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Unique challenges in the design and operation philosophy of solar thermal power plants

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Abstract

Solar thermal power plant design and operation philosophy involves unique challenges as compared to design of conventional thermal power plants. The solar receiver operation should be able to absorb maximum solar load during transient events like daily start-up and shut-down. This requires aggressive ramp rates for transient operation of the power plant. However, the component and system level limitations must be considered in formulating these modes of operation and ramp rates.

A solar receiver which usually receives heat from heliostats is designed to receive high heat flux to operate at high temperature and pressure during daytime. However, during night-time the receiver receives no heat flux and is losing heat to the environment. Day-night cyclic operation of a solar thermal power plant induces thermal cycles in the solar receiver pressure parts. Since solar receiver tubes are not insulated, the amplitude of thermal cycling is significant and needs to be addressed with proper tools and design approach. Besides, higher plant cycle efficiency requires higher operating temperature and pressure of a solar receiver, further increasing the amplitude of thermal cycling. The system level and component level response to these day-night cycles has a significant impact on modes of operation as well as on the life usage of various components. It also affects the design, specifications and operation of various plant level components.

The solar thermal power plant design and operation process is optimized by having a system level thermal-hydraulics model for the solar receiver to simulate the transient start-up and shut-down events. Since all of the major components of the system are included in the model, it reflects the transient response of each of the components on each other and on the overall system. This simulation can be used to generate input conditions for component level life usage analysis. The component level life usage analysis is done using the finite-element method. The component level life usage analysis determines the permissible ramp rates. The thermal-hydraulics dynamic simulation outlines the operational philosophy of the system.

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Keywords: Solar tower receiver; start-up; shut-down; transient; dynamic modeling; fatigue; FEA; Alstom; plant intigration, plant optimization

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1. Introduction

A variety of technologies are currently used for concentrated solar thermal power plants. With an eye on decreasing the cost of power generation using solar thermal technologies, there is a clear trend towards increasing the efficiency of the power plant. Various parameters need to be considered for calculating the efficiency of a solar thermal power plant including operating temperature, losses and concentration factor.

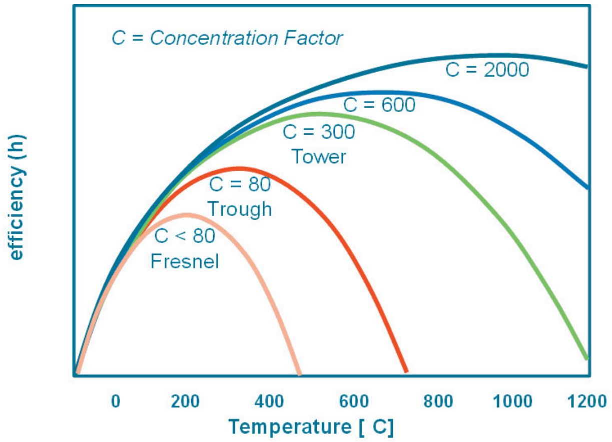


Fig. 1. Solar thermal plant efficiency variation with temperature

Fig. 1 illustrates the relationship between efficiency and temperature for different CSP technologies [1]. Among the major CSP technologies currently used, the tower receiver provides the highest efficiency. High heat flux and higher operating temperature results in increased overall efficiency of the tower type receivers. Besides, the water-steam cycle is designed for high pressure to raise the saturation temperature and thus the overall operating temperature in the rankine cycle.

Increased overall operating temperature and pressure imposes unique design and operational challenges related to start-up, shut-down and transient operation of solar thermal power plant. This paper explores these challenges and talks about Alstom's solution to address these challenges with emphasis on the solar power tower design along with consideration towards other important components in like the steam turbine.

1.1 High temperature and pressure

Recent trends in direct steam tower receivers indicate operating temperatures in the range of 540^{o}C -585^{o}C and operating pressures in the range of 140bar to 190bar [2]. For example, Alstom's 250MWe solar thermal power plant is designed to supply steam at 585^{o}C and 170bar [1]. Considering the pressure drop within the steam piping and superheater section, the evaporator for these receivers is at even higher pressure (approximately 190bar). As the pressure increases, the thickness required for the pressure part components that carry water-steam through the various sections of the receiver also increases. This makes large diameter pressure part components like the steam drum, manifolds and headers very thick. Moreover, high grade alloy materials (like Grade 91) need to be considered for high temperature sections of the receiver like superheater and re-heater.

Similarly, high temperature and pressure requires use of high grade material in the steam turbine.

1.2 Cyclic operation

A solar tower receives heat flux from the sun through large numbers of mirrors in the mirror field. The SRSG (Solar Receiver Steam Generator) is operating during day-time and is shut-down and not producing steam during night. The SRSG thus follows a cyclic operation due to the day and night cycles. Fig. 2 shows a typical plot of variation of solar load as well as day-night cycles. In fig. 2, the peak amplitude will vary based on the capacity of the mirror field and solar insolation, however, the general cyclic trend of the plot would still remain same. The SRSG has to undergo daily start-up in the morning, steady load operation during the day and then shut-down in the evening. High thermal stresses are induced in the thick walled components since they are subjected to thermal transient cycles. Table 1 shows typical number of cycles or start-ups during a year. During the life-time of the power plant, various components will be exposed to a large number of such thermal transient cycles. Therefore, these components need to be analyzed for low-cycle fatigue. The low cycle fatigue calculation needs to include weighted life consumption for each type of transient cycle described in Table 1 so that the severity of each type of start-up and its occurrence is taken into account in order to derive the life usage.

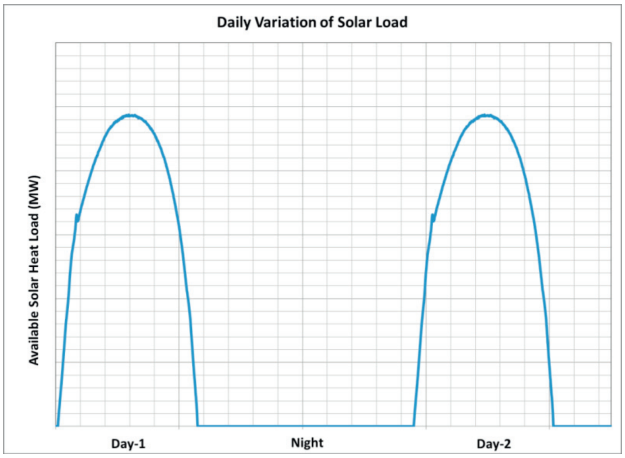


Fig. 2. Typical solar load cycle

Table 1. Typical yearly start-up requirements for SRSG.

Start-up condition	Number of starts/year
Warm-start (daily morning start-up)	300-350
Hot-start (start-up after short intra-day shut-down)	10-45
Cold Start(start-up after several days of shut-down)	5-15

The design of the SRSG includes tubes arranged in panels that receive solar radiation from the heliostat field. During night-time, these panels lose heat and cool down to ambient temperature. Therefore, the tower type solar receiver has unique design challenges for the SRSG and overall plant. Since the fluid from the SRSG flows through other components in the balance of plant like the steam turbine, feed water pumps and so on, these components also experience thermal transients. Design for fatigue introduces limitations on the start-up and shut-down ramp rates for various components in the power plant. Due to the combined effect of these constraints on various components the solar power plant start-up is slow and not all the solar load available from the mirror field is absorbed by the receiver. A similar situation occurs during shut-down where the plant needs to undergo a gradual coast down. Fig. 3(a) shows ideal start-up and shut-down behavior of the power plant where the ramp rates do not limit the transient operation. The entire solar load available is absorbed in this case. The plant starts generating power quickly after sunrise and late until sunset. However, the actual operation of the plant is very much like Fig. 3(b). The actual absorbed heat is less than the available. The plant starts producing power sometime after the sunrise in order to allow gradual ramp-up of various components in the power plant.

There is a scope for maximizing the absorption of available solar load during start-up and shut-down while respecting the life usage and ramp-up limitations of various components. This requires knowledge of transient events, ramp-up limitations of various components in the power plant as well as use of advanced design and simulation tools. A faster daily start-up is the major re-occurring event and its optimization increases the capacity factor of the solar power plant. For the design for tower type direct steam CSP plant, Alstom used its expertise and experience in the design and optimization of combined cycle power plants along with detailed analysis of unique aspects of solar receiver.

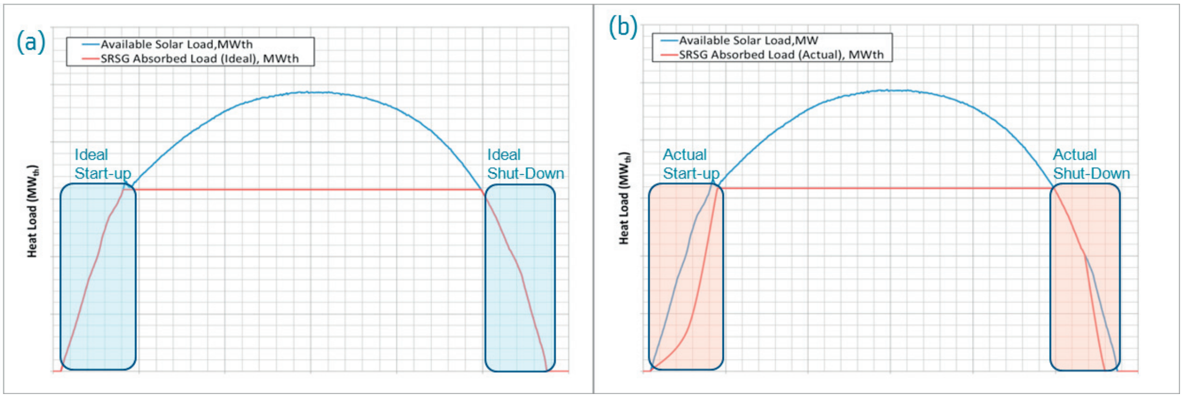


Fig. 3. (a) Ideal start-up and shut-down; (b) Actual start-up and shut-down

2. Challenges in transient operation

Alstom’s utility scale SRSG is designed for 250MWe capacity. The heat flux incident on the SRSG is very high and is comparable to (or even higher than) utility boiler furnace heat flux. Therefore, the evaporator and superheater tube design is derived from utility boiler design procedures; whereas, the thick walled pressure parts like steam drum, manifolds and headers are influenced by HRSG designs that have been optimized for cyclic operation. However, both the utility boiler and the HRSG are enclosed in an insulated casing. Therefore the pressure part tubes are not exposed to direct ambient temperature after the unit is shut-down and the tube metal temperature does not rapidly drop to ambient temperature. The tube and header metal temperature is not significantly different.

In the case of an SRSG, the tube panels are not enclosed in a casing. They are exposed to ambient in order to receive solar heat flux from the heliostat field. Therefore, as soon as the power plant is tripped in the evening and the heat flux on the tubes goes down, the tubes are exposed to ambient condition. The hot panel tubes are at 200°C to 550°C temperature depending on the evaporator and superheater section. Metal tubes, at this high temperature, start losing heat due to radiation and convection. The large temperature differences between the tubes and the ambient results in fast cooling of tube panels. However, the internal piping including the steam drum, superheater headers and connecting piping are insulated and retain the temperature. Fig. 4 shows the fast cooling of SRSG tubes while the internal piping retains high temperature. Thus, before the morning start-up there is a large temperature difference between tubes and rest of pressure part piping. If the tubes are not heated before steam starts flowing through these cold panels, the steam will form condensate. This cold condensate will roll down to the hot header at the bottom of the panel, thermally quenching the inner metal surface of the header and inducing a high thermal stress due to temperature gradient through the header wall thickness.

In order to gradually cool the headers and other pressure parts; drum steam can be bled to induce steam flow through the superheater tubes. This can be done after turbine trip in the evening (sunset). However, the drum steam is at saturated temperature. The saturated steam flowing through the superheater panels with no heat flux availability will generate a lot of condensate. This condensate at low pressure saturation temperature thermally quenches the finishing section superheater headers and consuming high fatigue life. Moreover, bleeding steam out of the steam drum reduces the drum pressure and increases the amount of heat and time required to pressurize the drum next day morning. An extension of this approach is to have turbine trip few minutes early and use the heat flux to heat superheater panels while drum steam is bled. This would avoid condensate formation. However, this will reduce the power generation during peak demand evening hours and thus affect the overall economics of the power plant.

The steam turbine is operating at high temperature before turbine trip in the evening. The turbine rotor is at high temperature at turbine trip and slowly cools down overnight. Based on the turbine rotor temperature, steam from the SRSG must be introduced at a specific temperature range such that it is not too high or too low as compared to turbine rotor temperature. The steam turbine has very stringent requirement for temperature ramp rate during start-up as compared to pressure ramp rate. Thus, the while the turbine is following slow temperature ramp rate during start-up, its pressure and flow rate can be increased faster to maximize power generation. The SRSG superheater outlet temperature control must be capable of adhering to such a requirement. Likewise, the main steam line and steam turbine by-pass design and the control concept must consider the transient response and thermal inertia between the SRSG and turbine.

Hot starts mentioned in table 1 occur usually after an emergency trip. A unit trip may result from many scenarios including loss of power, drum-level, component failure and high metal temperature. The transient response of the system to these unit trip events is important to mitigate the risks. For example, a loss of power event at full load operation will stop the feed water flow as well as the recirculation pumps in the evaporator. This starves the evaporator and superheater tubes of the cooling flow. The mirror field needs to be de-focused as soon as possible in order to protect the tubes from overheating. Study of the transient response of the SRSG system between the occurrence of the loss of power event and the de-focusing of the mirror field is critical to mitigate the risk of tube overheating and failure.

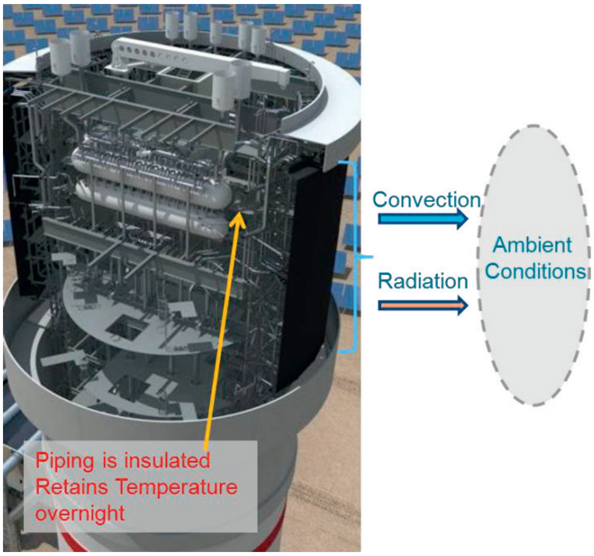


Fig. 4. SRSG tube panels and internal piping arrangement

3. Advanced modeling tools

3.1. Dynamic modeling

Alstom has wide experience of dynamic modeling of thermal power plants. APROS is also used for modeling and simulation of conventional and combined cycle power plants along with advanced control concepts. Alstom has been using APROS for several years specifically for analysis of cyclic transient behavior of HRSGs and has validated APROS models with field data [3, 4].

APROS dynamic simulation platform has advanced features like 6-equation modeling, large number of component libraries, controls modeling capability, advanced two-phase flow physics and metal temperature calculation. The 6-equation capability enables simulation of two-phase flow transient system. This can handle situations like steam flowing up in tubes while condensate flowing down. APROS has an advanced set of equations to predict heat transfer in single as well as two-phase flow including departure from nucleate boiling. Metal temperature calculation is important for systems with large length piping like that of a solar receiver in order to account for the thermal inertia. Apart from Alstom's experience in dynamic modeling, APROS has also been used before for modeling of solar receiver by other companies and institutes [5, 6].

The dynamic performance model included the main heat absorbing components of the SRSG like evaporator and superheater panels. The model also included internal components in the SRSG like the steam drum, recirculation pumps, de-superheater, valves, drains, vents and connecting piping. Fig. 5 shows a snapshot of main components of the APROS dynamic model for evaporator. The SRSG system was modeled as a lumped system in order to increase the robustness of the model during complex transient simulations. Thus, if several evaporator panels were in parallel, they were modeled as a single lumped system. All SRSG heat absorbing tube panels were modeled as wall panels with heat flux applied on just one side. Recirculation pumps were modeled in the system using actual pump curves from the vendor. The pumps in the model also included coast down time and flow resistance to capture the behavior during a loss of power event. Similarly, all major valve specifications including valve time to closure were modeled. The model was validated with other thermal performance tools for steady state condition full load and part load.

The basic conventional control system of three-element drum level control, pressure control and temperature control were included in the dynamic model. Temperature control was done primarily based on heat flux incident on different sections of the SRSG. De-superheater was also included for finer temperature control as required. Feed water temperature variation was included as a boundary condition. A complex heat flux model was developed to include the incident heat flux as well as radiation and convection losses. The SRSG load demand for performance was compared with available heat load from the solar field. The heat flux model included provision to selectively vary heat load on different components and sections within the SRSG in order to optimize start-up.

The dynamic model also included detailed representation of the main steam line to steam turbine. The main steam line is long as it runs down the tower and thick due to high pressure operation. This introduces significant thermal inertia during transient operation. The insulation on the piping and heat loss overnight through the insulation was modeled to calculate the pipe metal temperature before start-up.

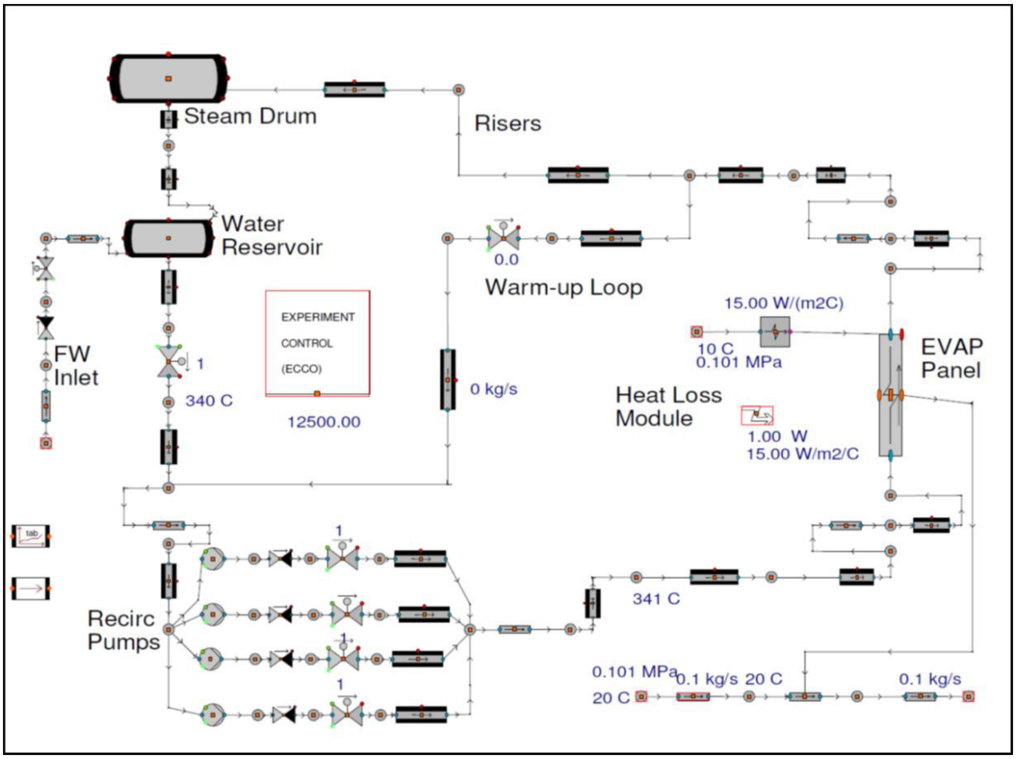


Fig. 5. Snapshot of SRSG dynamic model in APROS

The dynamic simulation provided a system level understanding of start-up and shut-down, input to other plant level components like the steam turbine, feed water pumps and turbine by-pass. The SRSG dynamic simulation was followed by generating component level heat transfer coefficient variation with time which was used as an input for detailed component level finite-element analysis.

Apart from the daily start-up, the dynamic model was used for simulating other start-up scenario like cold-start, loss of power, and cloud-cover.

3.2. Finite element analysis

ABAQUS 6.11 finite element code was used to analyze thick wall components in the SRSG. The component geometry like the steam drum and the superheater header were modeled and meshed. The mesh is refined at the nozzle weld location to accurately capture weld stress.

Transient thermal boundary conditions were applied based on input from the dynamic analysis. Complex two phase flow boundary conditions were used to represent the actual physical process where necessary. For example, considering the geometry of the pressure parts, the fluid flow generated turbulence in areas like a tee joint or tube openings in a header. The heat transfer coefficient in this zone would be much higher than the fully developed flow. Based on field data from other thermal power plants, Alstom had developed a method to calculate turbulent heat transfer coefficient

The transient finite element analysis provides stress distribution history of the component for the entire transient. The condition analyzed include a complete cycle starting with full load operation, shut-down, night preservation, start-up followed by full load operation. The element with the highest peak and lowest valley stress values were probed for fatigue life calculation. Fig. 6(a) shows the steam drum metal temperature distribution at a point of time of the transient and Fig. 6(b) shows tresca stress range for the steam drum. Creep life usage was also calculated to derive the combined creep and fatigue life usage of the component.

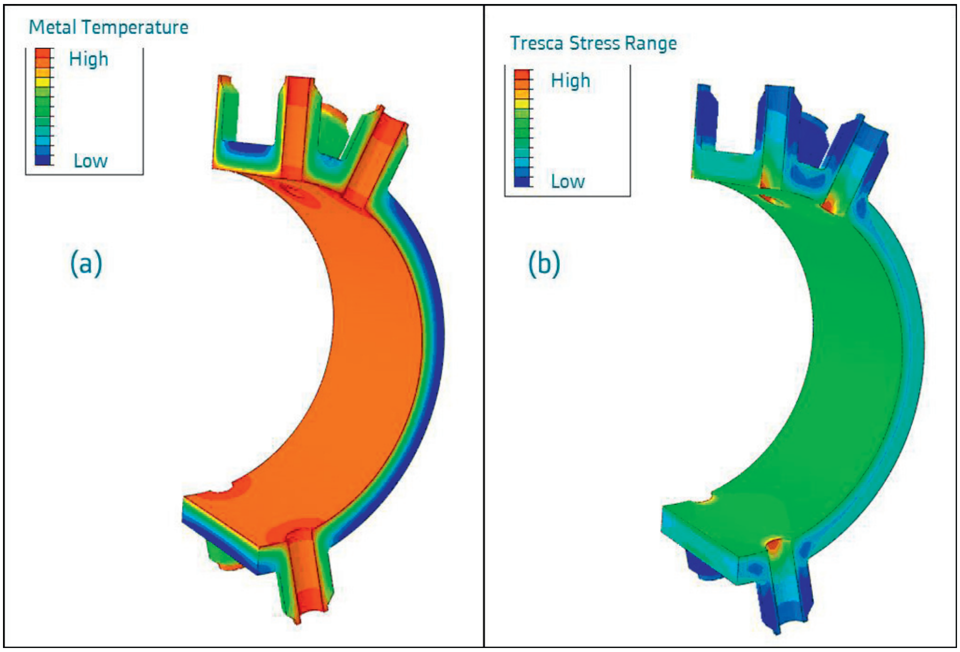


Fig. 6(a). Mesh geometry of superheater header; (b). Stress variation in the superheater header

4. Results and discussion

To optimize plant operating modes, several iterations of simulation and analysis were performed. Each iteration included a system level dynamic simulation followed by finite element analyses for multiple components while considering the plant level effects. This involved working with the steam turbine and plants team to develop an optimized solution. Efforts to improve the fatigue usage of components included altering the start-up and shut-down transient, changing the strategy of pre-heating or post cooling of the component before start-up and after shut-down respectively, changing the geometrical arrangement of the component and considering high grade materials. It was also observed that some transient changes improve fatigue life usage of one component while deteriorating the life usage of another component. For example, operational changes to decrease the transient thermal stress in final superheater inlet header affected the final superheater outlet header thermal stress. Therefore, efforts were directed to achieve good overall life usage for all components while optimizing the fast start-up and shut-down. An outcome of this exercise is the refined and optimized start-up and shut-down operational procedure.

For large solar receivers, the steam flow rate is high. Due to high flow capacity the drum size required is big. Moreover, the drum size should be such as to continue to supply water to the evaporator panels for a period sufficient for the solar field to de-focus in case of sudden loss of feed water supply. These requirements demand a large inside diameter for steam drum. The shell thickness required for the steam drum is directly proportional to inside diameter. The large capacity of the steam drum along with high operating pressure makes the drum shell very thick. The thicker the drum shell, the higher is the temperature gradient during temperature transients, negatively impact fatigue life. One way to counter this challenge is to design the evaporator with multiple drums. This allows lower diameter of drums and relative lower drum thickness. However, this imposes challenge from component layout point of view. SRSG components like steam drum, down-comers, supply pipes, recirculation pumps are arranged inside the panels. The receiver overall diameter and height is dependent on the mirror field, insolation and capacity. This leaves very less space within the receiver to arrange these components and having multiple drums can complicate things. Steam separators, risers and drum length are some of the other criterions that need to be considered here.

4.1. Pre-heating of panels

Before start-up, the SRSG panel tubes are at ambient temperature while the insulated pressure parts are at high temperature. Fig. 7 shows a typical plot of variation of stress in a thick walled superheater header during start-up and shut-down transient along with other process parameters. It is interesting to notice that the stress peaks occur during the cooling during shut-down and heating during start-up. If the cooling or heating of the panel tubes is controlled by limiting the rate of change, the peak stress value would decrease. The evaporator is less problematic in this scenario, since the panels and pressure parts in the circulation system are all at saturation temperature. Recirculation pumps allow the operator to better control the cooling of the evaporator. Moreover, the operating temperature of the evaporator is below 375^{o}C and not as high as in the superheater. In the case of the superheater panels, post cooling and pre-heating becomes important. This can be achieved by several ways:

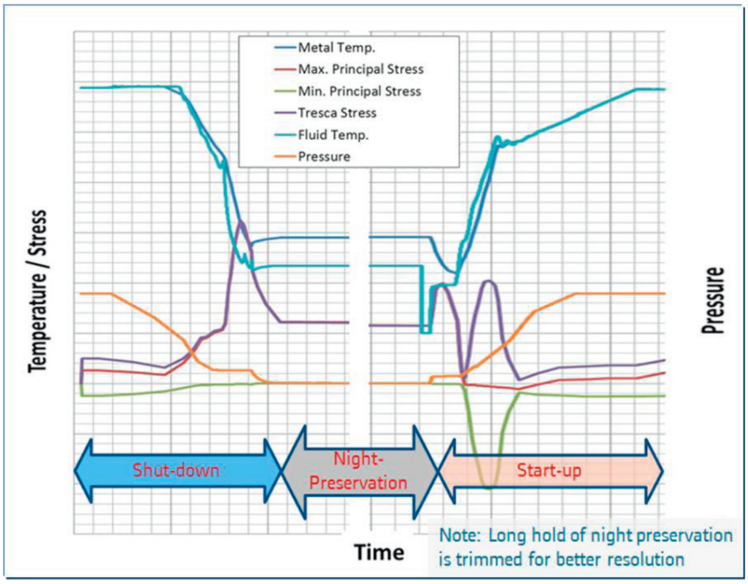
- Applying heat flux from heliostat field on the superheater panels after shut-down and before start-up.
- Introduce auxiliary boiler steam in the superheater to gradually cool or heat the superheater panels.

Applying heat flux on the superheater panel would decrease the thermal stress. However, this activity can commence only after the sunrise. It will take some time after sunrise for the tube metal temperatures to be near to the temperature of insulated pressure parts. Moreover, late evening and early morning, the sun is near the horizon and at a very low angle. Therefore, heat flux incident on the SRSG is not uniform around the circumference; it is biased on east or west side.

Use of steam from the auxiliary boiler is a good alternative to gradually post-cool and pre-heat the SRSG. The auxiliary steam introduced in the superheater must be substantially above the saturation temperature to avoid quick condensate formation. Thus as it flows through the panels, it gets cooled but does not form condensate instantaneously. The location where auxiliary steam is introduced in the superheater is crucial. Before shut-down, the SRSG is providing steam to the turbine. The superheater steam temperature increases from saturation temperature at superheater inlet to above 500^{o}C at the superheater outlet. It is important to consider the range of superheater metal temperatures and their locations when selecting the auxiliary steam conditions. The advantage of using auxiliary steam is that, the SRSG tubes panels can be heated before sunrise, so that the solar receiver goes online as fast as possible during start-up. Besides, since the auxiliary steam temperature can be controlled, it provides an additional handle for fast start-up.

Use of auxiliary steam is an active handle to support the shut-down and start-up events. However, the auxiliary boiler increases capital cost of the plant as well as operation cost. The levelized cost of electricity is a function of capital cost, operational cost and the capacity factor. The use of auxiliary boiler will impact levelized cost of electricity. In the Middle East countries or in the USA, use of an auxiliary boiler might be justified since gas cost is relatively low. However, in economies like South Africa or India, use of auxiliary boiler might increase the operating cost too high. Therefore, the method of post cooling and pre-heating should be decided weighing capital cost and operational cost of auxiliary steam boiler against increased power generation due to fast start.

Another important part of the start-up curve is the steam turbine ramp-up. Steam can be introduced into the steam turbine when its temperature and pressure is in the permissible range. The turbine rolling temperature is dependent on the capacity of the turbine, nominal temperature (585°C in case of the current study) and rotor temperature before start-up. For Alstom's turbine technology for high nominal temperatures and fast starts, the daily start-up turbine rolling temperature is above 400°C. Therefore, the steam turbine start-up operation comes into play only after the superheater steam temperature is above 400°C. It was learned during the dynamic simulation and FEA analysis that the thermal stress peak in the SRSG components due to transient start-up occurs before attaining the turbine rolling temperature. Thus, the critical operation with respect to the SRSG fatigue life precedes the critical operation for the steam turbine start-up. This provides some liberty to focus on SRSG transient during early part of start-up and then concentrate on optimizing the turbine start-up.



Note: Long hold of night preservation is trimmed for better resolution

Fig. 7. Superheater header shut-down and start-up transient

4.2. Night preservation

Maintaining the pressure in the evaporator significantly reduces the time to achieve power generation in the morning. During a normal shut-down, the SRSG is operating at part load since less solar load is available. After shut-down, the drum pressure goes down gradually overnight due to cooling. Fig. 8 shows the variation of steam saturation temperature against pressure. It is observed that the saturation temperature increases rapidly with increasing pressure at lower pressure values. At higher pressure values, the temperature rise is not very steep.

Having higher drum pressure overnight will also correspond to higher drum temperature overnight. Therefore, the drum will experience lower temperature change during start-up, reducing the start-up time and allowing for a faster ramp rate. Moreover, turbine rolling cannot be done at low pressures. Starting with a higher drum pressure will help achieve the turbine rolling pressure earlier further helping fast start-up.

As the steam in superheater cools after shutdown, it results in condensate formation. The superheater drain system should be designed to manage the condensate. The system should be designed to account for condensate formation and to avoid any potential corrosion issue.

4.3. Plant integration for start-up optimization

For the 250MWe CSP tower plant, Alstom has used the approach of plant integration for optimizing modes of operation. This is derived from its experience in combined cycle power plants [7]. The steam turbine has its own start-up curves for each kind of start-up mentioned in table 1. This includes ramp up of major operating parameters like live steam temperature, pressure and flow rate for safe operation and life of the turbine. During the early part of the SRSG start-up, the quality of steam generated by SRSG is not suitable to be introduced in the turbine. Therefore, this steam is passed through the turbine by-pass system to the condenser. Based on the quality of this steam and the flow rate, it can be used in feed-water heater train where a part of the heat from the steam is recovered. When the steam temperature and pressure condition are met, steam is introduced in the turbine. Based on the capacity of steam turbine and type of steam turbine, steam can either introduced in the high pressure section or in the intermediate pressure section for start-up.

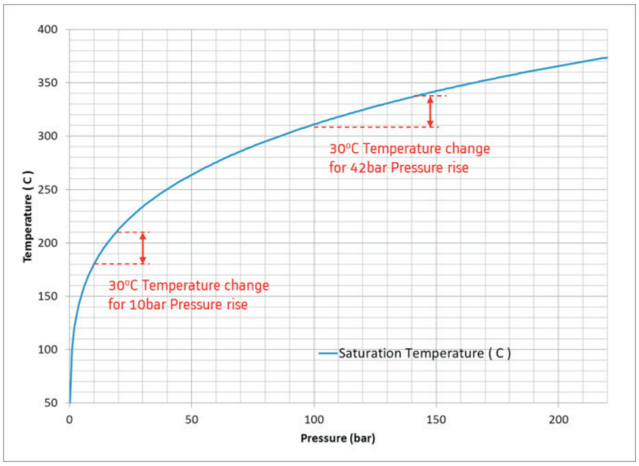


Fig. 8. Variation saturation temperature against steam pressure

CSP plants are usually installed in desert locations since high solar insolation is available at such locations. However, desert location also corresponds to water shortage. To design for scarce water resource, the CSP plants are designed with air-cooled condenser. During night-time, there is a high potential of corrosion and iron oxide formation at the air cooled condenser location. Alstom CSP plant design takes this into consideration in order to avoid iron oxide formation and its carryover into the system.

A high capacity solar plant has multiple feed water pumps running in parallel to supply feed water at required pressure and flow rate to the SRSG. From the plant efficiency perspective, it is beneficial to have some of these feed water pumps driven by steam extracted from the steam turbine. While this is good for a steady state operation condition, during start-up it becomes an issue to ramp up the system capacity. For example, if two feed water pumps are provided, one is electric motor driven and the other is steam driven, the system can be ramped up to 50% capacity until the steam turbine is online and extractions are opened. Otherwise, other sources of steam like the auxiliary steam boiler should be considered to drive the other pump until turbine extractions are opened.

Each SRSG section has non-uniform response to start-up and temperature rise. As discussed earlier, in order to harness the fast start optimization, the heat flux should be selectively focused on different sections of the SRSG.

5. Conclusion

Utility scale tower type solar thermal power plants have challenges in terms of optimization of operation modes including start-up and shut-down events while meeting the life usage of the components. In case of the SRSG, these challenges are exacerbated by the daily cyclic operation and panel tubes open to the ambient. There is a need for fast start-up and shut-down in order to increase the daily power generation but component level limitations need to be taken into account. Utility scale SRSG design and operation has unique aspect including the high operating pressure and temperature, cyclic operation, no casing on tube panels and night-time cooling of tubes. These were discussed along with plant level challenges including steam turbine start-up, condenser and feed water pumps. Alstom 250MWe solar thermal power plant was used as a reference for this discussion.

The solution for these unique challenges as well as optimization of operational modes can be achieved by use of advanced design, modeling and simulation tools. System level dynamic modeling followed by component level finite-element analysis was the approach used for design of its 250MWe solar plant. Alstom's extensive experience in operational modes and optimization for conventional thermal and combined cycle power plants was harnessed for solar plant design. Alstom's experience in plant level integration was used to develop modes of operation and overcome the challenges.

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