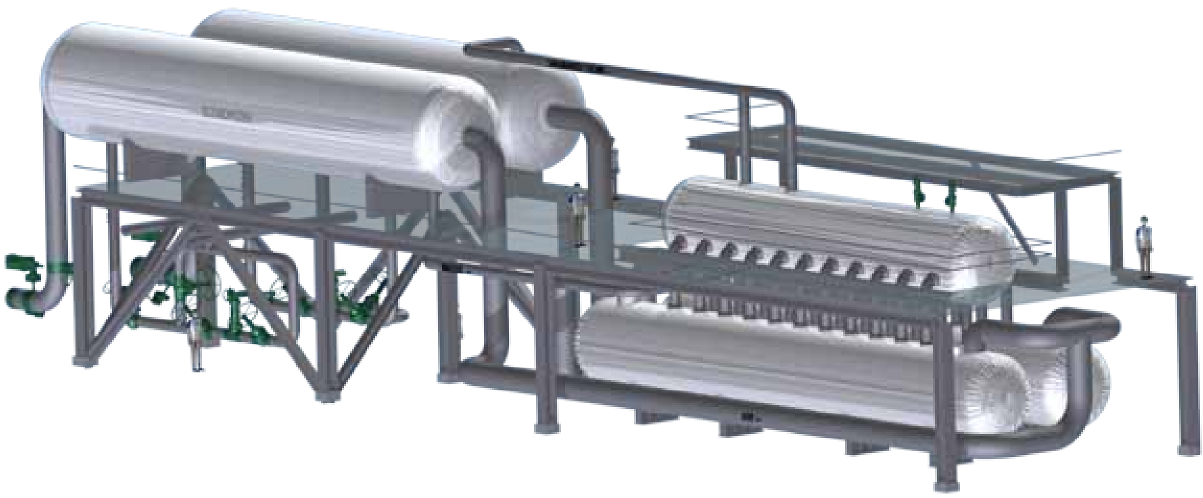
AALBORG CSP

- Concentrated solar power

Aalborg CSP steam generators

Technical information

- Millions of dollars to be saved by correct selection of steam generator!



Aalborg CSP is an innovative boiler company from Denmark and a big player in the steam generator market for concentrated solar thermal power plants. Our approach to the steam generator plant is based on steam boiler technology and therefore superior to ordinary heat exchangers.

All the Aalborg CSP designed heat exchangers are of header type, which has several significant advances:

- **No tube plates - no cracks**
- **Fast start-up, higher temperature gradient**
- **Very high steam quality, hardly any carry-over**
- **Insignificant fouling, good internal circulation**
- **Excellent for molten salt as HTF**
- **Fully optimized system**
- **Low pressure drop on the oil side**

Aalborg CSP - Background

In 2005, a major developer asked the former company BK Aalborg – now Aalborg CSP, for a study for optimizing a direct steam solar tower receiver based on Aalborg CSP's more than 25 years of boiler experience. The study was one among several others and was chosen as the best study, and Aalborg CSP was asked to deliver their first solar powered boiler for a concentrated solar power plant based on conventional boiler technology.

During the construction of the first solar boiler plant, we developed a steam generator system for parabolic trough solar power plants. At Aalborg CSP, the steam generator design is based on conventional boiler technology. This has proven to be a great success, and since then a total of 5 plants of each 50MWe have been delivered and are in operation.

Since the delivery and commissioning of the 5 solar plants, Aalborg CSP has further developed the steam generator plants in both performance and price reduction.

Fig. 1: 50MWe steam generator system for parabolic trough CSP power plant

Aalborg CSP steam plant configuration

The parabolic trough solar power plant operates with a heat transfer fluid (HTF) that is heated by the sun in linear concentrators. The HTF is heated to maximum 393°C by the sun and cooled to a temperature just below 300°C in the steam generator. From the steam generator, the HTF is heated again to 393°C to form a closed cycle.

The HTF is cooled in heat exchangers for generation of high pressure steam and is used in a high pressure steam turbine generator for generation of electric power. The steam from the outlet of the steam turbine is normally reheated and used in a low pressure steam turbine generator for increasing the efficiency.

The data in the fig. 2 are typical for a power plant with 25MW electric power output. Some variation in data may be seen depending on the steam turbine chosen.

The high pressure (HP) steam generator consists of one superheater, one evaporator unit and one economizer. The reheater is a separate heat exchanger operated in parallel.

The steam flow is around 28.5kg/s per 25MW electric output. The HP steam is generated at around 105bar at 380°C for the HP turbine. The reheater heats the outlet steam from the HP steam turbine to 380°C again before it enters the low pressure (LP) steam turbine. The inlet steam to the reheater is typically 15 to 20bar with a water content of around 1%.

The plant can be configured with several parallel steam generator lines. A 100MWe power plant can, for example, has four steam generator lines generating 28.5kg/s each. Line sizes can vary, and Aalborg CSP offers lines with capacity of 28, 56 and 75kg/s steam flow as standard. Other capacities can be designed and supplied upon request.

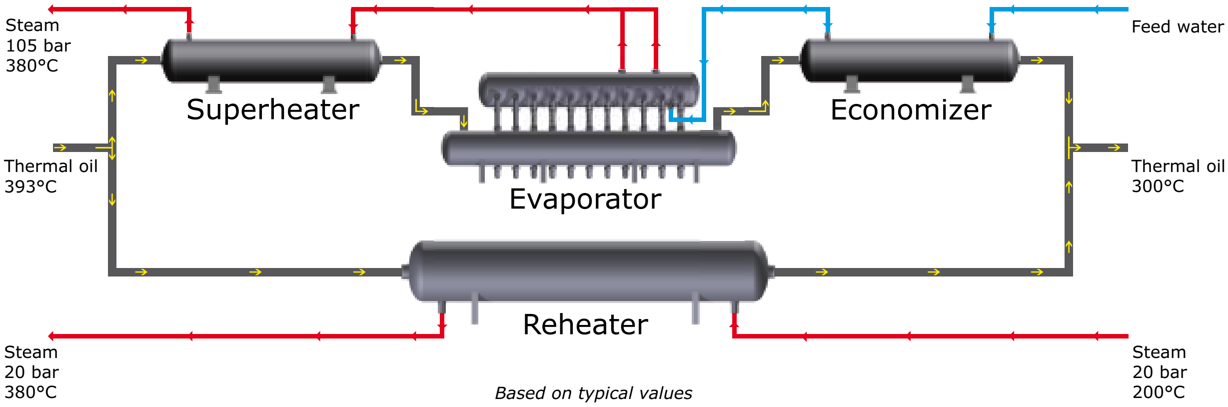


Fig. 2: Heat balance for typical 25MWe line

Metric system		Imperial system	
28.5	kg/s	63	lb/s
56	kg/s	123	lb/s
75	kg/s	165	lb/s
200	°C	392	F
300	°C	572	F
380	°C	716	F
393	°C	740	F
20	bar	290	psi
105	bar	1523	psi

Fig. 3: Unit conversion table

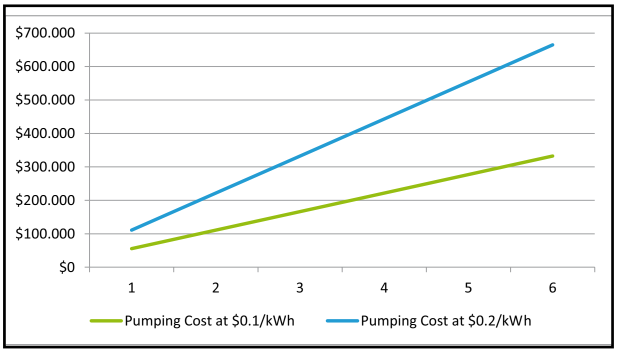


Fig. 4: Annual pumping costs for various pressure drops for 100MWe CSP power plant

Fig. 5 shows an enhanced configuration where all HTF passes through the evaporator. This plant has two reheaters, RHe and RHs, each parallel with the economizer and the superheater. This configuration will result in a lower HTF flow for the same steam output, or alternatively the reheater surface area can be made smaller. The configuration in fig. 2 will often result in a very large reheater depending on the HTF flow available for the reheater.

The steam generator plant supplied from Aalborg CSP has HTF side pressure drop of approximately 2.5bar. Typical values in the market are pressure drops two times higher. The lower pressure drop results in savings of the power for the HTF circulation pumps. For a 100MWe power plant, the difference in pump power is approximately 700kW. This saving in electric power has significant impact on overall plant economy in the range of millions of dollars over the plant's lifetime, see fig. 4.

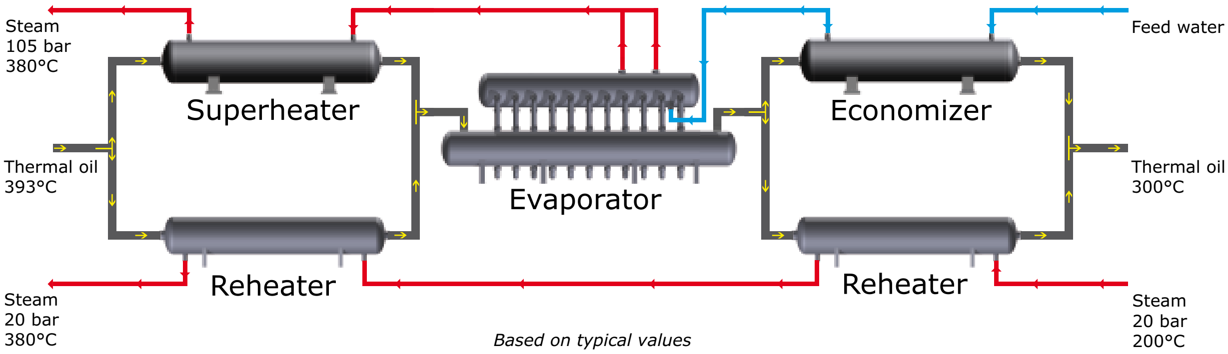


Fig. 5: Enhanced configuration for 25MW line

Evaporator design

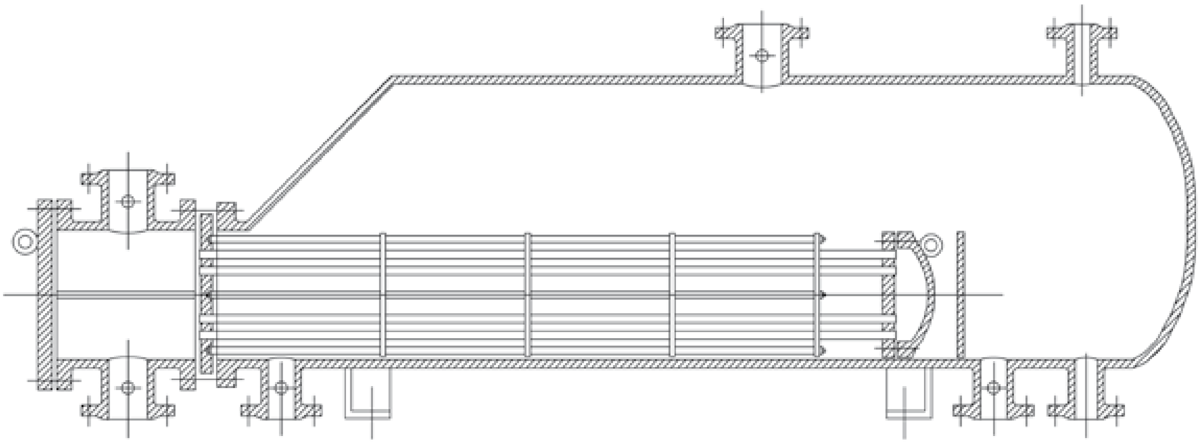
The evaporator is the main component of the steam generator plant with respect to weight and cost. Two types of evaporators will be compared: The kettle-type and the Aalborg CSP coil-type.

Kettle-type evaporators are heat exchangers for steam generation with tube bank and steam space enclosed into one common shell designed according to TEMA* standard. The shell has a diameter which is bigger than the tube bundle diameter and the steam space is in the top of the shell. The tube bank has two passes with inlet and outlet from one single tube plate. The heating medium flows inside the tubes and evaporation takes place on the shell side.

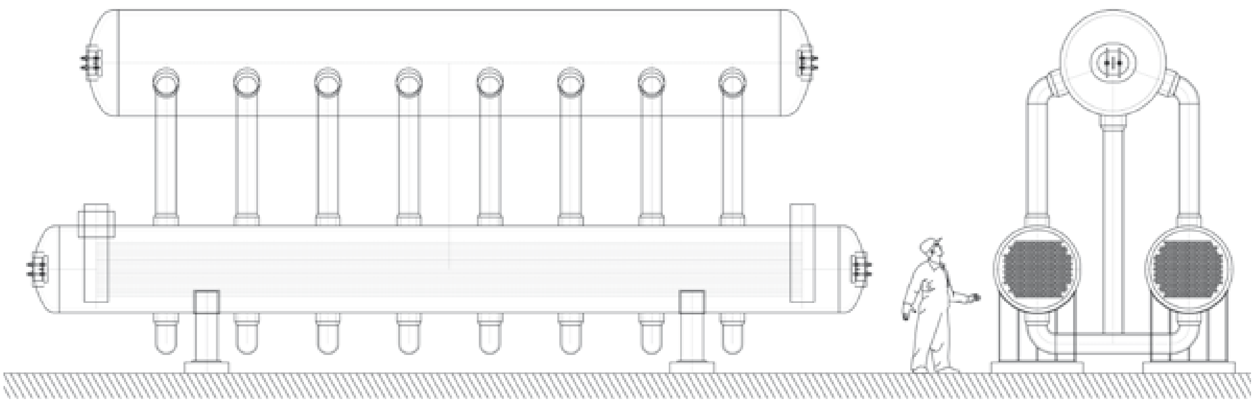
The coil-type evaporator designed by Aalborg CSP has been specially developed for solar energy applications, where high steam capacity and high steam pressures are required with frequent starts/stops and load changes.

The Aalborg CSP evaporator, designed according to demanding ASME** standards for steam boilers, consists of two evaporator heat exchangers and a separate steam drum. Evaporation occurs on the shell side. The steam drum is connected to the evaporators with external down comers and risers. The tube bank has typically three passes which results in a flexible tube bank relative to the shell.

**TEMA - Tubular Exchanger Manufacturers Association*
*** ASME - American Society of Mechanical Engineers*



Kettel-type evaporator



Aalborg CSP coil-type evaporator

Fig. 6: Illustration of kettel-type evaporator and Aalborg CSP coil-type evaporator

Circulation

Kettle-type evaporators are pool boiling devices, meaning that circulation of water in the tube bank is internal circulation only. Evaporation will cause the water/vapor mixture to rise from the tube bank and the saturated water to flow down along the sides of the shell.

In the coil-type evaporator from Aalborg CSP, the steam drum is connected to the evaporators with external down comers and risers. The circulation in this type of evaporator is natural circulation caused by the difference in density between the saturated liquid in the down comer and the lower density of the vapor/liquid mixture in the evaporator and riser. Circulation is predictable, and the tube bank will have an effective cross flow of boiler water at all times. Down comers and risers are designed for a circulation ratio of at least 15. The circulation ratio is the ratio of total flow, liquid plus vapor, to the vapor flow generated.

Thermal stress

The kettle-type evaporators are well suited for relative small units used for generation of process steam at relative low pressures. For large units, when the capacity and pressure increase, care should be exercised in the design of this type of equipment.

In solar HTF steam generation plants, the operation pressure is typically 100bar or more. The tube plate in a kettle-type evaporator is subject to bending stress from the internal pressure in the vessel. In order to withstand the pressure, the tube plates must be thick, typically 200mm or more. Solar steam generators are subject to start and stop every day and also frequent and rapid load changes during passage of clouds. This will cause variation in temperature of the heating medium creating thermal stress in the tube plates. High material thickness is undesirable with respect to thermal stress, and fatigue cracking is a risk.

The Aalborg CSP coil-type evaporator has no thick tube plates. The hot oil flows are distributed to the heat transfer tube bank via a circular manifold, also called a header. The round shape of the header results in a relative small material thickness and therefore low thermal stress. By splitting the evaporator unit in two heat exchangers and a steam drum, the diameters of the individual pressure vessels are small compared to the kettle-type, and the wall thickness required to sustain the pressure is smaller too.

The Aalborg CSP evaporator has a relative low material thickness. The small wall thickness results in a design that is less sensitive to fast temperature ramps during starts, stops and load changes.

Critical heat flux

For the kettle-type evaporator, the designer often aims to reduce the overall shell diameter by using a tube bundle of closely spaced small diameter tubes, see fig. 7. As a result, the heat flux can become close to, or even exceed, the critical heat flux of the tube bundle. The tubes become blanketed with vapor and the heat transfer will be drastically reduced and unstable.

Aalborg CSP uses large and widely spaced tubes. Operation is therefore well below the critical heat flux, so operation is stable and safe.

Fig. 7: Picture of the difference between the tubes used in kettle-type evaporators and the coil-type evaporator

High steam quality

Saturated steam is extracted from the top of the steam space. A small amount of water will be mixed with the steam. This is called carry-over. The saturated steam is virtually free from impurities but saturated water contains impurities from concentrated salts and other undesirable elements. The carry-over must be limited to levels acceptable for operation with a steam turbine. Limits can be found in guidelines like ABMA*** 402. For example, the maximum carry-over is 0.1% at 100bar steam pressure.

Fig. 8: 2 x 25MWe steam generator line

The kettle-type evaporator has the evaporation and steam space integrated in one common shell. Steam qualities acceptable for operation with a steam turbine can only be achieved with an external steam/water separator.

The Aalborg CSP evaporator has a separate steam drum, which is equipped with a double-stage water steam separation system as used in a conventional water tube boiler. First stage is the cyclone separators and second stage is the chevron separators.

Other components

The other heat exchangers in the system are the superheater, the economizer and the reheater.

When using TEMA-type shell and tube heat exchangers, a high material thickness will be needed for all components, even for the reheater. This is due to bending stresses in the tube plates from internal pressure.

All the heat exchangers designed at Aalborg CSP are unique coil-types without tube plates. The heat exchange surface consists of a tube bank with high pressure inside the tubes and the lower pressure HTF flowing in counter-flow outside in cross flow. The tube bank is contained in a cylindrical pressure vessel containing the HTF. The tube banks are welded to inlet and outlet manifolds (headers) that pass through the shell in thermo sleeves for low thermal stress.

The tube bank has a high degree of flexibility because of the many bends. The thermal stresses due to differences in temperature between the tubes and the surrounding shell are virtually zero.

Fig. 9: Aalborg CSP coil-type superheater

The HTF passes through the tube bank in counter flow without change of direction in one pass. The pressure drop for the HTF is very low for this configuration while the heat transfer coefficient is high.

Summary

The choice of appropriate steam generator technology has a significant impact on reduction of parasitic electricity losses in solar thermal power plants.

Aalborg CSP keeps on refining the steam generators and at present develops systems for molten salt as heat transfer medium and energy storage - the next generation of concentrated solar power.

**** ABMA - American Boiler Manufacturers Association*

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