When water and steam reach the level of absolute pressure 221.2 bar and the corresponding saturation temperature of 374.15°C, the vapor and liquid are indistinguishable and this point is called the Critical Point. Hence steam generators in which steam generation section (typically the furnace water walls of conventional boilers) operates at full load above the critical pressure (> 221.2bar a) is called a supercritical steam generator and below the critical pressure is called subcritical steam generator. In a supercritical steam generator actual boiling ceases to occur, and the boiler has no water - steam separation. The term "boiler" is not relevant for a supercritical pressure boiler, as no "boiling" actually occurs in this device. Water-tube boilers are classified according to the method of water circulation. Water-tube boilers may be classified as
a) Natural circulation boilers
b) Forced circulation boilers.

The ratio of the actual mass of water flow through the circuit to the steam generated is called circulation ratio. The circulation ratio in large utility boilers with natural circulation ranges from 4 to 8. Forced circulation boilers however depend upon pumps for circulation within the boiler and the circulation ratio is below 4. Boiler in which water flows, without circulation/steam drum, sequentially through the economizer, furnace wall, and evaporating and superheating tubes is called once through boilers. Once through boiler the circulation ratio is 1. The advantages of once through steam generators are as follows:

- Steam pressure is not limited
- Less boiler weight
- Rated steam temperature can be achieved over a wide load range
- Elimination of heavy walled drum decreases metallurgical sensitivity of boiler against pressure changes
- Quick response to load changes and faster rate of start-up and shut down.
- Ability to sustain rapid pressure fluctuations without any danger of circulation disturbances
- No blow down loss
- Has better fuel flexibility and can adapt to fuel variation.

The main reason to the advancement of cycle efficiency through the adoption of supercritical parameters was the development of an economic and reliable once-through boiler. Units operating with supercritical pressure and superheater steam temperatures of above 593°C, are termed as ultra supercritical (USC) units.

DEVELOPMENT OF SUPERCRITICAL STEAM GENERATOR

In late 1950s, USA showed interest in using supercritical steam parameters, using then proven once through boilers which has no limitation on steam pressure. The two major
holders of the ‘supercritical’ steam generator technology were Sulzer, Switzerland and Siemens, Germany. Siemens was and still is the licensor of the Benson once-through boiler technology. Combustion Engineering (presently Alstom) had an agreement with Sulzer where as Babcock& Wilcox and Foster Wheeler had signed with Siemens. The desire for increased efficiency led to the introduction of many large capacity plants with supercritical parameters operating at 245 bar/540°C in early 60’s, with few exceptions where higher pressures and temperatures have been used as indicated in the Table-1.

Some of the units tried with elevated temperatures with materials which were not proven for their suitability for those high temperatures. Most of the problems were due to the use of austenitic steels for heavy section components operating at high temperatures. These steels have low thermal conductivity and high thermal expansion resulting in high thermal stresses and fatigue cracking. These problems and the general low availability of many supercritical plant due to ‘teething’ problems temporarily dampened utility interest in building super or ultra supercritical plants and consequently most utilities reverted back to plants with subcritical conditions of about 170 bar and 525°C. EPRI initiated a phase-wise study for development of materials for suitability of higher temperatures starting from 566°C to 649°C in increments of about 25°C. In the early 80’s with the development of high temperature steels, a number of new units were designed with higher temperatures, of the order of 565°C and 580°C. With experience since 60’s coupled with improvements in design of once-through boilers, by late 80’s new plants could achieve availabilities similar to sub-critical plants.

In the 90’s, few utilities adopted ultra supercritical parameters of 285 bar/ 593°C. The current trend in advanced countries like Japan, Western Europe is to go for higher pressures as well as higher temperatures of 300 bar/ 600°C - 620°C. For the same material constraints, an additional temperature of about 25°C can be achieved in reheat steam temperatures because the re-heater pressures are much lower, so the tubes experience lower stress levels.

### TYPE OF SUPERCRITICAL STEAM GENERATORS & MANUFACTURERS

Around the same time, two once-through boiler technologies viz., spiral type furnace and vertical type furnace with high mass flux were developed by Benson and Sulzer respectively. These two technologies now dominate supercritical market. Further, Sulzer also developed supercritical steam generator of spiral type furnace with minor differences from that of Benson type.

Despite different histories, the Benson design (owned by Siemens AG of Germany) and the Sulzer design (presently owned by Alstom, formerly known as ABB) look very
similar. Both can offer two-pass, tower designs and both employ spiral-wound furnace tubing and separator vessels for start-up. Although the license holders, Siemens, do not themselves manufacture boilers, the Benson license is the market leader. There are about twenty licensees and sub-licensees who carry out detailed design and manufacture.

The major manufacturers holding Benson licenses include Doosan-Babcock, Steinmüller (Germany), AE&E (Austria), BWE (Denmark), Mitsui Babcock Energy Limited (MBEL, UK), Babcock-Hitachi KK (Japan), IHI (Japan), Babcock & Wilcox (USA) and Ansaldo Energia (Italy). Alstom now hold the Sulzer license and are moving away from licensing agreements, preferring to manufacture the plant themselves where possible, or alternatively using local partners in joint ventures. The number of Sulzer license holders is therefore reduced but still includes Korean Heavy Industries (Korea) and Formosa Heavy Industries (Taiwan), Mitsubishi Heavy Industries (MHI, Japan) and Alstom (France) are former licensees and their current designs derive from a Sulzer pedigree. BHEL have technical collaboration with Alstom and L&T have a joint venture with MHI to manufacture supercritical steam generators in India.

**SUPER CRITICAL STEAM GENERATOR DESIGN**

Operation at supercritical parameters, where there is no distinction between liquid and vapor, requires unique design features, most notably in furnace circuitry and components. The design is also very much influenced by the intended operating mode, constant pressure or sliding pressure. Constant pressure SGs are of high mass flux and maintained constant supercritical pressure. This was achieved by installing a throttle valve between evaporator and super heaters. They employ furnace recirculation over the entire operating range. As these units stay only in single phase region, the constant pressure furnace can be sized similar to a high pressure sub-critical natural circulation unit.

To handle rapid and continual load ramping, to minimise turbine temperature transients the boiler shall be designed for sliding pressure. Sliding pressure design calls for different criteria to size the furnace, and material selection apart from construction and component design compared to constant pressure.

**CONSTANT PRESSURE VS SLIDING PRESSURE**

Constant pressure operation implies maintaining stable pressure in both steam generator and main steam line over the unit’s load range. The steam turbine generator requires steam pressure in proportion to the load, for maintaining the same efficiency. If the SG varies its pressure as required by the STG for each load, the mode is referred to as pure sliding pressure operation. However, units adopt modified sliding pressure operation in order to have fast response load reserve.

A typical 262 bar a steam pressure rating, a (modified) sliding-pressure steam generator operates at subcritical pressures at loads below about 73% maximum continuous rating (MCR) refer Figure-1.
Fig. 1: Steam Generator Operating Mode

BASIC DESIGN CONSIDERATION

Furnace walls are formed by finned or fusion welded tubes that form a continuous water-cooled envelope. The biggest concern with any sliding pressure, supercritical design is created by the requirement for once-through operation and designing for sufficiently high mass velocity that ensures cooling of the furnace tubes. Drum units require smaller mass flux which is maintained by the use of either natural or forced circulation. These boilers can have higher diameter furnace tubes and are designed to generate steam in the furnace walls under nucleate boiling conditions. Nucleate boiling is characterized by formation and release of steam bubbles at the surface-liquid interface with the water continues wetting the inner surface of the tube. The heat transfer coefficients in the nucleate boiling regime are high and a temperature gradient between the metal tube and the fluid inside the tube is relatively small refer Figure-2.

Fig. 2: Boiling heat transfer inside furnace tube

Once through steam generators require higher mass flux to ensure cooling of tubes even in dry out (DO) region. These boilers shall have smaller diameter furnace tubes and are
designed to generate steam in the furnace walls under both nucleate and film boiling conditions. In these steam generators, water wall mass flow changes in direct proportion to steam flow. In the supercritical pressure region, the fluid inside the tubes is heated and the heat is directly converted into a higher temperature. In the subcritical pressure region the process of heat transfer is more complicated and the process involves a change in phase from liquid to steam as well as superheating. Normally water enters the furnace tube in a sub-cooled state and progressive vaporization and slight superheating occurs in the tube. As the quality of the steam-liquid mixture increases, various two-phase flow patterns are encountered.

The designers must be concerned with two critical conditions: Departure from Nucleate Boiling (DNB) and DO. DNB and DO are characterized by formation of a flow of steam which covers the inner surface of a tube, a sharp decrease in heat transfer coefficient, and a consequent high metal temperature rise. DNB is of major concern at operating pressures of 204 bar and higher since, at these pressures, it is possible for DNB to occur even in sub-cooled and low quality regions of the furnace where heat fluxes are relatively high. While DNB may also occur at lower pressures, of greater concern at these pressures is DO which is unavoidable as long as a boiler operates in once-through mode.

Once-through operation brings about a second design challenge; namely, elimination of potentially damaging stresses resulting from temperature differences at the furnace wall outlet. With once-through design, the steam outlet of the furnace walls is slightly superheated. Therefore, tube circuits can be at different temperatures due to the variation in heat absorption patterns around the furnace perimeter. These temperature differences must be maintained within acceptable limits.

**FURNACE WALL**

The most popular tube arrangement in the combustion zone is that spirally wound membrane walls utilizing smooth bore tubing. This inclined tubing arrangement reduces the number of parallel paths compared to a vertical wall arrangement and therefore increases the mass flow of fluid (steam/water mixture) through each tube. This high fluid mass flow improves heat transfer between the tube metal and the fluid inside, and cools the tube metal adequately and uniform heat loading of tubes. The spiral water wall arrangement with inclined tubes in the furnace region is shown in the Figure-3.

[Fig. 3: Spiral Wall System]
For sliding pressure operation boilers maintaining uniform fluid conditions at low load and low pressure operation becomes critical to reduce the potential of tube damage caused by high metal temperature. The lower part of the furnace water walls are arranged in a spiral configuration such that the fluid path wraps around the boiler as it travels up the furnace. This flow path arrangement smoothen the effects of the local heat hot pots in the furnace and around the burners, which ensures the uniform fluid temperature distribution at the outlet of the furnace wall. The spiral wall does not require any flow adjusting orifices. The comparison of the fluid temperature distribution between the conventional vertical wall and the spiral wall is shown in the Figure- 4.

![Water Wall Type and fluid Temperature](image)

Alternative arrangement is of vertical furnace wall design also require high mass flux, but lower than spiral design. These boilers use vertical tubing with internal rifling in the lower furnace to enhance heat transfer. In the upper furnace, the industry standard design is vertical membrane smooth tubing, where the heat flux from the furnace is much lower. The internally ribbed tubes provides sufficient tolerance against departure from nucleate boiling (DNB) for all the furnace upset conditions. The application of the internally ribbed tubes minimizes system pressure drop through the furnace because of the superior heat transfer properties achieved at lower fluid mass velocities. Proper water distribution according to heat absorption of each tube can be realized by throttling orifices installed at inlet of each water wall tube. Further an inlet strainer with many holes is located in the manifold to avoid plugging of orifices.

Spiral design has an advantage of using smooth tubes with better heat absorption characteristics. However, this will have a higher pressure drop, complex support arrangement of the spiral tubes which would require longer installation time. High mass flux vertical tubes (Sulzer design) have an advantage of lesser pressure drop with traditional tube support system which would require less installation time. However, this requires orifices across each tube to maintain the required mass flow. The temperature variation in the fluid at the water wall outlet is more than the spiral design.
As continuous development, Benson is coming up with new furnace design ‘Vertical furnace with low mass flux’, having advantage of approaching the conventional furnace design with lower mass flux, and also elimination of orifices which are otherwise essential in ‘high mass flux vertical design’. These boilers will have self compensating hydraulic behavior and use optimized ruffled tubes.

STEAM GENERATOR STARTUP SYSTEM

Today’s supercritical power plants are designed with flexibility to operate in two shift or rapid and contunual load ramping. To meet these requirements the steam generator must be designed for sliding pressure operation. This means that SG shall be able to operate in supercritical mode during normal operation and sub critical mode during low load and start-up. To facilitate this requirement, a low load start-up system is provided. For boilers that are primarily base loaded, the once-through minimum load should be selected as high as possible. This results in the lowest pressure drop in the water walls at a full-load condition. Steam generators that operate in cyclic loading must be designed for a lower once-through minimum load. Commercial experience with a minimum once-through flow down to 35% to 40% load has proven to be successful. Lower once-through loads are also feasible. The start-up system refer Figure-5 includes a water separator located between the water walls and the primary superheater, a water storage tank and a drain water discharge system with heat recovery capabilities. The water separator consists of one or more vertical vessels with tangential inlets, steam outlets are located in the upper part and the drain is discharged through the lower part. The water separator is in “wet condition” when it operates in flow recirculation mode and it is “dry” when the flow is once-through.

Fig. 5: Startup System
There are two types of direct heat recovery systems that are available. The first one is a system with a low load recirculation pump the second one is a system that includes a drain return line via a heat exchanger into the deaerator / feed water storage tank. The suitability of each system depends on the economic evaluation associated with operational requirements of the steam generator.

**SALIENT FEATURES OF SUPERCRITICAL UNITS**

The salient features of the supercritical units as compared to subcritical units are:

a) Improved thermal performance  
b) Reduction in emission  
c) Plant availability  
d) Load response  
e) Fuel flexibility  
f) Requirement of improved material  
g) Feed cycle chemistry

**THERMAL PERFORMANCE & EMISSION REDUCTION**

The main advantage of a supercritical unit is to increase the overall plant thermal efficiency thereby reducing the fuel consumption per unit of electricity generated. This can be increased either by increasing superheater / reheater steam temperatures or pressures or both. The improvement in plant heat rate due to different steam parameters is furnished in Table 2.

**Steam Parameters at turbine inlet (Bar(a) / Deg. C / Deg. C)**  
**Improvement in plant heat rate**

<table>
<thead>
<tr>
<th>Steam Parameters at turbine inlet (Bar(a) / Deg. C / Deg. C)</th>
<th>Improvement in plant heat rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>170 / 538 / 538</td>
<td>Base</td>
</tr>
<tr>
<td>170 / 538 / 565</td>
<td>5.0 %</td>
</tr>
<tr>
<td>246 / 538 / 538</td>
<td>1.6 %</td>
</tr>
<tr>
<td>246 / 538 / 565</td>
<td>2.1 %</td>
</tr>
<tr>
<td>246 / 565 / 565</td>
<td>3.0 %</td>
</tr>
<tr>
<td>246 / 565 / 593</td>
<td>3.6 %</td>
</tr>
<tr>
<td>306 / 598 / 593</td>
<td>5.0 %</td>
</tr>
</tbody>
</table>

Table – 2: Improvement of heat rate due to steam parameters

Along with fuel reduction, there will be reduction in CO₂ emissions, e.g. there will be reduction of about 8-10 % in CO₂ emission in supercritical units compared to subcritical units. Similarly, all other emissions, viz., NOₓ, SOₓ are also reduced with reduced fuel consumption. These advantages, improve with the higher selected steam parameters, giving the scope for continuous improvement. Worldwide R&D efforts indicate realization of coal fired power plants with ultra supercritical parameters of 350 bar (a) / 700 deg. C / 700 deg. C. by the year 2015.
PLANT AVAILABILITY

The initial reliability and availability of supercritical units were not as good as sub-critical ones. Nowadays, the reliability and availability of supercritical units reaches to or even exceeds the level of sub-critical units due to the improvements in material technology, use of oxygenated treatment, development of more responsive control processes, and the accumulation of operation experience.

LOAD RESPONSE

There are no operational limitations due to once-through boilers compared to drum type boilers. Moreover once-through boilers are better suited to frequent load variations than drum type boilers, since the drum is a component with a high wall thickness, requiring controlled heating. This limits the load change rate to 2% per minute, while once-through boilers can step-up the load by 5% per minute.

FUEL FLEXIBILITY

Fuel flexibility is not compromised in once-through boilers. All the various types of firing systems (front, opposed, tangential, arch firing with slag tap or dry ash removal, fluidized bed) used to fire a wide variety of fuels have already been implemented for once-through boilers. All types of coal have been used.

MATERIALS OF CONSTRUCTION

Increase in the cycle steam temperatures was possible because of the development of materials suitable for higher temperatures. Materials must be developed to get the required properties for the specific application within the cycle.

Evaporator tubes (Furnace walls)
The water walls in boilers for subcritical steam conditions are generally configured as evaporators. At increasing steam temperatures and pressures, the fraction of evaporator heating surfaces decreases, with the result that parts of the water walls must also be configured as superheaters, i.e. downstream of the separator. Furnace wall is one of the most critical components, limiting the use of more advanced steam conditions. The walls experience the greatest heat flux of all heat absorbing surfaces because of the intense radiant heat transfer from the fire ball. To prevent tube rupture, not only the tube metal temperatures must be kept low, but also maintain uniform temperatures across all tubes. These criteria set both the minimum required water wall fluid mass flux and also the maximum temperature limits.

With current materials, the allowable metal temperature at the furnace exit is limited to about 480°C. This corresponds to mean evaporator outlet fluid temperature of about 450°C, normally using T11 (1%Cr,0.5%Mn). This corresponds to main steam temperature conditions of about 290bar/580°C. Withstanding higher furnace wall temperatures alone is not reason for selecting the water wall materials. Ease of welding, without pre or post weld heat treatment (PWHT) shall also be satisfied. In fact, there are many alloys which can tolerate higher furnace wall temperatures but require PWHT, which has driven for further material development. Finally, two steels have been developed. One of them is T23 (2.25% Cr, 0.1% Mo, 1.6 % W), developed by alloying T22 with addition of tungsten and reduction of Mo, and the second one is HCM 12 (12% Cr, 1% Mo, 1%W, 0.25 % V,0.05%Nb, 0.03% N) which is an improved version of HT91(12% Cr, 1%Mo,0.25% V) by adding tungsten and Nb, N in small amounts. These
materials are suitable for water walls (including upper section) from creep strength point of view, up to steam temperatures of 595-650°C. Available materials for the water walls are T22, T23, T24 and T91.

**Superheater & Reheater tubes**

In a boiler, superheaters undergo severe service conditions. The materials shall meet stringent requirements with respect to fire side corrosion, steam side oxidation, creep rupture strength and fabricability. For header and piping, material temperature is nearly equal to the steam temperature. For tubing, the metal temperature is generally higher than the steam temperature by up to 28°C (50°F). These materials shall have improved properties to operate at higher temperatures. The required improved properties could be achieved by alloying the basic ferritic steels with various other elements either by precipitation strengthening (With Nb, V, Ti, Mo, W), solution strengthening (with Ni, Cr, Mo, W) or interstitial element strengthening (with B & N). The limitation of steam temperature for ferritic steels is 565°C. At higher temperatures austenitic steels viz., SS347, TP347 HFG, can be used up to steam temperature 593°C and materials viz., Super304H, 310 NbN can be used up to steam temperature of 620°C. Inconel 617, NF 709 can be used up to 650°C steam temperature. PWHT is always required for welded joints of advanced 9 to 12 Cr alloys to ensure minimal stress and operational ductility.

**Header and Steam Pipes**

Material property requirements for headers and steam pipes are more or less similar, with minor differences. Thermal-fatigue strength requirements are greater for headers than pipes. Higher wall constructions are permitted for headers. Headers have many welded attachments and might require dissimilar welded joints depending on its location. Material P22, P91 are suitable up to 565°C and 593°C respectively. P92 is developed from P91 by adding tungsten. P92 is having excellent properties at elevated temperatures. It is suited up to steam temperatures of 620°C. Materials NF12, SAVE 12 which are 12 % Cr steels are in the development stage and are expected to withstand up to 650°C.

**FEED CYCLE CHEMISTRY**

As a part of commissioning activities prior to keep the boiler in operation, acid cleaning is performed in the boilers. During this process, intentionally black layer of magnetite (Fe₃O₄) is made to form on the boiler tube surfaces, which prevents further corrosion of the parent material. However, oxygen that enters the condensate system will oxidize the protective layer of magnetite to brownish red colour ferric oxide (Fe₂O₃). Nodules of corrosion products and pits may form at the corrosion sites. Corrosion products will enter the solution and be transported to downstream to the boiler, where higher heat loads cause the particles to precipitate. These deposits either can set up corrosion cells or inhibit heat transfer the across the tube boundary and can shorten the tube life on long time due to overheating. Oxygen being an aggressive corroden, control of its leakage and removal of dissolved oxygen are very important in any power plant.

All-volatile treatment (AVT) was primarily developed for once through boilers, since these units can not tolerate dissolved solids. As there is no steam drum in once through boilers, boiler water chemistry is a function of feed water chemistry. Considering the ALARA (As–low–as–reasonably-achievable) principle, the cation conductivity in condensate and fed water is set at, 0.2 uS/cm for both high pressure drum type and once through steam generators.

AVT treatment is also applied in high pressure drum type boilers, to minimize mechanical carryover. Depending on the cycle metallurgy, either AVT® or AVT (O) will be used. For mixed metallurgy (use of both copper and ferrous based materials) AVT ©
is the best suitable, where as for ferrous metallurgy AVT (O) is best suited.

In AVT®, hydrazine is used as a reducing agent and injected into the condensate prior to LP heaters. The cycle chemistry is maintained with cation conductivity of less than 0.2 uS/cm, pH of 9.1 to 9.3 and dissolved oxygen less than 5 ppb. In AVT®, with hydrazine injection, thicker and porous magnetite layer is formed, results in a higher iron content in the water, hence not suitable for ferrous metallurgy.

In AVT (O) no reducing agent is used and the cycle chemistry is maintained with cation conductivity of less than 0.2 uS/cm, pH of 9.2 to 9.6 and dissolved oxygen less than 10 ppb for drum type units and less than 20 for once through units. In AVT (O), both hematite (Fe₂O₃) and FeOOH are formed on top of the magnetite, which are less soluble and hence more stable than the magnetite layer of AVT®. This prevents flow assisted corrosion and flow orifice fouling, hence suitable for ferrous metallurgy.

In cycles with all-ferrous metallurgy a feed water treatment other than AVT(O) may also be used. OT program in which ammonia is added for pH control, the program is designated as combined water treatment (CWT). The first large scale application of CWT was reported in Germany by Mr. Freier in 1969 and 1970 on units with once-through sub critical boilers. While elevated pH is the basis of AVT, CWT uses oxygenated high purity water to minimize corrosion and FAC in the feed water train. In contrast with AVT, CWT can be applied only in plant cycles with all-ferrous metallurgy downstream of the condenser.

In AVT units even with very good chemistry programs, some iron oxides are transported to the boiler, where they precipitate on the tube walls.

In OT, with controlled oxygen injection, the base layer of magnetite becomes overlayed and interspersed with an even tighter film of ferric oxide hydroxide (FeOOH). This compact layer is more stable than magnetite and release very little dissolved iron or suspended iron oxide particles in the fluid. This layer gives an excellent protective margin against FAC and minimise the orifice fouling. OT can be applied for sub-critical units also. The first drum unit was converted in the US in 1994, and there are now well over 100 drum units worldwide that have been converted to OT.

With OT, the oxygen control is very important. For once-through units, an oxygen level of 30–150 ppb is maintained across the whole plant cycle. For drum units the oxygen levels are 30–50 ppb at the economizer inlet. Any departure from this dissolved oxygen range depletes the protective layer and results in detrimental FAC.

The use of oxygen as a corrosion inhibitor allows satisfactory operation over a wide pH range. Thus, a marked reduction in plant cycle pH is possible. Even if this reduction is not always practiced, the application of a pH range from 8.0 to 8.5 for once-through units has an advantage in the reduction of condensate polisher regeneration frequency. In all the supercritical units, it is essential to adopt OT feed cycle chemistry, with 100% condensate polishing unit to maximize plant availability.

**CODES & STANDARDS**

Different counties follow different codes for boiler pressure part design/calculations like IBR, ASME, BS1113, TRD 301, IJS, KS etc. Worldwide ASME is acceptable for design of boiler, whereas in India, IBR Code is used. IBR code mainly deals with subcritical boilers, and for supercritical steam generators it covers only certain aspects but not design requirements. For example, IBR defines the criteria for selecting the working metal temperature of the furnace wall tubes as ‘Td= Sat. temp. corresponds to working pressure +28°C’. This is however not sufficient and valid for supercritical steam generators, as the furnace tubes are subjected to two phase flows. IBR also does not include advanced materials which are normally used in supercritical steam generators with higher steam parameters.

Even when the present IBR is followed for supercritical steam generator design, there
are some differences between the IBR and other International codes, in areas like, set pressures and relieving capacities for the safety valves, requirement of main steam stop valve, design pressure of the feed water system, requirement of startup vent and its capacity, permitting HP bypass valves with safety function in lieu of separate set of spring loaded safety valves etc.

In view of the above, there is a need to revise IBR to include supercritical steam generators design also, considering the differences that presently exist between IBR and other International codes.

For revision, IBR may consider design practices stipulated by ASME and other International codes. In the mean time, till such revision is effected, IBR could permit use of American / European codes in designing supercritical steam generators.

OPERATIONAL ASPECTS OF SUPERCRITICAL UNITS

Start-up and Minimum load

For start-up of a boiler, a minimum flow feed water flow must be established and maintained before firing commences. This minimum flow is typically around 30-40% MCR flow and it determines the ‘minimum once-through load’. This fixed minimum flow is necessary in order to provide adequate cooling to the furnace wall tubes. The excess water over and above the extent of steam generation is dumped/re-circulated through a start-up separator vessel by a level control loop. Once steam generation matches the minimum feed water flow the separating vessel will run dry and once-through mode is then established. The feed water flow must then be increased to match the increase in steam generation.

Higher Feed pump power consumption

The power consumption of the feed pump is higher than for a drum boiler because in addition to the pressure drop in economizer and super heater, there is the pressure drop in evaporator to be considered. This is the drop required to obtain sufficient velocities in the small diameter boiler tubes and also to cover the pressure drop in water separator. The total pressure drop in once-through boilers is normally 30-50 bar compared to pressure drop 15-25 bar of drum type boilers.

Rate of Load Changes

Higher loading rates are possible in a once-through boiler compared to a drum type boiler as the once-through boiler has a lower thermal inertia. The thickness of the separating vessel in a once-through boiler is lower than the drum thickness in a drum type boiler. This separating vessel may represent a limitation on the rate of pressure rising in a boiler from a cold condition but once the unit is on-load, these components would not pose any limit to normal load changing.

Steam Generator Control

For supercritical units, since there is no energy reserve in the form of steam drum, the control system must match, exactly and continuously, feed water flow and boiler firing rate (both fuel and air) to deliver the desired generator power. The ability of the control system to achieve stable and steady-state operation, without oscillations is critical to achieve supercritical unit efficiency. The lower thermal storage capacity of the oncethrough boiler means that the pressure is more sensitive to system upsets. For example on a frequency excursion the deviation of the pressure from the set point in a oncethrough boiler will be more than in a drum type boiler. Because of the absence of a fixed final evaporation point in a once-through boiler, the boiler must be controlled in such a manner that there always exists a constant ratio
between feed water rate and firing to the boiler. Only this type control action can maintain constant steam pressure and temperature for a constant feed water temperature. A certain compensation for the absence of water level indication is found in the ratio of spray water to feed water in a once-through boiler, refer Figure-6. Spray water flow will be used to control steam temperatures for a short term only until the effects of the change in feed water flow, reflected in the steam outlet temperature.

CONCLUSION

Supercritical technology is a matured technology. There are several large capacity power plants operating in the world with supercritical technology. Supercritical power plants would provide not only higher efficiency and lower emissions but also offer flexibility in unit operation. In order to meet the rapid capacity additions in India, large capacity units with supercritical technology are necessary. There is a need to revise IBR to include supercritical steam generators design, considering the differences that presently exist between IBR and other International codes. For revision, IBR may consider design practices stipulated by ASME and other International codes. In the mean time, till such revision is effected, IBR could permit use of American / European codes in designing supercritical steam generators.

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