Chapter 1
Generator Classification

1.1 Classification According to the Employed Fuel

Based on the employed fuel, generators may be classified into fuel oil, natural gas, coal (or lignite), and low-grade fuel generators.

Fuel oil generators of any kind and power are built. These generators require the installation of stocking as well as service tanks, where the oil is heated electrically for starting and through steaming at 30/40°C, and a pumping and heating plant to reduce viscosity at the required value to obtain good atomizing.

Viscosity varies considerably from 3–4°E at 50°C ($\approx$ 140–180 SUS at 100°F) for low-viscosity fuels up to 50°E at 50°C ($\approx$ 3500 SUS at 100°F) and more for high-viscosity fuels used in generators for thermoelectric power plants. The viscosity of oils used industrially as fuels usually goes from 25 to 50°E at 50°C ($\approx$ 1900–3500 SUS at 100°F).

Good atomizing with burners without the intervention of steam requires viscosity up to 3–4°E (100–140 SUS). In the case of steam atomizing, good results may be obtained with a viscosity of 7–10°E (240–350 SUS). Therefore, it is necessary to heat the fuel oil to a temperature that varies from 80 to 100°C. Big units are started using low-viscosity oils or gas oil.

The positioning of burners is typically horizontal. They can also be placed vertically or tilted, and in the case of big units, tiltable burners are employed to be able to vary the radiation of heat in the furnace, that is, when it is required because of output variations.

The turbulence of the air exiting the burner is quite important to obtain good combustion and to adjust the length of the flame to avoid damage of the refractory material of the burner housing with a flame that is too short, as well as the impact on refractory walls or tube walls with a flame that is too long. To this extent, the correct sizing of the furnace is crucial to ensure complete combustion before the gas exits and to avoid the impact of the flame on the walls through correct plan size dimensions.

In the case of natural gas steam generators, the latter is fed with the pressure of a few thousand pascals (Pa) (excluding special high-pressure burners with sucked

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air). Therefore, it must be decompressed before it is led to the burners by the gas network. It is very important to obtain an efficient mix between air and gas.

The positioning of the burners is similar to that of fuel oil burners. Burners using oil or natural gas are often employed to be able to switch from one fuel to the other depending on availability and seasonal costs. In this case, the emissivity of the flame with combustion by fuel oil differs from that by natural gas. The heat transmission by radiation differs, as well, and so do the temperature of flue gas at the exit of the furnace and the thermodynamic conditions under which the heat exchange occurs in the convection section of the boiler, as well as in the superheater. In other words, to use both fuels it may be necessary to adopt certain measures to be able to modify the exchange conditions that will lead to the desired results in both instances. At any rate, fuel oil and natural gas are most easily interchangeable fuels, and this possibility is used the most nowadays.

In the case of natural gas, the danger of bursts is quite high, considering that this gas easily produces an explosive mix when in contact with air. This must be factored in by planning for adequate protection machinery.

Natural gas is not the only gas used for combustion even though it is the most common one. Among gas generators, we cannot forget the ones using, for example, refinery gas, coke oven gas, and blast furnace gas. The use of such fuels is obviously limited to those industries developing them as a by-product of their production processes.

In the case of coal (or lignite) generators, the coal is burned on a grate or in special burners after pulverization. In big units, it is burned as pulverized coal, frequently as an alternative to fuel oil or natural gas. The use of pulverized coal is limited to big units because these justify the costly installation of the necessary stocking, pulverization, and transportation systems.

In generators using pulverized coal, the charging hoppers fed by conveyor belts in turn feed the mills through a metering device (see Fig. 1.1), where the coal is thinly pulverized and carried to the burners through pumped air. In the furnace, secondary combustion air is added to primary air.

Combustion can also occur in a cyclone burner before the entrance into the furnace. In this case, pulverization is not required to be as thin as before.

The sizing of the furnace is very important to ensure that combustion is completed in the furnace. This depends on numerous factors, such as the turbulence of the air-pulverized coal mix at the inlet of the furnace, the position and tilt of the burners, the speed of the mix through the furnace, and the time it takes the pulverized coal to burn. The latter is in turn influenced by a number of factors and diminishes with the increase in excess air and the reduction of volatile matter. Good combustion requires the reduction of moisture in the pulverized coal and the heating of the air.

As far as the ashes, the furnace is designed with a hopper for collection in the lower part. The ashes may be scavenged in solid or melted state. In the first case, through cooling obtained through water pipes displaced as grates that solidify them; in the second case, by letting the ashes flow along the walls into a cooling container where water is kept stirring and where they are scavenged through mechanical means (conveyor belts) or pneumatic means.

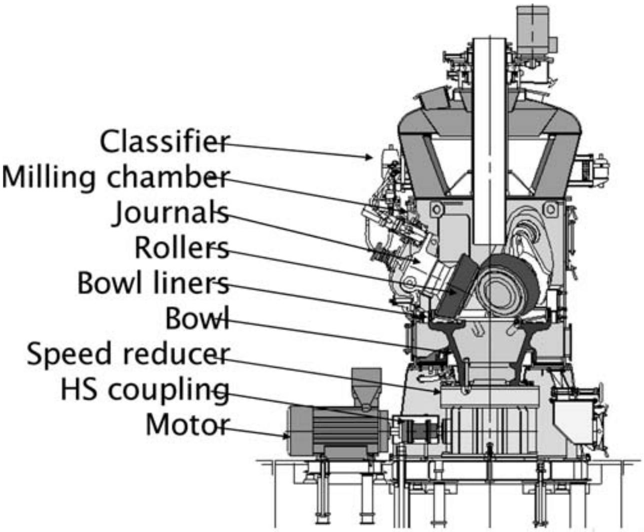


Fig. 1.1 Mill for coal pulverizing (Courtesy of Alstom)

As pointed out earlier, big generators are frequently designed to work with fuel oil, natural gas, or pulverized coal to ensure performance even when it becomes necessary or convenient to abandon one or the other fuel due to cost- or procurement-related problems. In that case, the adaptability problems of the generator to the different fuels increase with respect to the simple combustion of fuel oil and natural gas, given the combustion characteristics of coal that are sensibly different from the other two.

The dimensions of the furnace must be greater than those necessary for fuel oil and natural gas to ensure correct combustion of the coal. Given equal inlet heat in the furnace, the amount of flue gas differs in the two cases. Thus, the amount of inlet heat per mass unit of flue gas is different, as well. All this impacts the exit temperature of the flue gas from the furnace and the thermal exchange in the superheater following the furnace along the route of the flue gas. These differences must be eliminated through adequate structural measures, such as the recirculation of flue gas that is partially taken at the end of the generator and reintroduced into the furnace. We will return to this later on.

Generators using low-grade fuel generally burn it on grates. In fact, excluding special burners for the combustion of saw dust and low-grade gases, all solid low-grade fuels are burnt on grates. Of course, these are by-products of special production processes, thus they are only employed in plants that produce them in-house. By comparison, they are grape husk (by-product of the processing of grapes during production of alcohol), olive husk (by-product during the processing of olives), wooden shavings or saw dust, bagasse (by-product during the processing of sugar cane), and rice husk (by-product of rice polishing).

Moreover, it is worth mentioning the generators used to burn urban waste. The double result of eliminating it while producing steam or superheated water generally allocated for the heating of urban homes is achieved. There are also examples of electricity production.

The grate is placed in the lower part of the furnace, or in the pre-furnace, if the presence of extended walls of refractory material that re-irradiate the fuel bed is required for correct combustion. A huge problem caused by the combustion of solid low-grade fuels is the evacuation of the high amount of ashes produced. Generally, the ashes are collected in water containers and then eliminated either hydraulically or mechanically through conveyor belts. The low-heat value of these fuels and the deriving high volumes of gas, compared to the combustion of high-grade fuels, require certain sizing criteria of the generator as far as the volume of the furnace, the cross-sectional passage areas of gas, and so on.

Finally, it is worth noting that these generators using production residues are not expected to deliver high generator efficiency, given the predominance of the installation cost during evaluation of the maximum economic goal to achieve.

1.2 Classification Based on Heat Transfer

The generators classified according to heat transfer in the boiler may be characterized by convection, radiation, or indirect heating.

First of all, note that boiler is understood to be the bulk of steam-generating tubes in its entirety, that is, the tubes where the transformation of water into saturated steam takes place. Therefore, the economizer and air heater, as well as the potential superheater and reheater, are included in the steam generator but are not part of the boiler. From this point of view, there are generators that may be correctly called radiation generators. Instead, it would be wrong to speak of convection generators, given the fact that in all generators any smaller or greater amount of heat will be transferred to the boiler through radiation.

First of all, in the furnace the heat is transmitted by radiation only (or predominantly by radiation, as is the case in the flues of smoke-tube boilers). Furthermore, even inside the bank of steam-generating tubes where the heat is mainly transmitted by convection, a part of it is transmitted by radiation from the gas itself, as described in Chap. 8 (not to be ignored if the flue gas is still very hot).

Generally, in radiation generators heat is totally or predominantly transferred through radiation, whereas in convection generators heat is mainly transmitted through convection. This is a somewhat artificial classification that aims at distinguishing some generators from others from a structural and thermodynamic point of view.

Convection generators are smoke-tube generators and most water-tube generators of small and medium power where the bank of steam-generating tubes is important in terms of heat exchange.

The radiation generators are powerful units where the steam-generating tubes are located only on the walls of the furnace, or, in some cases, there is a modest bank of steam-generating tubes. In the first instance, it is strictly a radiation generator, in the second instance it is still an acceptable definition, given the predominance of radiated heat into the furnace.

In big units, the heat is transferred to the steam-generating tubes mainly or entirely through radiation for the following reasons. The air temperature is quite high and contributes to a temperature increase produced by combustion. Consequently, the amount of radiated heat goes up. On the other hand, these generators work under great pressure so that the heat of vaporization is rather low. The surface of the screens in the furnace is therefore sufficient to absorb all the heat required to transform the water into saturated steam. Sometimes there is excess surface and part of the furnace is screened by tubes of the superheater, as we shall see later on.

Finally, waste-heat generators cause the cooling of warm gas coming from an external source (open-hearth furnaces, glass furnaces, diesel engines, gas turbines, etc.). They can have both smoke and water tubes. In the latter case, the boiler can have a superheater in front and an economizer after it. The absence of the furnace and of the radiation from a flame is typical of these generators. Therefore, the heat is transmitted entirely by convection except for the heat radiated by gas (a modest quantity given that flue gas is usually warm but not hot).

Diathermic fluid boilers belong to the category of generators by indirect heat. Made of a furnace screened by tubes and a convection bank, there is a special fluid instead of water flowing inside it and warming up; upon leaving the boiler, it enters a heat exchanger where it warms up the water or transforms it into steam. After this cooling process, the fluid re-enters the boiler to be heated again. The nature of the fluid and the characteristics of the boiler will be discussed in Chap. 5. These fluids are heated up under atmospheric pressure in contrast to water. From a certain perspective and given the structural features, these boilers could be viewed as convection boilers. In terms of classification, though, note that the transmission of heat to the water occurs through an intermediate vector. Thus, the name indirect heating adopted for these boilers.

1.3 Classification According to Circulation

Based on the type of circulation, there are natural circulation generators, assisted circulation generators, and forced circulation generators.

In the first case, the circulation of water and of the water–steam mix (in the steam-generating tubes) occurs naturally. The specific conditions for this process to take place will be discussed in Chap. 10 on this topic. For now, it suffices to say that the circulation takes place due to the difference in density of warm water leaving the drum and feeding the lower headers of the boiler and the density of the water–steam mix returning to the drum through the steam-generating tubes and the upper headers.

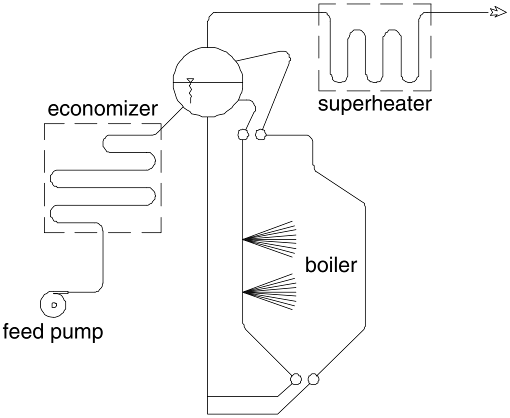


Fig. 1.2 Generator with natural circulation

The boiler is a closed circuit linked to the drum located in the highest position. The connection tubes of the potential economizer through which the pumped water is heated are also linked to the drum. In addition, the tubes carrying the saturated steam to the potential superheater start from the drum as well (see Fig. 1.2). In the absence of the economizer, the feed pump directly leads the water into the drum. In the absence of a superheater, the saturated steam goes to use right away. All generators of small and medium power and a percentage of superpower generators have natural circulation.

The generators with assisted circulation do not differ from the previous ones from a structural point of view, except for the fact that circulation in the tubes of the boiler does not occur naturally but through the help of pumps instead (see Fig. 1.3). Even in this case, the boiler consists of a closed circuit. The pump intervening with its head added to the head between the upper drum and the lower headers linked to the steam-generating tubes facilitates the circulation of water and the mix of water and steam in the circuit. This will lead to the correct functioning of the boiler, even if

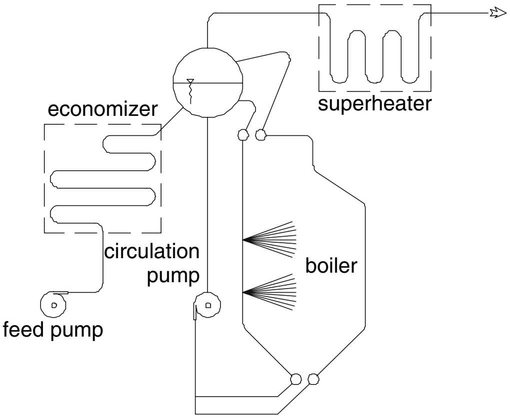


Fig. 1.3 Generator with assisted circulation

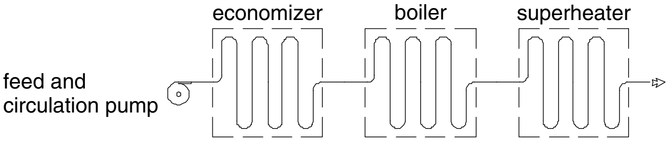


Fig. 1.4 Generators with forced circulation

the difference between the density of steam and water is small, as is the case under high pressure and as will be explained in more detail later on.

In generators with forced circulation, the pumped water is heated. Then it evaporates until the steam is superheated through a single circuit. Therefore, these are called one-through generators. In contrast to generators with natural and assisted circulation, the boiler consists of an open circuit preceded by the economizer and followed by the superheater (see Fig. 1.4). The drum is absent. With natural and assisted circulation, a huge quantity of water circulates, which is only partially transformed into steam, as will be explained later on. Instead, in the forced circulation generator, the feed pump coincides with the circulation pump and introduces the water required for the requested output, and the water is transformed into superheated steam, according to the specifications through the economizer, the boiler, and the superheater.

The necessity to abandon natural circulation in favor of assisted or forced circulation becomes real at high pressure, and this explains why all small- and medium-powered generators under low or medium pressure have natural circulation. In fact, natural circulation originates from the difference in density between the warm water in the downcomers (if the downcomers are hit by flue gas, there will be a mix of water and steam with low percentage of steam, but this will not be the case in big units) and the mix of water and steam in the steam-generating tubes. This difference decreases as the pressure increases until it disappears in correspondence of critical pressure. Figure 1.5 shows the ratio between the density of water and steam

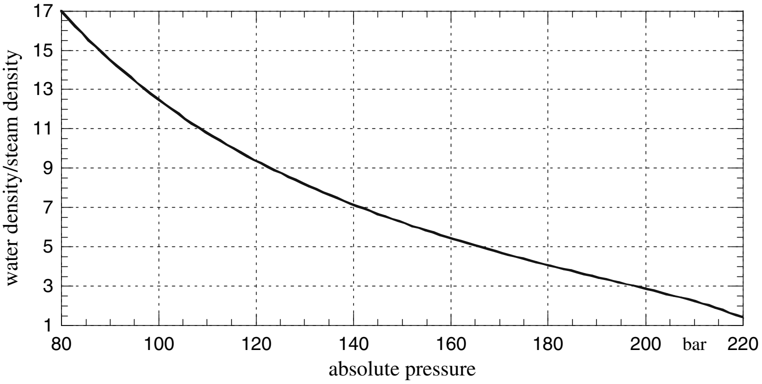


Fig. 1.5 Ratio between water density and steam density

between 80 and 220 bar. Beyond a certain level of pressure, assisted or forced circulation must replace the natural one. Generally, natural circulation is abandoned for pressures above 160 bar even though there are generators with natural circulation working at 180 bar. Some designers move to assisted circulation for pressure above 130 bar.

Assisted circulation has the following advantages. It provides the builder with more leeway as far as tube diameter, as well as the positioning of tube walls, their height, and so on. Natural circulation requires certain heads between drum and lower headers. Consequently, boilers will be narrow and tall. This greater freedom of assisted circulation generators makes it possible to design very compact units. The presence of circulation pumps makes the generator very flexible as far as quick starting and compensation for variable loads.

Moreover, it is possible to factor in more efficient steam dryers in the drum. They cause a greater pressure drop that may be neglected due to the presence of pumps. This leads to a better water-vapor ratio. The pumps also activate circulation during the starting process eliminating the danger of heat strokes and avoiding the build up of steam film on the surface of the tube that would cause it to superheat. Finally, the possibility to use tubes of smaller diameter reduces the danger in case of bursts and produces a cost reduction.

These are some of the disadvantages. Tubes with a small diameter cost less but also carry less water mass in the boiler. This leads to some instability during load variations, unless there are quite sensitive and quick automatic, hence expensive checks. In addition, these tubes require highly purified water.

Circulation pumps are responsible for greater setup and running costs, and given the fact that the water is at high temperature and pressure, they are costly and require attentive and frequent maintenance. Considering that breakdown is not admissible because it would stop the plant, there are usually back-up pumps, as well, and that necessarily increases the total cost of the plant.

If assisted circulation provides greater design flexibility on the one hand, on the other it may cause design problems to ensure the desired circulation in the different parallel circuits is fed by the pumps according to specifications.

As pointed out earlier, forced circulation does not include water recirculation, as is the case with both natural and assisted circulation. All the water entering the tubes is transformed into steam under the expected conditions.

Small diameter tubes are used, and high speed of both water–steam mix and steam is kept up to prevent superheating of the tubes and the deriving bursts where the cooling action of the water is missing. In the steam-generating tubes of well-designed natural and assisted circulation generators, the water is always present because the circulating water exceeds the produced steam.

The advantages with respect to other types of boilers are as follows:

- absence of a pressure limit, hence the design for hypercritical pressure;
- elimination of the drum and its deriving cost;
- elimination of downcomers and return tubes;
- fast lineup of steady-state condition.

The disadvantages, or rather the complications, are as follows:

- In generators with natural or assisted circulation, the sludge left by the water is removed by the drum. In this case, given that the drum is missing, the sludge must be removed by the tubes instead, and that is more complicated.
- These generators require extremely sensitive check and tuning systems.
- The temperature of the superheated steam varies quickly and sensibly upon load variations. It is worth recalling the danger of very fast evaporation of the water under reduced load, as well as the superheating and bursting of the tubes. Finally, in the area of passage from water to steam, the tube is vulnerable to corrosion.

As will be discussed in more detail further on, in diathermic fluid boilers, circulation is forced, given the necessity to keep the speed of the fluid high to prevent undesirable phenomena in the fluid and to guarantee efficient cooling of the tubes.

1.4 Classification According to Water Content

Based on the ratio between water content and heated surface, generators can be classified into high, medium, and low water content generators.

High water content generators hold between 50 and 100 kg of water for m^2 of heated surface. They allow relatively rapid starting and are not exceedingly sensitive to flame irregularities. Considering the water mass, in a way they work as steam accumulators. The smoke-tube boilers belong to this category.

The medium water mass generators hold between 20 and 50 kg water for m^2 of heated surface. They are more flexible but also more sensitive to irregularities of the flames. Variations in requested steam must rapidly be matched by variations in burnt fuel given the modest heat accumulation in the water. More accurate tuning and increased surveillance are therefore necessary during runtime. The treatment of water must be pushed further, particularly if the pressure is high. Single block, low power, transportable convection water-tube generators belong to this category.

Small water content generators have similar characteristics, fast starting time and specific requirements in terms of tuning and treatment of water. The biggest convection units and the big radiation units belong to this category.

In the case of large water content, a reserve of heat to fulfil sudden requests of steam is available, but this possibility is not to be overestimated.

The enthalpy and the density of the water at maximum allowable running pressure are indicated with h'_{w} and ρ'_{w}, respectively. Moreover, h''_{w} and h''_{s} will be the enthalpy of the water and the steam under minimum running pressure, respectively. β indicates the quantity of steam developed by $1\,\mathrm{m}^3$ of water going from maximum to minimum pressure.

Thus,

$$\beta = \frac{h'_{\mathrm{w}} - h''_{\mathrm{w}}}{h''_{\mathrm{s}} - h''_{\mathrm{w}}}\rho'_{\mathrm{w}} \tag{1.1}$$

If, for example, at $p' = 14$ bar and $p'' = 9$ bar and therefore $h'_\mathrm{w} = 830.08\,\mathrm{kJ/kg}$, $\rho'_\mathrm{w} = 870.4\,\mathrm{kg/m^3}$, $h''_\mathrm{w} = 642.64\,\mathrm{kJ/kg}$, and $h''_\mathrm{s} = 2772.1\,\mathrm{kJ/kg}$, then $\beta = 37.5\,\mathrm{kg/m^3}$.

Let us assume a smoke-tube boiler filled with 100 kg of water for m^2 of heated surface. The boiler produces $44\,\mathrm{kg/m^2}$ of steam. This value corresponds to specific output of these kinds of boilers. Based on the value of β and with reference to $1\,\mathrm{m}^2$ of heated surface, $0.1 \times 37.5 = 3.75\,\mathrm{kg/m^2}$ of steam are freed that represent 8.5% of output. Note that even though the maximum value of water content $(100\,\mathrm{kg/m^2})$ and a considerable reduction of pressure (5 bar) were factored in, the increase in production amounts to only 8.5%.

Finally, note that the calculation shown above is based on the assumption that the boiler is filled with water up to the normal level. In reality, as we shall discuss in Chap. 4, the boiler contains a mix of water and steam. Actually, only the water contributes to free the steam, and this is why the increase in production is definitely lower than the computed one.

1.5 Classification According to Furnace Pressure

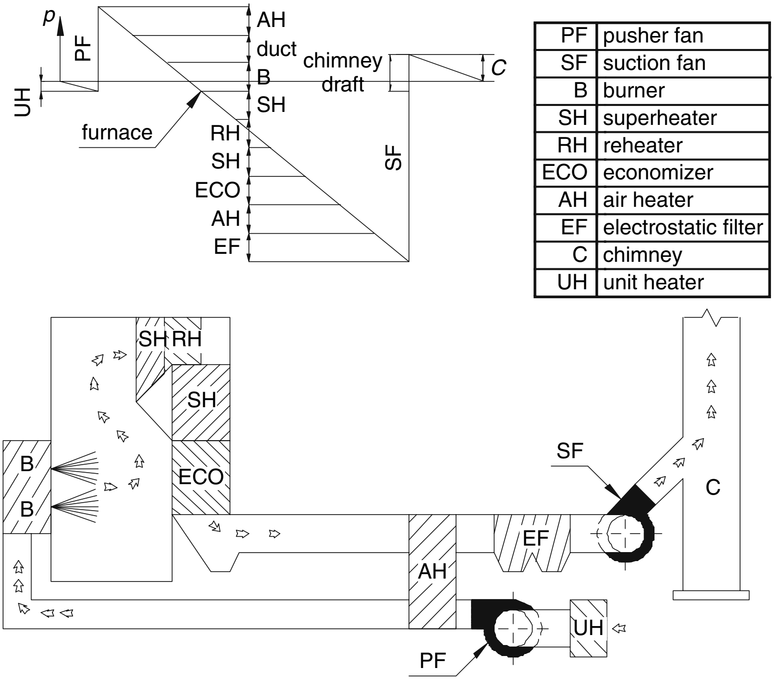
Generators may be classified as generators with a depression furnace and as pressurized generators. Initially, all generators had a depression furnace and worked through natural draught. Due to the chimney, a depression formed at its base. It would provoke the suction of flue gas from the furnace through the tube banks.

The increase in larger generators meant pressure drops of such high entity to make runtime through natural draught impossible. This increase in pressure drops did not depend on a greater number of tubes passed through by flue gas only but mostly on the opportunity to increase the speed of the gas itself to increase the value of the overall heat transfer coefficient, thus reducing exchange surfaces and costs. This led to the introduction of a suction fan placed at the base of the chimney.

The tall chimneys of thermoelectrical plants are not meant to generate totally insufficient natural draught but to keep the flue gas at the level required by ecological constraints.

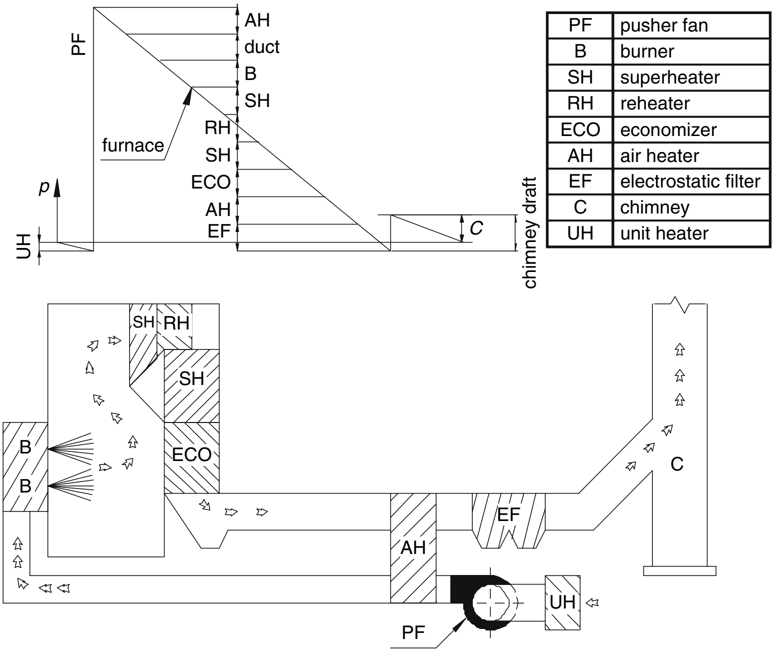
In summary, the features of a generator with a depression furnace include a suction fan for the circulation of flue gas through the generator, in addition to a pusher fan to introduce combustion air into the furnace (see Fig. 1.6). These generators with a depression furnace were once widespread. Nowadays, they are quite rare and limited to some coal generators.

The generally adopted solution consists of the so-called pressurized generator because the furnace is under pressure. Of course, the pressure is on the entire generator with value decreasing from the furnace to the exit of the generator (see Fig. 1.7). These generators have only one pusher fan or even two pusher fans in great units to control the air flow in a more rational way and to reduce the power of every fan, as well as to allow the development of at least 50–60% of the maximum generator



PF	pusher fan
SF	suction fan
B	burner
SH	superheater
RH	reheater
ECO	economizer
AH	air heater
EF	electrostatic filter
C	chimney
UH	unit heater

Fig. 1.6 Generator diagram with balanced draft



PF	pusher fan
B	burner
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AH	air heater
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C	chimney
UH	unit heater

Fig. 1.7 Pressurized generator diagram

power in case of breakdown of a fan. The air sucked by the fan through a potential unit heater (steam exchanger) that increases the temperature compared to room temperature is pumped through a potential air heater into the burners and then into the furnace. The pressure is higher in this case compared to a non-pressurized generator, given that one pusher fan only must compensate for pressure drops through the generator.

Flue gas under decreasing pressure runs through the different tube banks, that is, through steam-generating banks, the superheater, the reheaters, and the economizer. At the end of the process, it may run through an air heater, and in some instances through a soot precipitator, to reach the base of the chimney.

In the case of smoke-tube generators, the fan must compensate only for the pressure drop occurring inside the tubes passed through by flue gas in addition, of course, to the pressure drop through the burner.

The pressurized generators represent the vast majority of generators for the production of energy and the totality of industrial water-tube generators of low and medium range. These have a series of advantages. Only one pusher fan is required instead of two (one of pusher type and one of suction type) that are required if the furnace is in depression. The cost is reduced even though the required power for the pusher fan is naturally higher to compensate for the pressure drops of the flue gas. This is due not only to the fact that two fans cost more than one fan as powerful as the two combined, but also because the pusher fan pumps air at low temperature and, given its smaller volume, the absorbed power is less than that required by fans of non-pressurized generators.

The smaller amount of absorbed power equals both smaller installation and maintenance costs that considerably impact the budget of large plants. In addition, the suction fan running in the presence of warm gas and soot always causes trouble because of thermal dilations and deposits on the blades of the wheel. Compared to generators with balanced draught, pressurized generators that are tight to prevent gas leaks eliminate air infiltrations that determine a reduction in efficiency. The savings obtained through pressurized generators due to a reduced power absorption by the fans, as well as the absence of infiltrations, is estimated to be about 0.5–0.7% of the cost of energy output. Finally, the presence of one fan instead of two considerably simplifies both manual and automatic tuning.

The generators of this kind also have disadvantages. In fact, besides the necessity of special attention to prevent flue gas leaks from the eyepieces and from the openings for the soot blowers and the spuds of the burners, they require a more expensive metal coating to ensure a perfect seal and the ability to withstand internal pressure.

The advantages, though, greatly exceed the disadvantages.