STEAM GENERATORS AND STEAM DISTRIBUTION NETWORKS

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Contents

Summary

The different types, technologies, and operating modes of steam generators and steam distribution networks are presented, and laws, regulations, guidelines, and standards

mentioned. The main control systems such as fuel–air–flue gas, feedwater, and steam temperature are described in detail, as are limiting (safety) controls. Advanced control methods such as SCO, MIMO, Fuzzy Control, and so on, and monitoring, validation, analysis, diagnosis, expert systems, and their integration into power plant management systems are described. Finally, some experiences and practical suggestions are given.

1. Steam Generators

1.1. Types and Technologies

To design a proper automation and control system a profound and detailed knowledge of the process itself and of the control is required. It is therefore essential that there is fruitful discussion and cooperation between steam generator and control engineers.

Different types of steam generators are in general the result of the:

- capacity range (1–3000 t h^{-1}),
- pressure range (1–250 bar (350 bar in the future)), and
- temperature range (saturation temperature depending on evaporator pressure up to 600 °C (up to 700 °C in the future))

of the live-steam flow, which of course are dependent on the purpose the steam is used for. Nevertheless, steam generators of very different steam parameters can use common principles, for example, a once-through evaporator (Benson or Sulzer-type steam generators), or an evaporator with circulation (circulation steam generators), which can be provided by a circulating pump (forced circulation) or by gravity (natural circulation) resulting in similar automation and control systems.

Of course there are additional influences on the design of the steam generator and control system resulting from:

- the heat source used, for example, nuclear reactor, fossil fuel (coal, oil, gas), or waste, and so on; for example, in the case of combustion, a firing system including fuel preparation, air heating, and flue gas cleaning system, and so on, is used and has to be controlled;
- the pressure stages (one or double reheating or more); and
- other auxiliary systems like feedwater-pump, feedwater storage vessel, bledsteam feedwater preheaters, valves, safety and start-up equipment, soot blowers, and so on.

Table 1 gives an overview of the steam generator types and the evaporator systems. The newest development will be the ultra supercritical steam generator with a live steam pressure of 350 bar and a live steam temperature of 700 °C and an expected power plant efficiency higher than 50%. Supercritical steam generators have been built since the 1950s but with little economic success.

Steam generator type			Evaporator system	Usual live steam parameters			
				T h^{-1}	**bar**	**° C**	**reheat**
shell boilers	fire tube boiler economic boiler fire box boiler			<25	<25	saturation small super-heating	no
water tube	inclined/vertical tube boiler with		natural circulation				
		lengthwise and crosswise drum		<100	<70	<500	no
	bent/vertical tube boiler with						
		three, two, one drum(s) corner tube boiler					
	radiant boilers		natural circulation	<2000	160	530–540	one
			forced/controlled circulation	<2000	180	530–540	one
			forced/combined circulation	<2000	>250	530–540	one

			once through (Benson,Sulzer)	<3000	250- 350	530– 650	one– two

Table 1. Steam generator types

Figure 1 shows a shell-boiler, which is used for small industries such as slaughterhouses, breweries, paper mills, and laundries to produce not only saturated but also superheated steam. A shell-boiler is also used for heating larger buildings like hospitals, schools, and so on to produce hot water. This very simple (low cost) steam generator only needs simple controls: for example, an on/off control for the feedwater-pump if the water level is either too low or too high, and an on/off control for the firing system if the pressure is either too low or too high. How these simple controls work is shown in Figure 2. Of course with this simple control it is not useful to superheat the steam because there can be a steam flow without firing, and thus no heat is available for superheating. Such steam generators, using oil or gas as fuel, can also easily be operated by remote control without any operator on site for several days (if regulations permit) and they can also be monitored via the Internet.

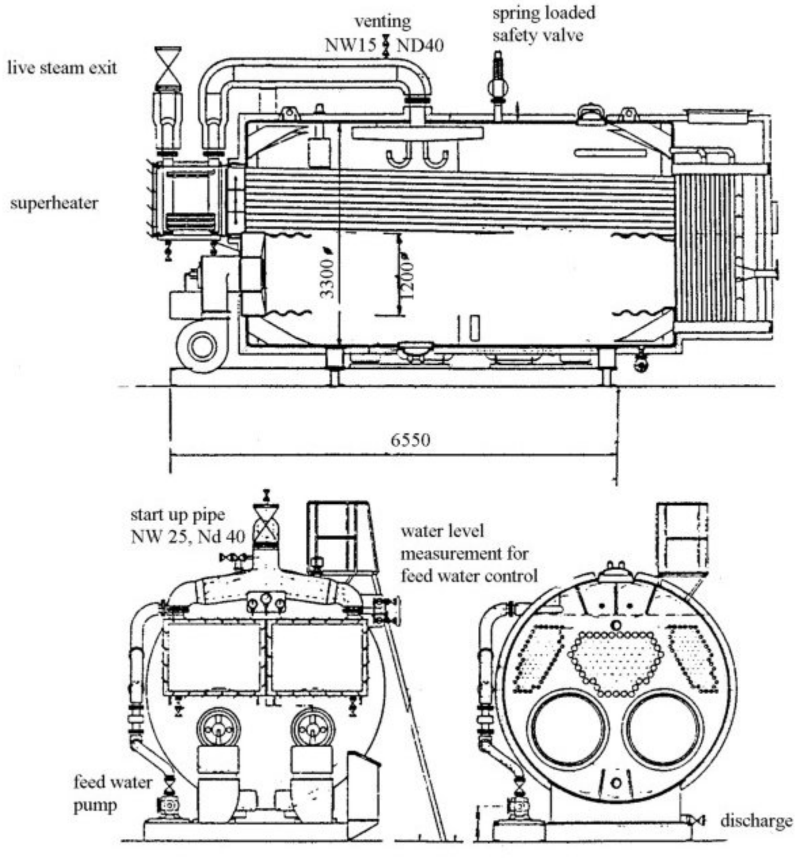

Figure 1. Shell boiler design (economic boiler) (Source: Alstom Power Boiler GmbH, Stuttgart)

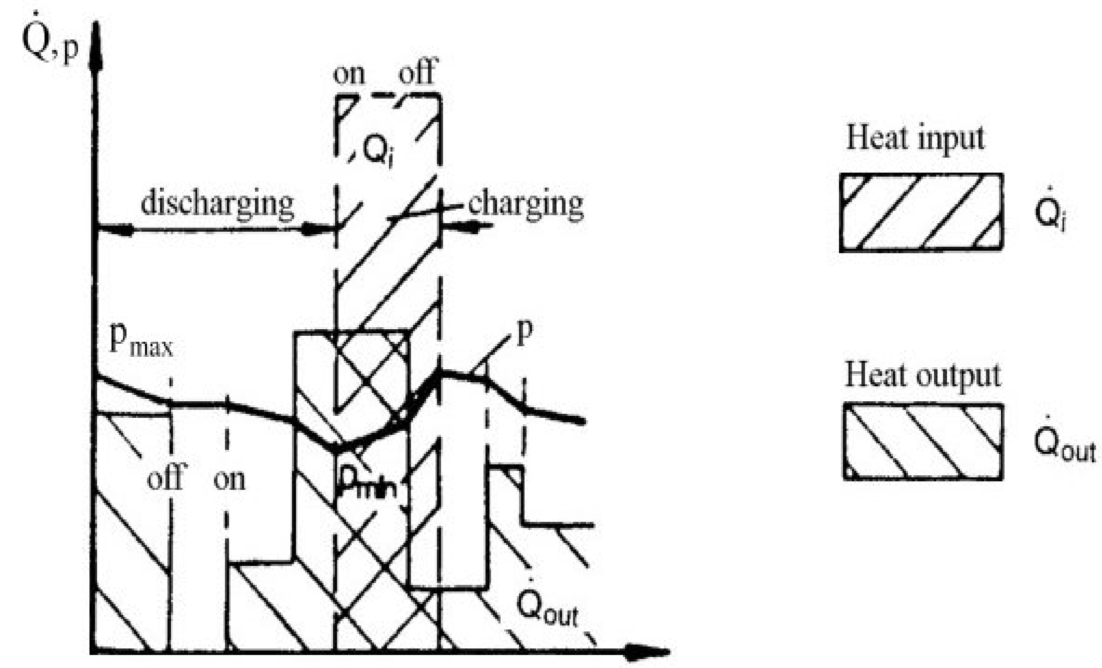

Figure 2. Pressure control by simple switching on/off firing system (fuel and air flow). (Similar control of water level by switching on/off feedwater-pump.) (Source: Dŏlecal, 1985)

The reason for the ease of control is the high storage capacity resulting from the high amount of saturated water stored in the vessel representing also a high amount of energy and potential of destruction in the case of the vessel bursting.

The steam storage capacity can easily be calculated according to the following formula (ignoring steam produced by the heat released from the steel of the tubes and drum and so on, according to the changing saturation temperature):

$$\Delta \dot{m}_{St} = -\frac{m'}{r} \cdot \frac{dh'}{dp} \cdot \frac{dp}{d\tau} = -c \cdot \frac{dp}{d\tau} \quad (1)$$

Relating the steam flow change to the steam flow at maximum continuous rate (m.c.r.) and the pressure at m.c.r. (using $\Delta\dot{p}$ instead of $dp/d\tau$) one gets:

$$\frac{\Delta \dot{m}_{St}}{\dot{m}_0} = -\frac{p_0}{r} \cdot \frac{dh'}{dp} \cdot \frac{m'}{\dot{m}_0} \cdot \frac{\Delta \dot{p}}{p_0} \quad (2)$$

in which the formula

$$\frac{m'}{\dot{m}_0} = T_1 \qquad (3)$$

is the time required to fill the evaporator-vessel with a water flow equivalent to the steam flow at m.c.r., which should be at least the capacity of the feedwater-pump.

Knowing that in the usual pressure range for such steam generators of 5 to 20 bar

$$\frac{p_0}{r} \cdot \frac{dh'}{dp} \approx 0{,}11 \qquad (4)$$

and using

$$0{,}11 \cdot T_1 = T_2 \qquad (5)$$

the dimensionless storage capacity becomes

$$\frac{\Delta \dot{m}_{St}}{\dot{m}_0} = -T_2 \frac{\Delta \dot{p}}{p_0} \qquad (6)$$

The start-up time T_s of such a steam generator (neglecting again the heat stored in the steel and only taking into account the heat stored in the saturated water) using the m.c.r. firing heat rate $\dot{Q}_0$ as

$$\dot{Q}_0 = \dot{m}_0 (h'' - h_w) \qquad (7)$$

becomes

$$T_s = \frac{m'(h' - h_w)}{\dot{Q}_0} = \frac{m'(h' - h_w)}{\dot{m}_0 (h'' - h_w)} = T_1 \frac{(h' - h_w)}{(h'' - h_w)} \qquad (8)$$

and is of course connected to the storage capacity, that is, a high storage capacity means a long start-up time.

Figure 3 shows the flow diagrams of the five steam generator systems generally in use worldwide for larger industrial (>50 t h^{-1}) and power station water-tube steam generators with all possible fuels.

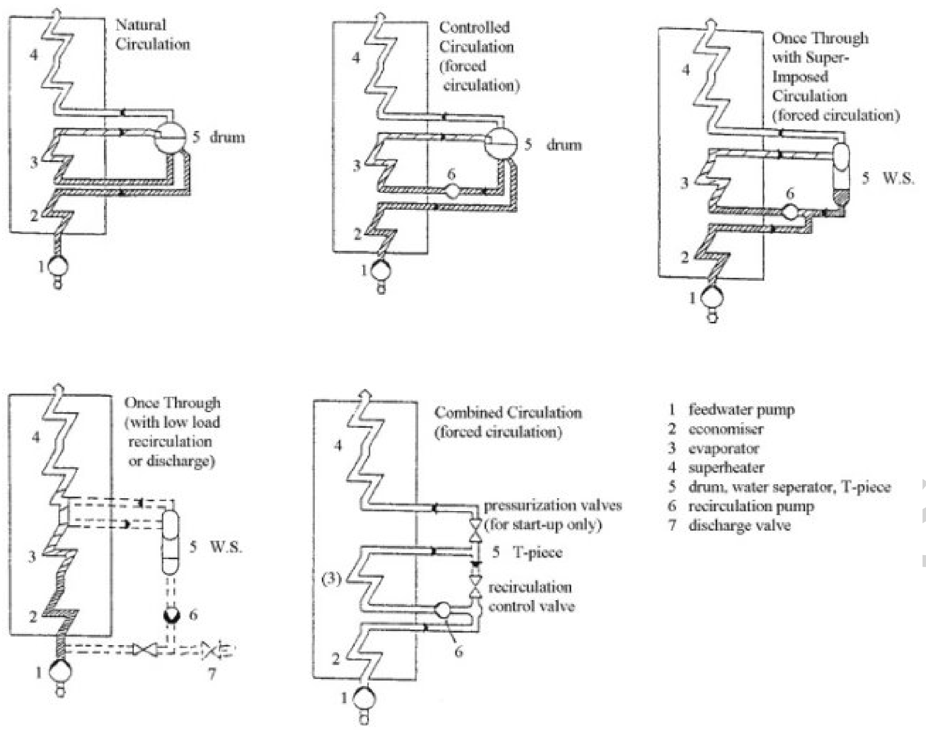

Figure 3. Flow diagrams of water-tube steam generator systems for industrial and power plant steam generators

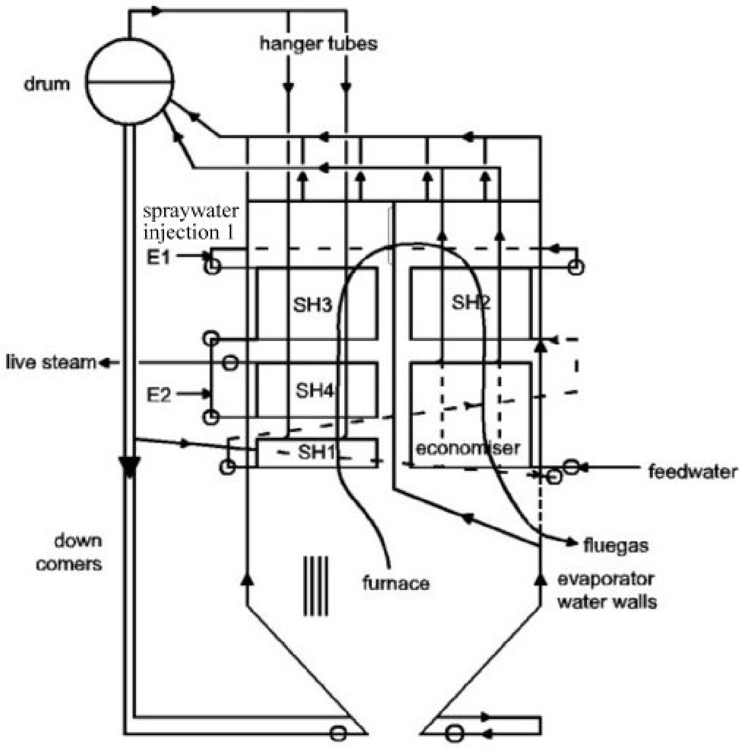

Figure 4. Simplified scheme of the arrangement of the heating surfaces of a water-tube steam generator

Figure 4 shows (in a simplified scheme) the arrangement of the different heating surfaces of a water-tube steam generator.

The most important difference concerning the evaporator system, and also the feedwater control of water-tube boilers, is the result of the method applied to avoid unacceptable high tube material temperatures and eventually tube failures in the evaporator tubes (usually used for the furnace walls). In principle there are only two possibilities when subcritical pressure is used:

- To superimpose a recirculated saturated water flow in the evaporator tubes to keep the steam quality below x_{DNB} (departure from nucleate boiling); this is used in natural and forced or controlled circulation boilers, $U = \dot{m}_{evt} / \dot{m}_{fw}$ being the circulation ratio given be $1/x_{eo}$ (because the steam flow at the evaporator outlet and the feedwater flow are identical). These steam generators usually have a high number of large vertical evaporator tubes forming the furnace walls (waterwalls).
- To increase the mass flow density to improve the heat transfer rate during film boiling. These steam generators usually have a lower number of smaller and inclined tubes forming the furnace walls (waterwalls), which is a disadvantageous and more expensive design compared with vertical tubes. The use of rifled tubes improves the heat transfer rate at much lower mass flow densities and allows a higher number of parallel tubes and therefore vertical tubing of the furnace walls of steam generators of smaller capacity. The furnace circumference increases less than linear with the boiler capacity resulting in an increasing angle of inclination of the waterwall tubes. This method is used for once-through steam generators. (At low loads (<40% m.c.r) once-through steam generators are also usually operated with recirculation in the evaporator).

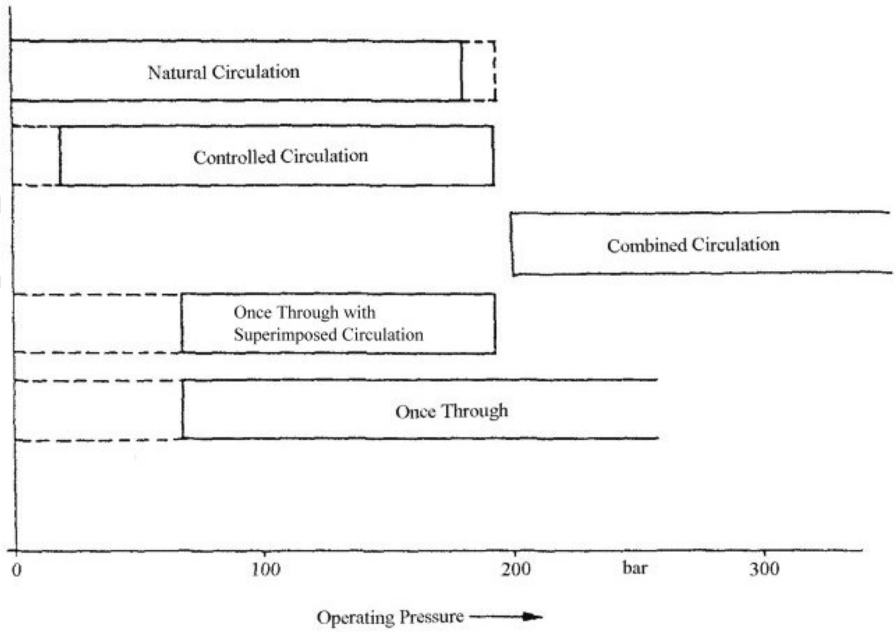

Figure 5. Applicable pressure range of steam generator systems for industrial and power plant steam generators

The pressure range applicable for these steam generator types is given in Figure 5

These two methods also result in completely different behavior of the boilers and feedwater and superheater temperature control (see Sections 4.2 and 4.3).

If supercritical pressure is used, the design can be either a once-through steam generator with a smaller number of parallel waterwall (furnace wall) tubes, which are inclined and have a smaller diameter, or a combined circulation steam generator with a higher number of parallel waterwall tubes, which are vertical and have a bigger diameter; these arrangements provide the high necessary mass flow density by a small flow area or a recycled mass flow respectively. During start-up in the once-through steam generators a separator and a circulating pump are usually used, whereas in the combined circulation steam generator throttle valves beyond the waterwalls provide for supercritical pressure in the waterwalls (and subcritical pressure at the live steam outlet) during start-up. This allows use of a T-piece instead of a separator to branch off the recirculation flow. The feedwater control of a combined circulation steam generator is similar to the feedwater control of a once-through steam generator. Usually the circulation (pump) of a combined circulation steam generator is not controlled.

Less important (or nearly negligible) for the control systems are the shape and size (above a certain limit) of the steam generator. Small steam generators usually have simpler control systems.

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VDI/VDE 3501 *Fuel and Air Control.* Düsseldorf, Germany: VDI.

VDI/VDE 3502 *Drum Level Control in Fossil Fired Steam Power Stations.* Düsseldorf, Germany: VDI.

VDI/VDE 3503 *Steam Temperature Control in Fossil Fired Steam Power Stations.* Düsseldorf, Germany: VDI.

VDI/VDE 3504 *Furnace Pressure Control.* Düsseldorf, Germany: VDI.

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Biographical Sketch

Prof. Dr. techn. R. Leithner was born in 1945 in Schärding, Austria. He graduated as Dipl.-Ing. (Mechanical Engineering) from the Technical University in Vienna in 1970 with a thesis on measurement and simulation of a heat exchanger. From 1971 till 1983 he worked in different positions with Energie- und Verfahrenstechnik GmbH (now Alstom Power Boiler GmbH), Stuttgart, one of the leading steam generator manufacturers in Germany. During his period at EVT he wrote a doctoral thesis on the mass flow from an equally heated tube at constant pressure and graduated as Dr. techn. from the Technical University in Vienna in 1976.

His last position in this company was head of the "main department for steam generator design, development and commissioning", where his responsibilities included stress analyses and control systems; also the power of a procurator was granted him. In 1983 he was appointed professor and director of the IWBT-TU BS. In all these positions he has always been involved in power plant design, calculation, control, and simulation.