Research Journal of Engineering Sciences ISSN 2278 – 9472
Vol. **2(1),** 27-34, January **(2013)** *Res. J. Engineering Sci.*

Review Paper

Effect of Parameters in Once-Through Boiler for Controlling Reheat Steam Temperature in Supercritical Power Plants

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Available online at: www.isca.in
Received 5th November 2012, revised 15th November 2012, accepted 25th November 2012

Abstract

In once through boilers, superheated steam is generated at a pressure and temperature above the critical point of 221.2 bar and 375^{0}C. For controlling Reheat steam temperature in once through boilers, many methods are being adopted namely Burner angle, Gas Recirculation, divided back pass dampers, excess air and steam bypass as primary control and feed water attemperation is considered as an emergency control. When the boiler is operated in sliding pressure mode the cold reheat steam temperature is higher compared to constant pressure operation. The adjustment required for maintaining constant Reheat outlet temperature is larger in constant pressure operation mode. In general spray is not used for RH steam temperature control for boilers designed for constant pressure operation since the spray quantity required will be large and it will effect on plant heat rate. Utility boilers are operated under sliding pressure mode and hence Reheat steam temperature control by spray is a common practice especially for once-through boilers. This paper deals with the benefits and losses of using spray for Reheat steam temperature control in lieu of other control mechanisms. If the plant incorporates reheat and several stages of feed heating, there is about a 2% gain in overall thermal efficiency compared with the corresponding subcritical cycle.

Keywords: Once-through boilers (OTB), supercritical cycle (SC), reheat (RH), and superheat (SH), gas recirculation (GR), natural circulation (NC).

Introduction

In utility boilers, it is important to achieve best possible heat rate to reduce the fuel cost and hence the operators try to maintain superheat and reheat steam temperatures at a rated value to the extent possible[1]. In a once through boiler there is no distinction between liquid and vapor phases and there is a continual increase in fluid temperature[2] In once through boilers, SH steam temperature is maintained by means of coordinated feed water flow and spray attemperation. There are many methods to control RH steam temperature: like Tilting of burner, gas recirculation (GR), divided back pass dampers, excess air and steam bypass. Spray, though considered as an emergency control, is not preferred as a means of RH steam temperature control in constant pressure operation as it affects plant heat rate. However, in case of once through boilers which are generally operated in sliding pressure mode, quantum of RH spray is expected to be lower. In this case RH spray attemperation is preferred as it will result in simpler design and operation of the boiler and also less maintenance as systems like Tilt of burner, GR fans; divided back pass dampers are eliminated[3]. The Effect of optimum number of Feed water heaters on the overall plant efficiency improvement is explained by[4, 5].

Once-through supercritical boilers have been installed in the U.S. since the 1950s. Some of the earlier constructed units have experienced various problems related to operation and reliability[6]. The original supercritical units installed were designed for constant pressure operation, i.e. the boiler operates at full load pressure from start-up and across the entire load range. For start-up, constant pressure operation boilers require a start-up bypass system, which is complex in configuration and operation compared with the new sliding pressure Benson boilers. As a result, the start-up time for constant pressure boilers is longer and the plant minimum load must be kept higher than for the sliding pressure units[7]. Nearly 200 supercritical steam generators are operating world-wide today, with pressures up to 310 to 320 bar. In Supercritical Power Plants the Feed Water Temperatures can be raised up to 200^{0}C[8]. More advances in materials and designs introduced in the late 90's have raised steam temperatures as high as 620^{0}C achieving efficiencies of 44%[9]. At steam temperatures up to 650^{0}C, efficiencies of 50% are being predicted[10, 11]. The nature of supercritical steam generation rules out the use of a boiler drum to separate steam from water Drum less "once through" steam generators are universally used for Supercritical operation. The term "steam generator" will be used instead of "boiler" for once-through steam production, because boiling as such does not really take place. Turbines for subcritical systems are usually designed for steam pressures of 180bar. A drum operating pressure of 180 to 200bar is required to allow for pressure drops in the superheater and main steam line. The densities of steam and water rapidly approaching each other above this pressure level represents an approximate limit for drum-type boilers incorporating steam separation and recirculation. Thermodynamic analysis and its improvement in heat and power for power plants is explained[19].

Constant and Sliding Pressure Operation

The output of a condensation power station is set by means of the live steam mass flow $\dot{m}_{LS}$ The mechanical power, P_m of the turbine shaft depends on the live steam pressure P_{LS}, the cross-section of the opening A, or the lifting of the turbine intake valves, and the live steam temperature, T_{LS} according to the following relation:

$$P_m \approx \dot{m}_{LS} \approx A \frac{P_{LS}}{\sqrt{T_{LS}}} \quad (1)$$

The live steam temperature should remain constant throughout the whole load control range, so that a high efficiency rate is also achieved during part load and to avoid stress on the turbine caused by temperature changes. The turbine output and the live steam mass flow to the turbine are set during steady-state conditions, either when the live steam pressure is at a constant cross-section of the turbine intake valves (sliding or variable pressure) or when the intake cross-section is at a constant steam pressure (constant pressure).

Sliding pressure operation with a low-load recirculation system enables the Benson type boiler to start-up with similar operation characteristics and a start-up pressure profile as for an NC drum type boiler. While the start-up valves in a constant pressure supercritical boiler have to resist a large pressure difference during the bypass operation, the start-up valves in a sliding pressure boiler are only used during the swelling period, which occurs immediately after boiler light-off. The differential pressure during such swelling is less than 6.8 bar, and therefore the duty of the start-up valves is much less in a sliding pressure boiler than the constant pressure boiler. For the Benson boiler, the transition from recirculation mode to once-through mode, or vice-versa, is performed automatically with the operation of the low-load recirculation system and turbine bypass system.

By adopting the sliding pressure operation with lower boiler pressures at partial loads, the plant heat rate can be improved at partial loads due to i. improvement of high pressure (HP) turbine efficiency, ii. reduced auxiliary power consumption by boiler feed pumps, and iii. higher steam temperature at the HP turbine outlet. In addition to the plant efficiency advantages, there are other benefits such as reduction in start-up time, increase in ramp rate and reduced erosion of bypass valves. Sliding pressure operation can be utilized in certain drum type boilers as well as once-through steam generators (with some qualifications). The main advantage is higher part load efficiencies. In a conventional drum type boiler-turbine combination, the boiler pressure remains essentially constant throughout the operating range, with load control accomplished by the turbine throttle valves. Throttling steam flow is not a reversible process and therefore introduces inefficiencies to the cycle. With sliding pressure operation with drum type boilers, the turbine operates essentially with throttle valves wide open throughout most of the load range, but admits steam to only a portion of the throttle valves (partial arc admission) rather than all of the valves (full arc admission), and the turbine power is controlled by varying the boiler pressure. Sliding pressure operation has the further advantage of maintaining full superheat temperature over a wider load range than conventional throttling control. This reduces the cyclic thermal stresses experienced during cycling operation. Cycling operation may be defined as rapid rates of load increase and a significantly larger number of starts up and shut down cycles compared to a base load unit.

In once through steam generators, load is a function of the steam flow, which in turn is controlled by the feed water pumps. If the pressure throughout the steam generating tubes is allowed to drop below the critical pressure, two-phase flow and steam-water separation will result. This will result in some of the secondary superheater tubes having variations in the steam-water mix. Because of the differences in densities between steam and water, flow will be restricted in the tubes having a greater steam concentration, and uneven heat transfer could cause tube failures.

In order to take advantage of the benefits of variable pressure operation during load turndown, pressure control division valves are installed between the primary and secondary superheaters. These valves keep the steam generator tubes above the critical pressure, while permitting the turbine to operate under its optimum pressure for a given load. With partial arc steam admission, the full steam throttle pressure can be maintained down to about 60% load. Because of the requirement to maintain steam generator pressure, the advantage of reducing feed pump pressure at reduced loads cannot be realized with supercritical cycles. The steam temperature is controlled by the firing rate, and is augmented in some units by injecting superheating water between the superheat stages. A once through steam generator requires a more precise balance of Inputs and outputs than drum type boilers because of the lack of the flywheel effect of a boiler drum.

In sliding-pressure operation, the turbine output and the steam flow are adjusted by the pressure at the outlet of the boiler. In natural sliding-pressure operation, the live steam valves of the turbine are completely opened, and the cross-section of the turbine intake is constant throughout the whole load range.

Advantages of sliding-pressure control are a load-independent temperature distribution in the turbine, a lower pressure stress on the steam generator and a lower power demand of the boiler feed water pump in part-load operation. Disadvantages are the changes of the boiling temperature in the evaporator, due to the pressure changes. The advantage of the decreasing power requirement for boiler feed pumping is stronger when the live steam pressure becomes higher. The general outcome in applying natural sliding pressure is a heat rate (including that of the boiler feed pumping power) which is slightly better than with nozzle-governed constant-pressure operation; with modified sliding pressure the heat rate is higher.

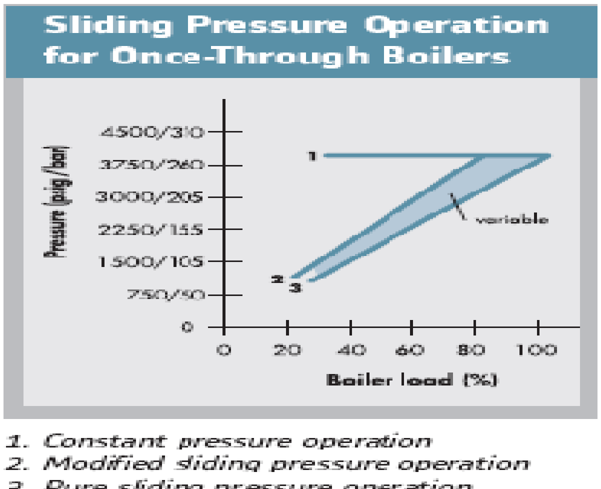


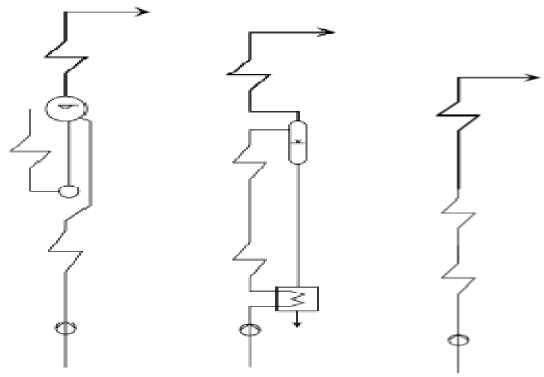
Figure-1
Graphical Representation of OTB pressures at different Boiler loads[18]

Supercritical Steam Generator Design Configurations

The major differences between the various once-through steam generator designs on the market are the configuration of the furnace enclosure circuits and the systems used to circulate water at start up and low loads.

The three leading designs are: i. Vertical Tube multipass furnace, upon which early Supercritical designs were based. These proved suitable for the base load operation, but were not as well –suited for cycling because of the thermal stresses involved. ii. The spiral tube Benson furnace configuration, in combination with a boiler recirculation pump was developed to minimize thermal shock during transients. iii. Spiral tube Sulzer furnaces are very similar to the Benson furnaces; both use Seperator vessels for start up.

Impact of HP spray water Flow on Once-Through Steam Generators by Sliding-Pressure or Constant-Pressure operation: Circulation systems are almost exclusively operated with constant-pressure control, while once-through systems mostly use sliding pressure, though in some cases constant pressure as well. For steam generators operated with constant pressure only in the evaporator, sliding-pressure operation does have the well-known operating advantage, though not the economic advantage, of the disproportionately decreasing power consumption of the boiler feed pump in part-load operation.



(a) (b) (c)
Figure-2
a) Natural Circulation[1] b) Once Through and residual water separation[1] c) Once through Benson Boiler[1]

In both boiler systems, greater output changes are always initiated by increasing the firing rate. Drum and once-through boilers differ in controlling the feed water. In drum boilers, the feed water is designed to be controlled by the drum water level. The feed water control is coupled with the fuel control via the evaporator and the circulation system. Changes in the feed water flow do not immediately influence the flow through the superheater. When the firing rate is increased, delayed steam generation in the circulation system, due to the large storage capacity of the evaporator, may result in insufficient superheater cooling. With rapid load changes, the spray attemperators often do not suffice to control the live steam temperatures, so this circumstance places another limit on the load change rate in drum boilers. Once-through boilers are capable of coping with load change rates of 5-8% per minute, which is higher than the rates of 2-3% per minute that drum boilers can deal.

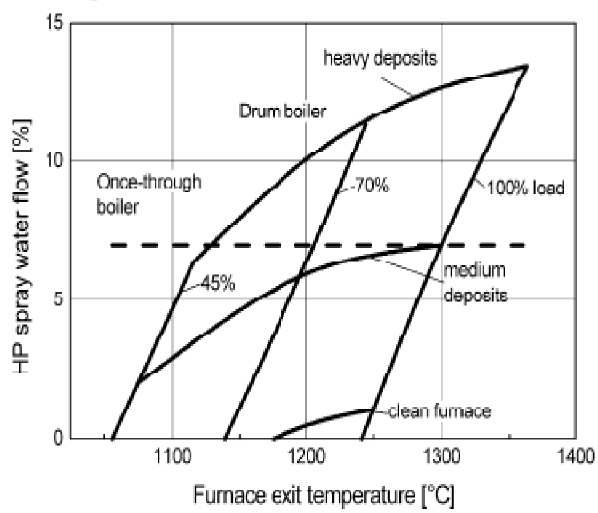


Figure-3
Dependence of the HP spray water flow on the unit output and on the fouling state of the furnace[1]

Need for steam temperature control

Superheat and reheat steam temperatures should not be allowed to increase beyond the rated value as it will result in metallurgical problems in superheater and reheater tubes and also turbine components. On the other hand, steam temperature lower than rated value will result in higher cycle heat rate. Typically a temperature reduction of 10^{0}C in large capacity power plant will result in about 0.3 % increase in plant heat rate. Hence it is essential to maintain the superheat and reheat temperatures within a narrow range around the rated values.

In a coal fired boiler, super heat and reheat pick up are influenced by many variables like coal quality, dirtiness of the furnace, fouling of heat transfer sections, etc,. When the furnace is cleaner compared to the design condition, the furnace absorption is more resulting in lower furnace outlet temperature and hence lower SH and RH temperatures. On the other hand, when slagging / fouling occurs due to deterioration in coal quality, furnace absorption will be lower resulting in higher furnace outlet temperature and hence higher SH and RH outlet temperatures. Normally superheat steam temperature is maintained over the load range by means of coordinated feed water flow and spray attemperation. Various methods are employed to maintain the reheat steam temperature at rated value over the control load range. The after effect of reheat temperature control on superheat temperature increase or decrease is regulated by feed water attemperation[12,13].

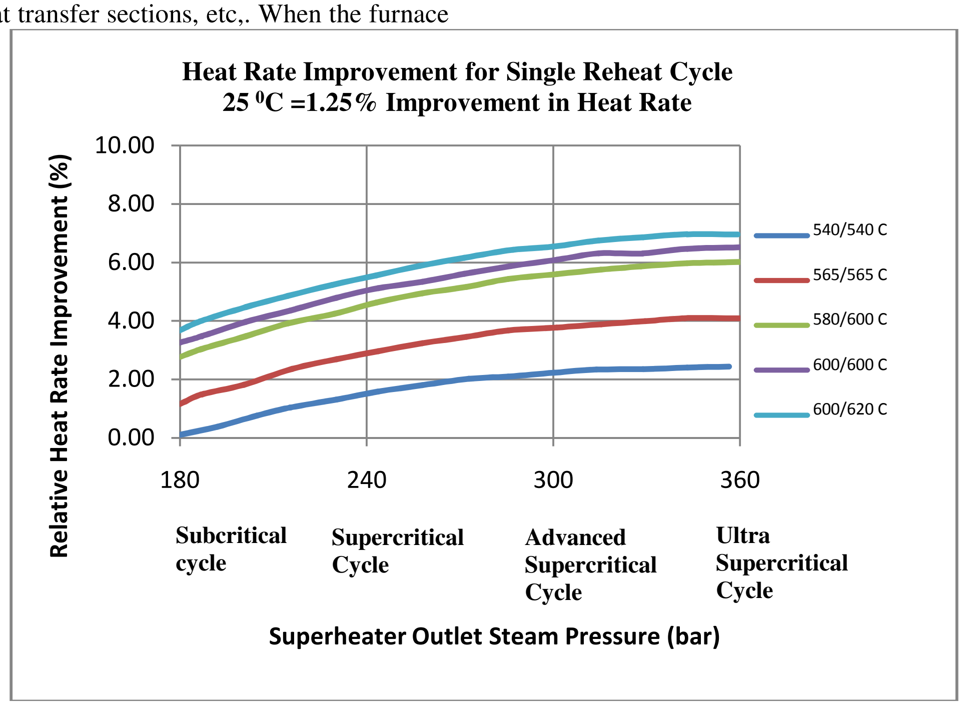


Figure-4
Effect of Relative Heat Rate Improvements for different superheater outlet pressure for Boiler

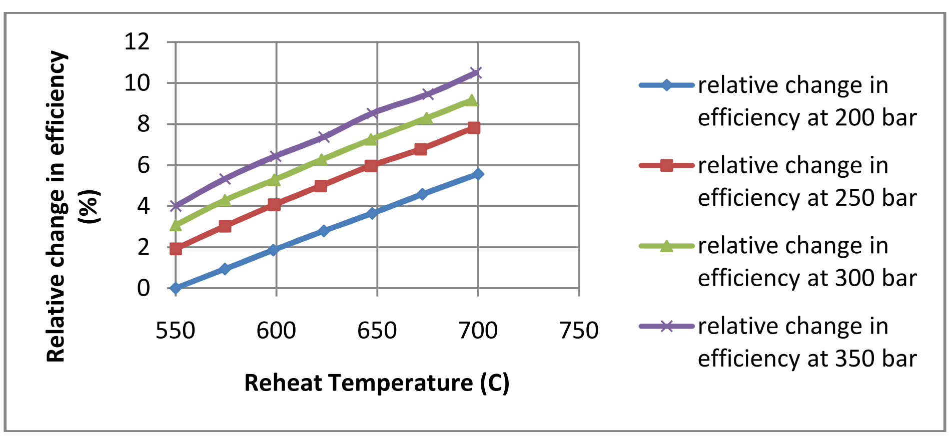


Figure-5
Effect of Relative Change in Efficiency for Reheat Temperature at different Pressures

Burner angle

Tilting burners are provided in corner or tangential fired boilers. The burners can be tilted up or down in unison in all the four corners to move the fire ball inside the furnace either upward or downward to change the furnace absorption. When RH temperature is lower than the rated value, burners are tilted up to reduce the furnace absorption and increase the furnace outlet temperature. As more heat is now available for RH pick up, RH temperature can be maintained. When RH temperature is more than the rated value, the burners are tilted down shown in figure 6.

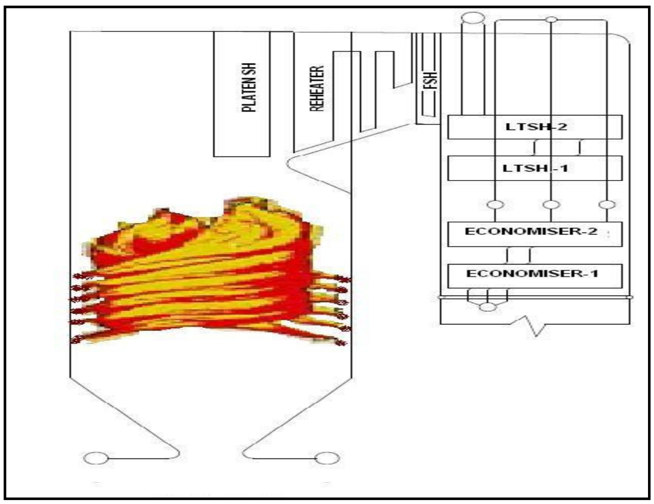


Figure- 6
Burner angle[16]

Divided back pass dampers

The divided back pass arrangement is used in wall fired boilers with fixed burners. In wall fired boilers, the convective back pass is divided into two gas passes. On one side, Low Temperature Reheat (LTRH) section is located and on the other side Low Temperature Superheat (LTSH) section is located. These two sections are divided by steam cooled wall or a baffle plate. A common economiser heat transfer section is located across both the LTRH and LTSH sections outlet. The gas mass flow through LTRH side can be increased or decreased (gas biasing) by the multi louver dampers positioned at the outlet of each pass (generally at the outlet of economizer section in lower gas temperature region). Figure-7 for a typical arrangement of dived back pass with control damper.

Gas Recirculation

Flue gas at economizer outlet or ID fan outlet is drawn and reintroduced into the furnace by a Gas Recirculation (GR) fan. Tight shut off dampers are positioned both upstream and downstream of the fan. Refer Figure 8 for a typical arrangement of gas recirculation. As the quantity of re-circulated gas is changed, the quantity of heat absorbed in the furnace and the heat at furnace outlet are changed. When RH outlet temperature is lower than rated value, GR quantity is increased to increase the heat available for RH pick up. In this case power consumed by the GR fan is additional loss and will increase the net plant heat rate.

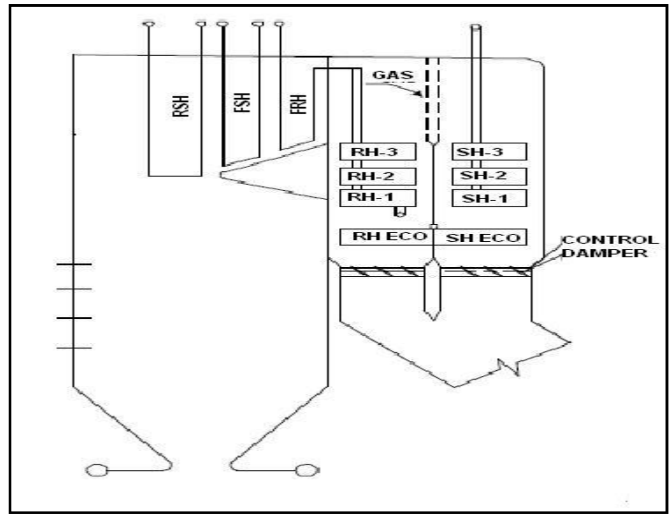


Figure-7
Divided back pass damper control[16]

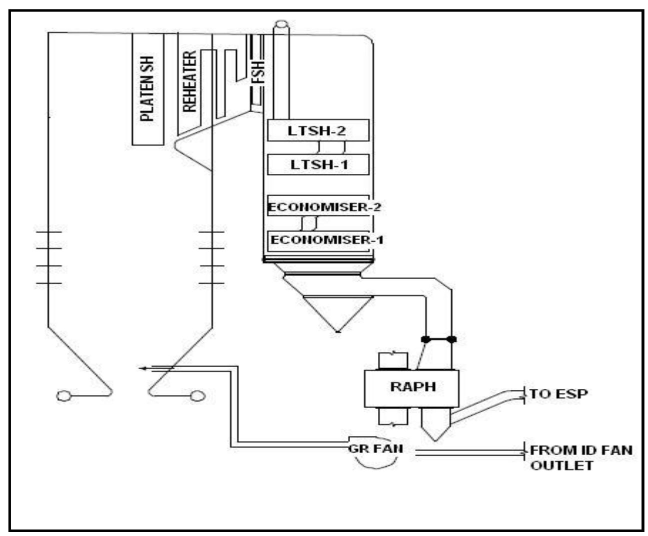


Figure-8
Reheat Steam Temperature control by Gas Recirculation[16]

Excess air

Excess air by itself is not used as a means of RH steam temperature control as an increase in excess air will increase the stack loss and reduces the boiler efficiency. Typically 0.3 to 0.4 % of boiler efficiency will be lost for every 10 % increase in excess air. In some cases especially when the control load is very low, in addition to burner tilt angle or gas biasing, excess air is also to be increased to achieve the Reheat steam temperature.

Maintaining Constant Reheater Temperatures

As in the case of superheating in high-pressure zones, heating surfaces with convection and radiation characteristics should be utilised in order to keep constant reheater steam temperatures. Reheating does not involve the balancing influence on the live steam temperature by migrating vaporisation and superheating zones in the furnace wall of a once-through steam generator. The operating regime of a steam generator - constant or sliding pressure - can have an influence, however, on the necessary temperature rise. In constant pressure operation, the reheater must be supplied with relatively more heat because the reheater inlet steam temperature drops as the output decreases[14]. But in sliding-pressure operation, the reheater inlet temperature is nearly independent of the output. A relatively simple method to control and limit the reheater outlet temperature is to spray feed water between two subsequent reheat surfaces at a pressure similar to the exit steam pressure of the high-pressure turbine[14]. In this case, the reheater is designed to be larger for full load and its steam exit temperature is limited to the allowable temperature by spray water admixing. When output diminishes, the necessary spray water flow decreases as well.

Reheater spraying for temperature control, however, has the consequence of a loss in efficiency, because the high-pressure zone of the steam generator is bypassed, and only steam at the reheater pressure is produced and exploited. The heating of the spray water by mixing at a low reheater pressure results in a lower temperature of heat addition.

Table-1
Main Specifications of the Once Through Boiler [17]

Item	Specifications
Generating Capacity (Gross)	1000 MW
Boiler Type	Babcock-Hitachi Supercritical Sliding Pressure Operation Benson Boiler
Main Steam Pressure	245 bar
Main Steam Temperature	605 ^{0}C
Reheat Steam Temperature	605 ^{0}C
Economiser Inlet Feed Water Temperature	287 ^{0}C
Combustion System	Pulverized Coal Fired
Draught System	Balanced Draught
Main Steam Temperature Control System	Water-Fuel Ratio Control and Staged Spray Attemperation
Reheat Steam Temperature Control system	Parallel Gas Dampering and Spray Attemperation

Other methods of temperature control avoid the disadvantageous effect of reheater spraying on the steam generator efficiency[15], for instance by transferring heat between the live steam and the reheater steam system or by shifting the heat flux through flue gas recirculation or tilting burner, to set constant reheater steam outlet temperatures. In order to control the heat transfer between the high-pressure superheater and the reheat surfaces, the reheat surfaces are designed to be either larger or smaller than without this control. Designed larger, they transfer heat to the live steam system in the upper output range. Designed smaller, they take heat from the high-pressure superheaters in lower output range. Excess heat of the reheater can also be used to preheat the feed water. This kind of temperature control only involves pressure losses.

Conclusion

Once through Boiler with Supercritical Steam parameters (240bar, 600^{0}C) improve the plant cycle efficiency by 40% where as with Constant pressure boilers give only 36%. Heat rate improvement of about 1.25% compared with constant pressure boiler gives 0.75% which results in reduced coal consumption. Reduced gaseous emissions and pollutants are possible with once through steam generators compared with constant pressure Natural Circulation boilers. Slight marginal effect on heat rate improvement, RH steam temperature control by spray attemperation in once through boilers is good for the plants.

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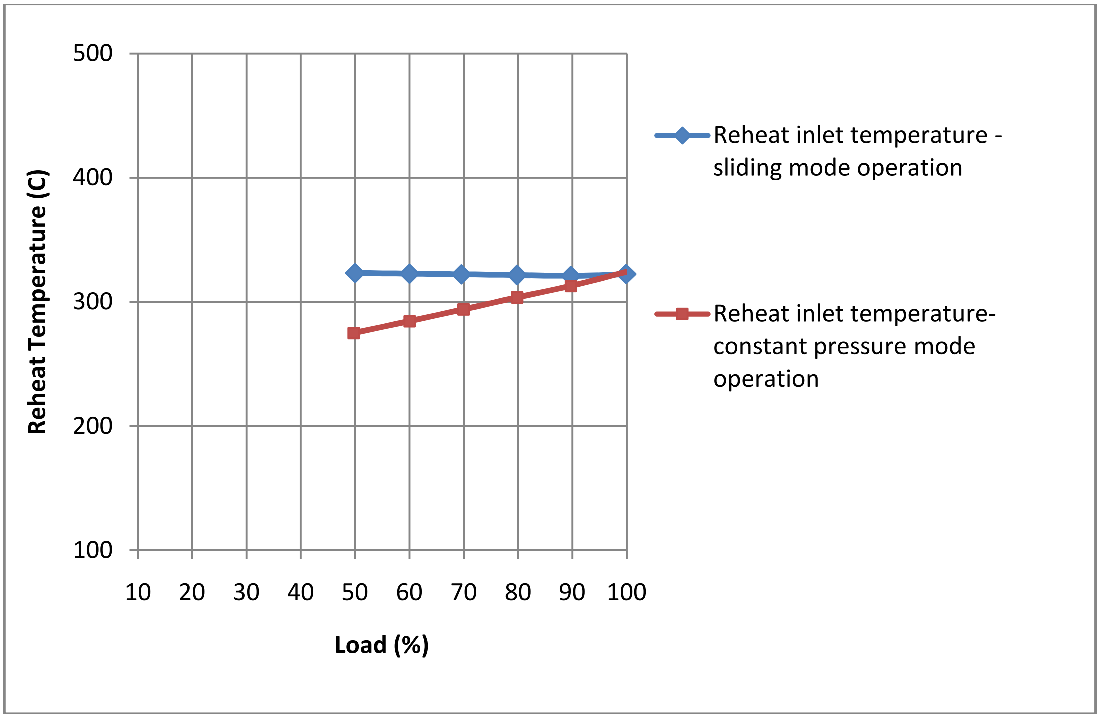

Figure- 9
Reheat Inlet Temperature control for both constant pressure and sliding pressure operation at different loads[16]

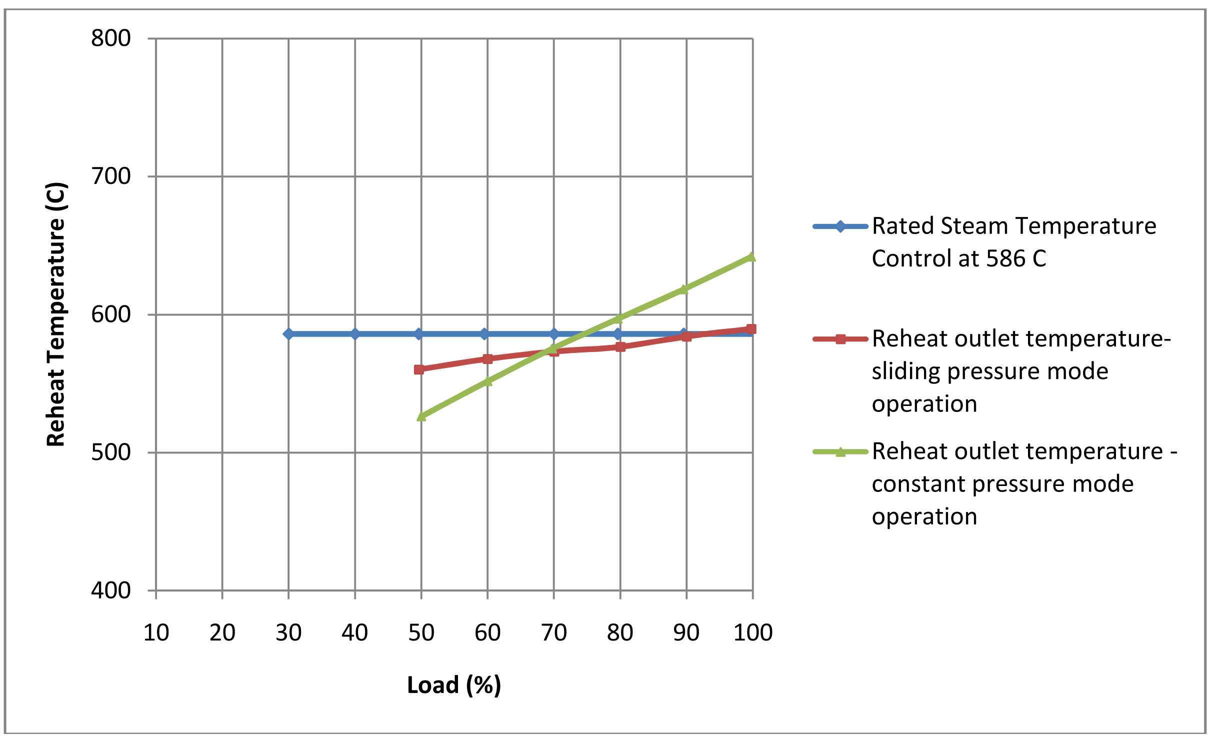

Figure-10
Reheat Outlet Temperature control for both constant pressure and sliding pressure operation at different loads[16]

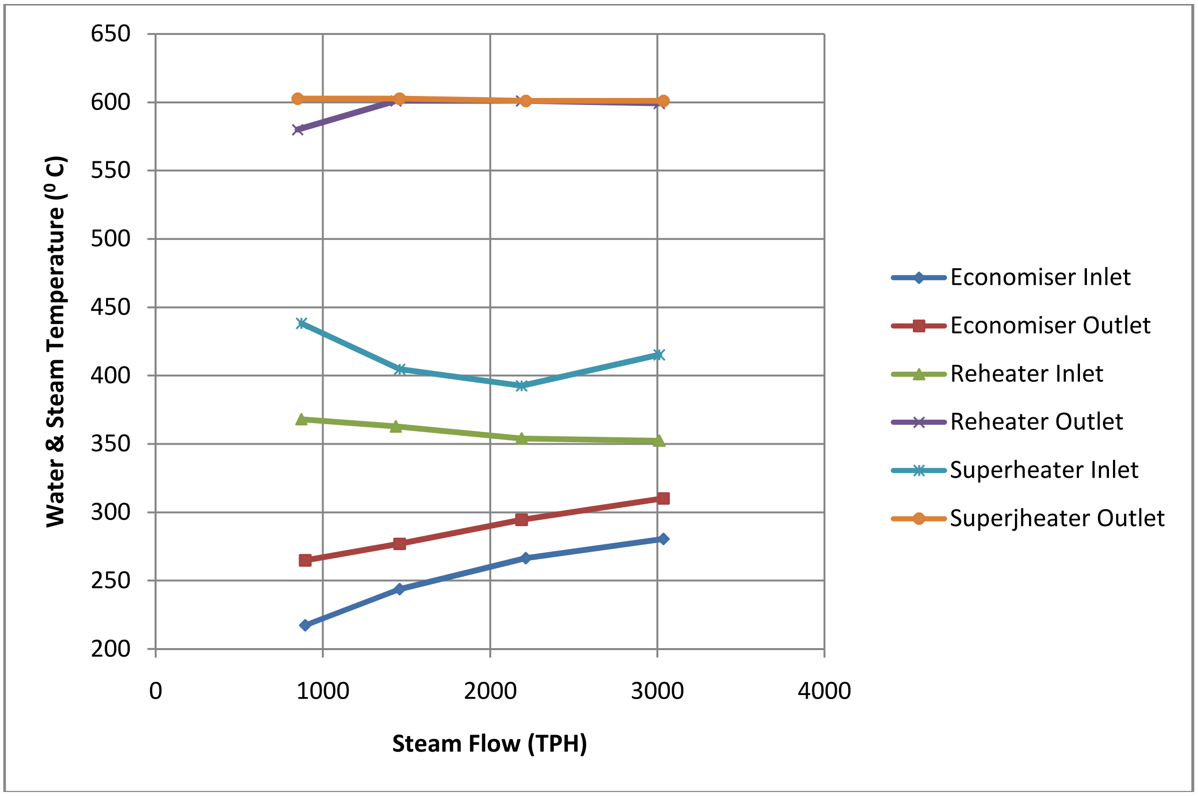

Figure-11
Static Characteristics Steam and Water flow in Boiler

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