Boiler Calculations

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Steam/water diagrams used in boiler calculations

Temperature-heat (T-Q) diagram

The T-Q diagram is a useful tool for designing heat exchangers. It can also be used to present the heat transfer characteristics of an existing heat exchanger or heat exchanger network. The T-Q diagram consists of two axes: The current stream temperature on the y-axis and the amount of heat transferred on the x-axis. Sometimes the streams are marked with arrowheads to clarify the direction of the streams, but these are not necessary: since heat cannot move from the colder stream to the hotter stream according to the second law of thermodynamics, the directions of the streams are explicitly determined: The hot stream transfers its heat to the cold stream, thus the flow direction of the hot stream is towards lower temperature and the flow direction of the cold stream is towards higher temperatures. For the same reason, the hot stream is always above the cold stream in the T-Q diagram (figure 1).
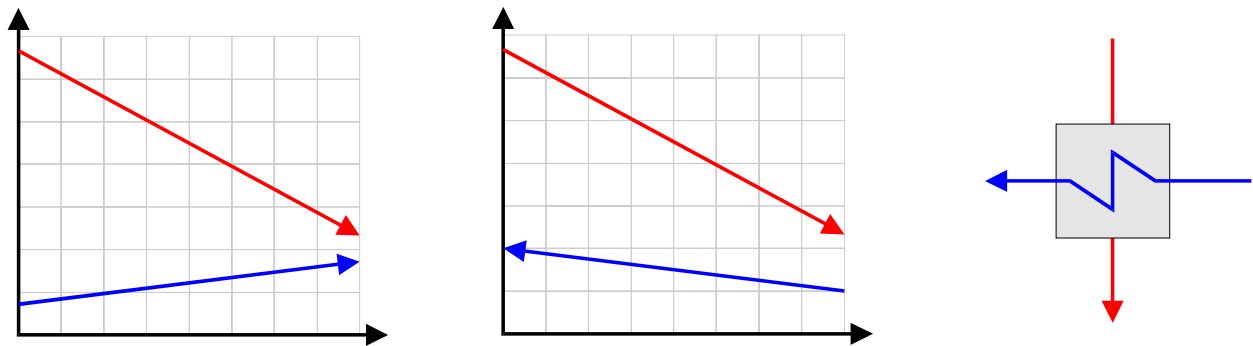
Figure 1: Examples of T-Q diagrams for a parallel flow heat exchanger (left), and a counter (or cross) flow heat exchanger (middle). The hot stream is marked with red color and the cold with blue color.

When designing or reviewing heat exchanger networks, the T-Q diagram gets useful. The T-Q diagram is therefore applied when designing boilers; especially the heat exchanger surface arrangement can be clearly visualized with a T-Q diagram (figure 2).
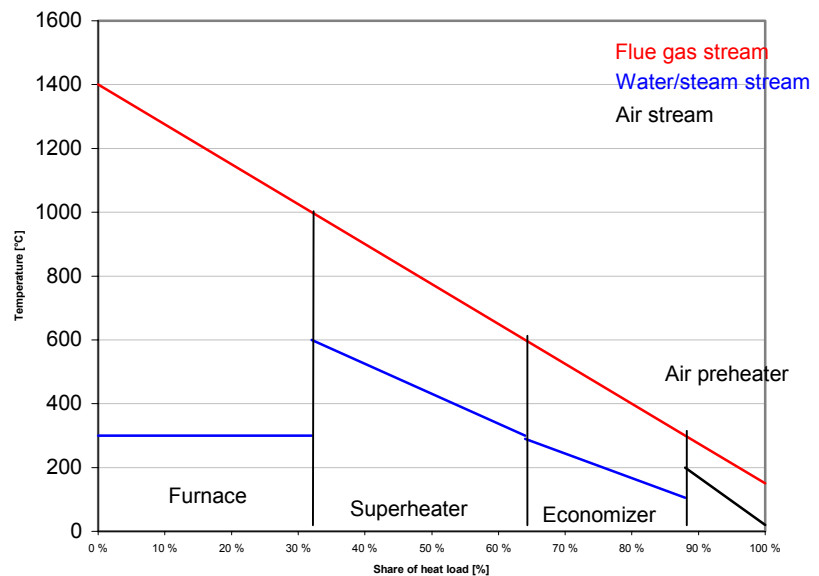
Figure 2: Example of a T-Q diagram representing the heat surfaces in a PCF boiler.

Temperature-entropy (T-s) diagram

The T-s diagram represents the various phases of steam/water with temperature as a function of the specific entropy. It is often used to visualize steam power processes. The T-s diagram is also commonly used for displaying reversible processes (or real processes simplified as reversible processes), which in the T-s diagram appear as closed curves (loop).

The left border, up to the critical point, is the border where the liquid is saturated (figure 3). That is, the water is still liquid and contains no steam. But if we go further right (increase the entropy), steam bubbles starts to form in the water. In other words, saturated water starts to boil when heat is added and entropy is increased.

The enclosed region in the middle is the region where water is a mixture of vapor and liquid. Steam that contains water in any form, either as minute droplets, mist or fog, is called wet steam. The quantity called 'x' in the diagram

Figure 3: Simplified T-s diagram of steam/water.

represents the amount (percentage by weight) of dry vapor in the wet steam mixture. This quantity is called the *quality of steam*. For instance, if there is 10 % moisture in the steam, the quality of the steam is 90 % or 0,9. The temperature of wet steam is the same as dry saturated steam at the same pressure.

The right border, down from the critical point, is the line where steam is saturated. When steam is heated beyond that border, steam is called superheated.

Water boils under constant temperature and pressure, so a horizontal line inside the enclosed region represents a vaporization process in the T-s diagram. The steam/water heating process in the boiler represented by the diagram in figure 2 can also be drawn in a T-s diagram (figure 4), if the boiler pressure is assumed to be e.g. 10 MPa.

Figure 4: Detailed T-s diagram of the PCF boiler steam/water heating process from figure 2 (note: color of the steam/water process line is changed from blue to red).

Pressure-enthalpy (p-h) diagram

Another tool used in boiler calculation is the pressure-enthalpy diagram for steam/water (figure 5). With the p-h diagram it is easy to visualize the partial shares of the total heat load on different heat exchanger surfaces in the boiler: drawing the steam heating process in the boiler onto the p-h diagram will give a horizontal line (if we simplify the process and set pressure losses to zero). Figure 6 shows the same boiler steam/water process from figure 4, drawn in the steam/water p-h diagram.
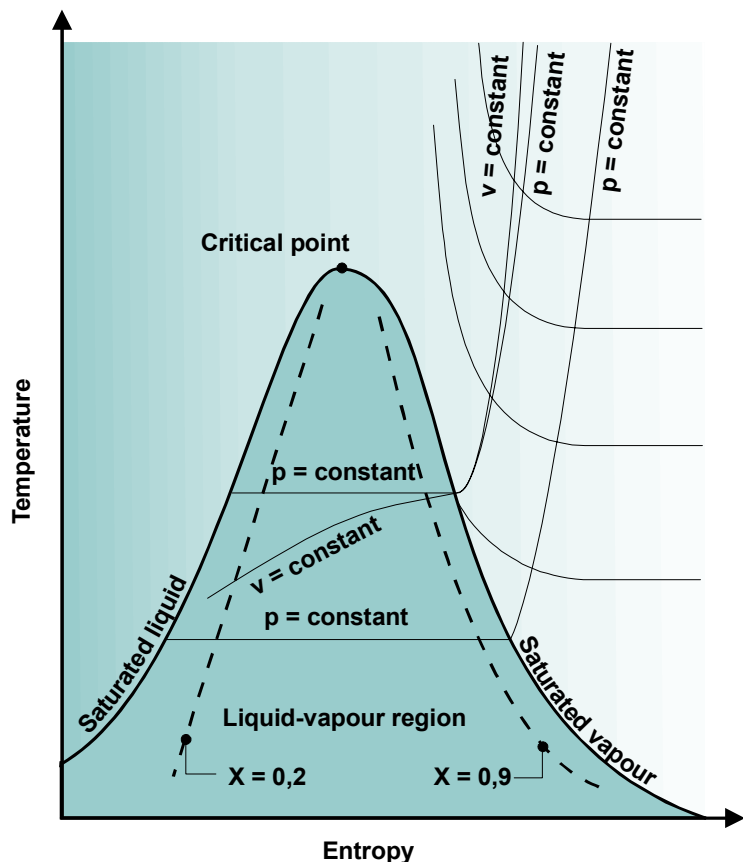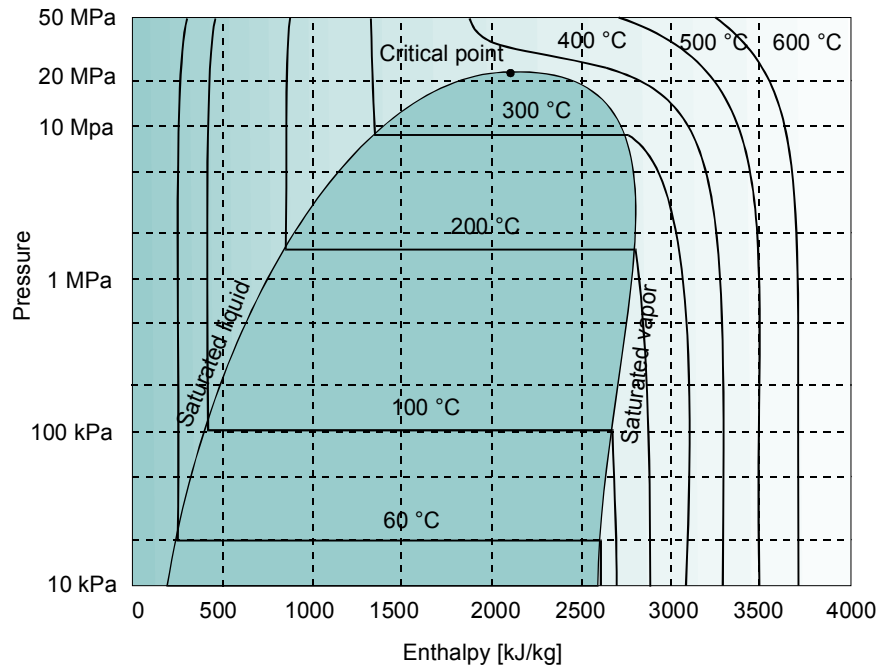

Figure 5: Simplified p-h diagram for steam/water.

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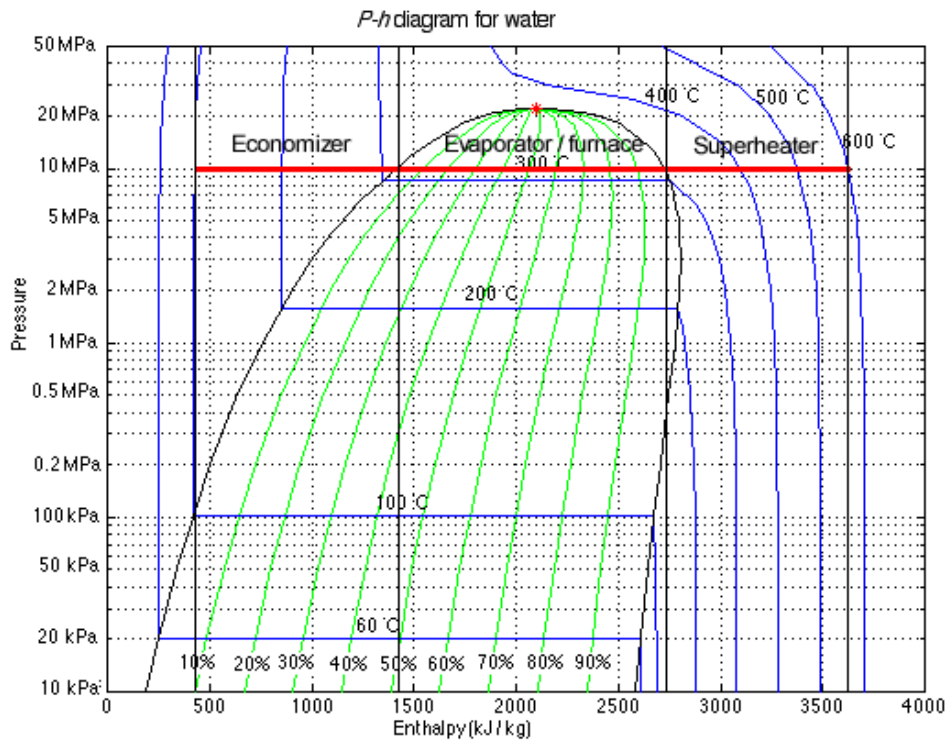
Figure 6: Detailed p-h diagram of the PCF boiler steam/water heating process (red line) from figure 4.

Enthalpy-entropy (Mollier, h-s) diagram

The most frequently used tool for determining steam properties is probably the enthalpy-entropy (h-s) diagram, also called Mollier diagram (figure 7). If two properties of the steam state are known (like pressure and temperature), the rest of the properties for steam (enthalpy, entropy, specific volume and moisture content) can be read from the diagram. A more detailed h-s diagram can be found in figure 8. Since the diagram is very large, the diagram is usually found as two versions, consisting of zoomed portions of the original: one for steam properties (figure 7) and another for water properties.
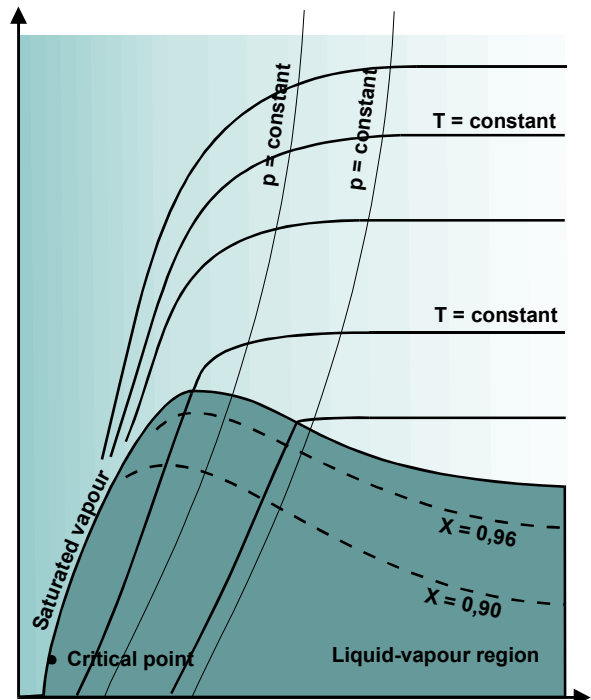
Figure 7: Mollier (h-s) diagram, simplified version.
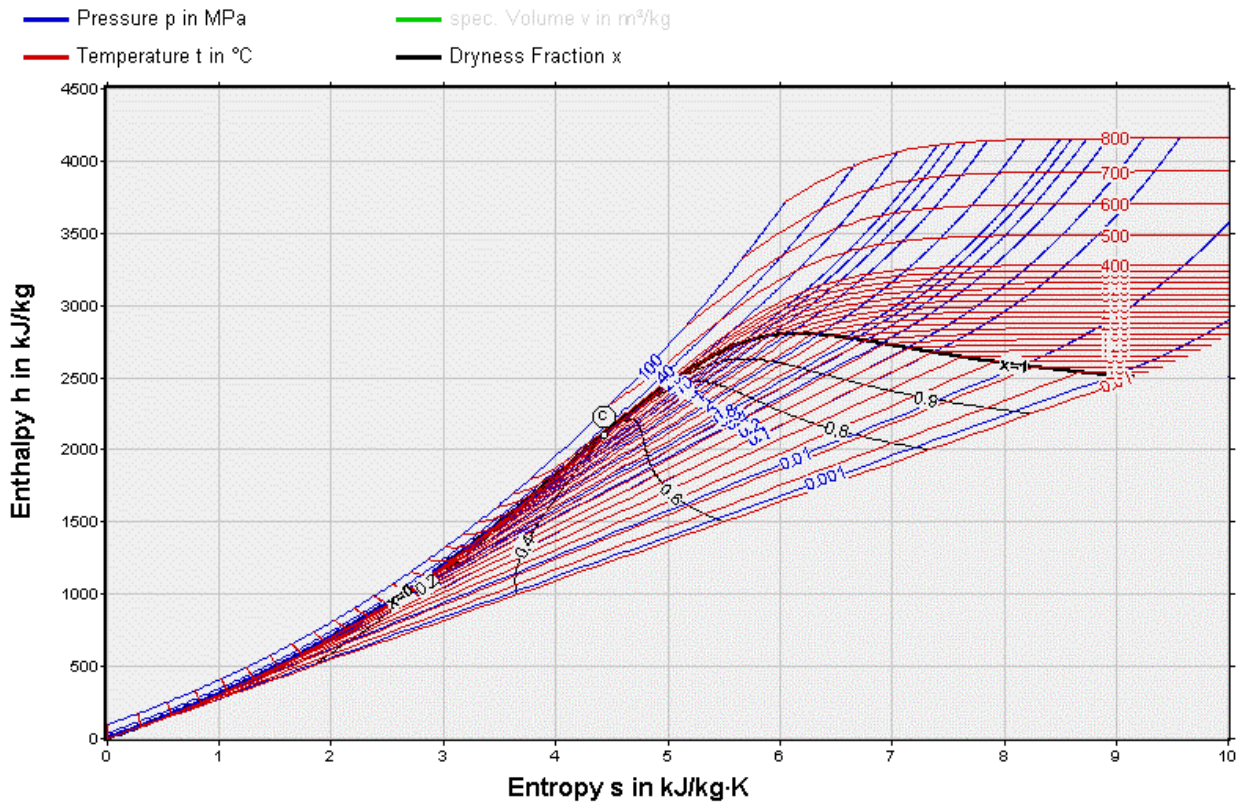
Figure 8: Large-scale Mollier h-s diagram for steam.

Determination of steam/water parameters

Given parameters

Normally in a steam boiler design assignment the parameters describing the live (output) steam, e.g. mass flow, pressure and temperature are given. If the steam boiler to be designed has a reheat cycle, also reheat pressure and temperature are given. Reheat steam mass flow can be given as well. These parameters are used to determine the rest of the steam/water parameters.

Pressure losses

The pressure losses in the heat exchanger units of the boiler are estimated according to the following approximations:

- **Economizer**: the pressure loss is 5-10 % of the pressure of the feedwater entering the economizer.
- **Evaporator**:
  - *Once through boilers:* in once-through boilers the pressure loss of the evaporator is between 5 and 30 %.
  - *Forced and natural circulation boilers:* the pressure drop in the evaporator part of drum-based boilers does not affect the pressure loss of the main steam/water flow through the boiler. This means that saturated steam leaving the steam drum has the same pressure as the feedwater entering the steam drum. The pressure loss of the evaporator has to be overcome using the driving force (natural circulation) or circulation pump (forced circulation).

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- **Superheater**: the total pressure drop of all superheater packages is less than 10 % of the pressure of the superheated steam.
- **Reheater**: the pressure drop in the reheater is about 5 % of the pressure of reheated steam

Pressure losses of connection tubes between different heat transfer surfaces (e.g. between evaporator and superheater) can be neglected in these calculations.

Procedure for determination of specific enthalpies and mass flow rates

1. The *specific enthalpy of the superheated steam* can be determined with an h-s diagram if both the temperature and the pressure of the steam are known. Thus, the specific enthalpies for live (superheated) steam and reheated steam can be calculated.

2. The *total pressure loss of the superheater stages* should be chosen. Thus, the pressure in steam drum (drum-type boilers) or pressure after evaporator (once-through boilers) can be calculated by adding the pressure loss over the superheater stages to the pressure of the superheated steam.

3. *Specific enthalpy of saturated water and steam* (in the steam drum) can be read from an h-s diagram or steam tables, as the pressure in the steam drum is known.

   In once-through boilers the determination of specific enthalpy after the evaporator is based on the temperature. The reason for this is the unclear state of supercritical steam after the evaporator in once-through circulation. The temperature after the evaporator in once-through boilers is typically between 400 and 450 °C.

4. For *removal of minerals* concentrated in the steam drum, a part of the water in steam drum is removed as blowdown water from the bottom of the steam drum. Normally the mass flow rate of blowdown is 1-3 % of the mass flow rate of feedwater coming into steam drum.

5. In principle, the feedwater coming into steam drum should be saturated water. To prevent the feedwater from boiling in the transportation pipes, the temperature of the feedwater reaching the steam drum is 15-30 °C below saturation temperature. The feedwater is then called *subcooled* (in contrast to supercooled). When the temperature in the steam drum and the value of subcooling are known, the temperature after the economizer can be determined. The water pressure after the economizer can be assumed to be equal to the pressure in the steam drum and specific enthalpy after the economizer can then be read from a h-s diagram.

   In once through boilers the pressure after the economizer can be calculated by adding the pressure loss in the evaporator to the pressure after evaporator. The temperature after the evaporator is normally between 300 and 350 °C (can be chosen). Knowing the pressure and the temperature, the specific enthalpy after the evaporator can be defined.

6. The pressure before the economizer can be calculated by adding the pressure loss in the economizer to the feedwater pressure after economizer. The feedwater temperature might be stated in the boiler design assignment. If it is not given, it should be chosen from the range of 200-250 °C. The mass flow rate before the economizer is the blowdown mass flow rate added to the mass flow rate from the steam drum to the superheaters.

Superheaters and reheaters

Reheating takes usually place in two stages. The pressure before the reheater is the reheated steam pressure added on the pressure loss in the reheater. The steam goes through a high-pressure turbine before it enters the reheater. In the high-pressure turbine, the specific enthalpy of steam decreases according to the isentropic efficiency of the turbine. Isentropic efficiency is normally between 0,8 and 0,9. A part of the low-pressure steam coming from high-pressure turbine continues to the high-pressure feedwater heater (closed-type feedwater heater). However, the mass flow rate of reheated steam is still 85-90 % of that of the live steam.
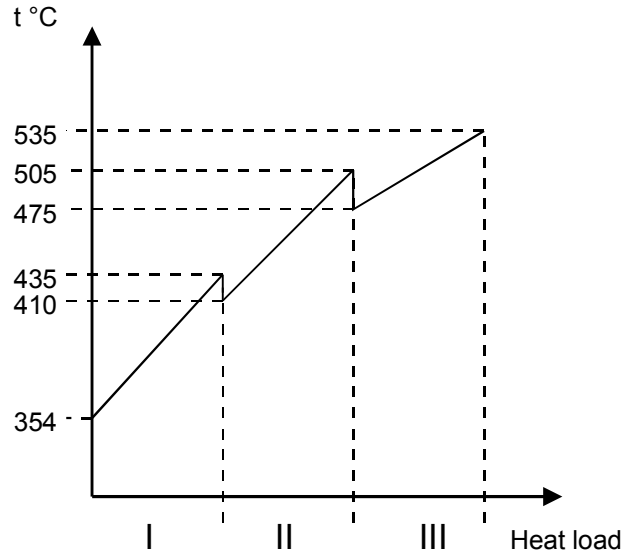
Superheating is often applied in three stages having spray water groups between each other to reduce steam temperature when necessary. Between reheaters, the steam temperature is controlled using other means. Spray water group dimensioning is usually based on a steam temperature decrease of 15-40 °C by water spraying. Spray water originates normally from the feedwater line before the economizer. Thus the pressure difference is the pressure loss of the heat transfer surfaces between the economizer inlet and the location of the spray water nozzle. An example of a possible heat load share between the superheater stages is shown in figure 9.

Figure 9: An example of the heat load share of superheater stages.

Pressure loss in superheaters can be divided into equal partial pressure losses corresponding to each superheater stage. Pressure loss of the spray nozzles can be neglected. Temperature rise over all superheaters can be divided into quite similar parts along the same principle.

Spray water group mass flow

Normally the mass flow rate of superheated steam (live steam) is known. Thus, mass flow rate calculations start usually by calculating the mass flow rate of spray water to the last spray water group (which is in this example between the second and third superheater stages). The mass flow rates can be solved with energy and mass balance equations. With the equations below (equation 1), the mass flow rate of steam after second superheater stage and mass flow rate of spray water to the last spray water group can be calculated. The mass flow rate of spray water to the first spray water group can be calculated along the same procedure:

$$\dot{m}_{SHII} + \dot{m}_{SPRAYII} = \dot{m}_{SHIII}$$
$$\dot{m}_{SHII} \cdot h_{SHII,2} + \dot{m}_{SPRAYII} \cdot h_{SPRAY} = \dot{m}_{SHIII} \cdot h_{SHIII,1}$$

$$(1)$$

where $\dot{m}_{SHII}$ is the mass flow rate of steam after second superheater stage [kg/s], $\dot{m}_{SPRAYII}$ the mass flow rate of spray water to second spray water group, $\dot{m}_{SHIII}$ the mass flow rate of superheated steam (live steam), $h_{SHII,2}$ the specific enthalpy of steam after second superheater

stage [kJ/kg], h_{SPRAY} the specific enthalpy of spray water (feedwater), and $h_{SHIII,1}$ the specific enthalpy of steam before third superheater stage. Figure 10 shows a flow chart with the symbols visualized of the boiler arrangement used in this calculation model.
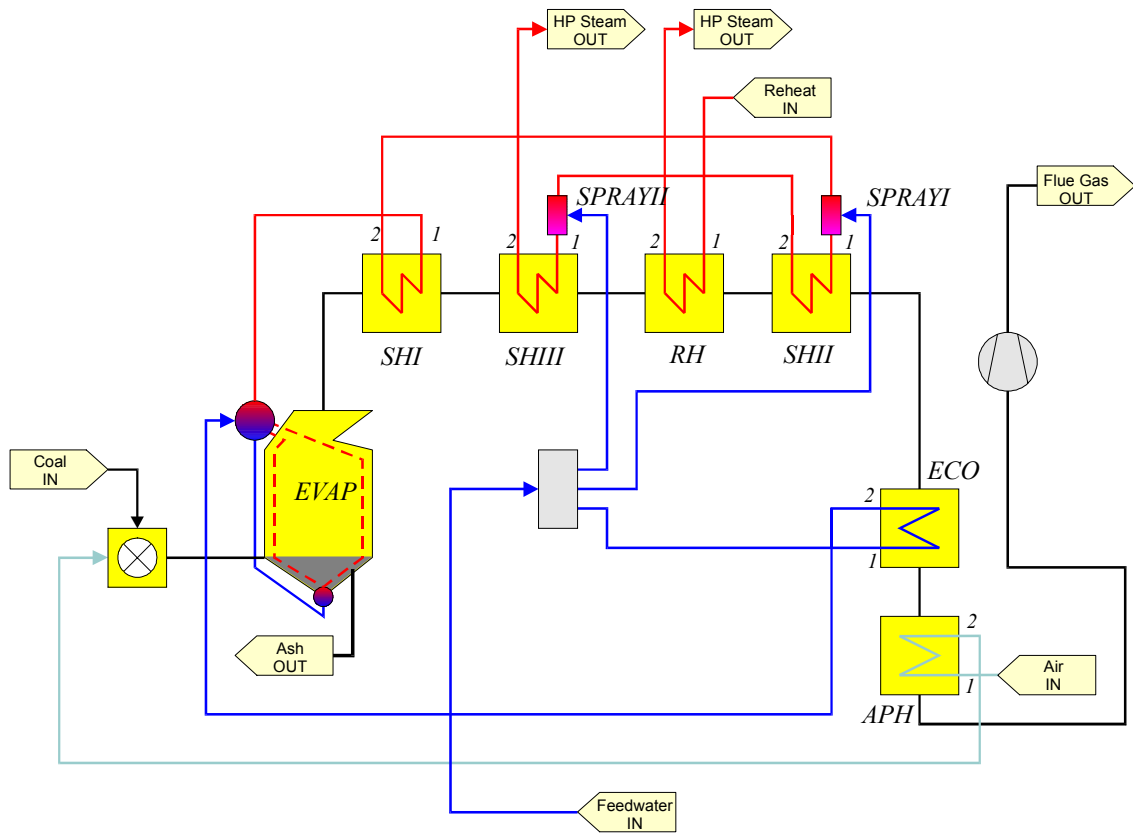
Figure 10: Flow chart of the PCF boiler arrangement used in this heat load calculation model.

Calculations of heat load

When the steam parameters and mass flows have been determined, the heat load of the heat exchanger units can be calculated. The heat load is the heat transferred by a heat exchanger (calculated in kW).

Evaporator

The heat load of the evaporator part of the boiler can be calculated as:

$$\phi_{EVAP} = \dot{m}_{SH}\left(h'' - h_{ECO2}\right) + \dot{m}_{BD}\left(h' - h_{ECO2}\right) \tag{2}$$

where $\dot{m}_{SH}$ is the mass flow of steam before superheater [kg/s], h'' the specific enthalpy of saturated steam at steam drum pressure [kJ/kg], h_{ECO2} the specific enthalpy after economizer $\dot{m}_{BD}$ the mass flow of blowdown water from steam drum, and h' the specific enthalpy of saturated water at steam drum pressure [kg/s].

Superheater

Normally superheating takes place in three or four stages in a big boiler. This calculation example is based on three stage superheating. The heat load of the first superheater stage is

$$\phi_{SHI} = \dot{m}_{SH}\left(h_{SHI,2} - h''\right) \tag{3}$$

where $h_{SHI,2}$ is the specific enthalpy of steam after the first superheater stage. In the second superheater stage the heat load added can be calculated as:

$$\phi_{SHII} = \dot{m}_{SHII}\left(h_{SHII,2} - h_{SHII,1}\right) \tag{4}$$

where $\dot{m}_{SHII}$ is the mass flow of steam before the second superheater [kg/s], $h_{SHII,2}$ the specific enthalpy of steam after the second superheater stage [kJ/kg], and $h_{SHII,1}$ the specific enthalpy of steam before the second superheater stage. Similarly, the heat load added in third superheater stage can be calculated as:

$$\phi_{SHIII} = \dot{m}_{SHIII}\left(h_{SHIII,2} - h_{SHIII,1}\right) \tag{5}$$

wher $\dot{m}_{SHIII}$ = Mass flow of steam before third superheater [kg/s], $h_{SHIII,2}$ the specific enthalpy of steam after third superheater stage [kJ/kg], and $h_{SHIII,1}$ the specific enthalpy of steam before third superheater stage [kJ/kg].

Reheater

The heat load of the reheater stage can be calculated as:

$$\phi_{RH} = \dot{m}_{RH}\left(h_{RH2} - h_{RH1}\right) \tag{6}$$

where $\dot{m}_{RH}$ is the mass flow rate of steam in the reheater [kg/s], h_{RH2} the specific enthalpy of steam after the reheater [kJ/kg] , and h_{RH1} the specific enthalpy of steam before the reheater.

Economizer

The heat load of the economizer can be calculated as:

$$\phi_{ECO} = \dot{m}_{ECO}\left(h_{ECO2} - h_{ECO1}\right) \tag{7}$$

where $\dot{m}_{ECO}$ is the mass flow rate of feedwater in the economizer [kg/s], h_{ECO2} the specific enthalpy of feedwater after the economizer [kJ/kg], and h_{ECO1} the specific enthalpy of feedwater before the economizer.

Air preheater

In order to calculate the heat load for the air preheater, we need to know the combustion air mass flow, the temperature of the flue gases and the incoming air. The combustion air fed into air preheater, is taken from upper part of the boiler room. The temperature of the combustion air before the air preheater is therefore between 25 and 40°C (in Finnish conditions). The flue gases

exiting the boiler are usually kept above 130-150 °C in order to prevent corrosion. The enthalpies can be taken from tables:

$$\phi_{APH} = \dot{m}_{FUEL} \cdot \frac{\dot{m}_{AIR}}{\dot{m}_{FUEL}} \cdot \left(h_{APH2} - h_{APH1}\right) \tag{8}$$

where $\dot{m}_{FUEL}$ is the mass flow rate of fuel fed into the boiler [kg/s], $\frac{\dot{m}_{AIR}}{\dot{m}_{FUEL}}$ the mass flow rate of combustion air divided by the mass flow rate of fuel fed into the boiler, h_{APH1} the specific enthalpy of combustion air before the air preheater [kJ/kg], and h_{APH2} the specific enthalpy of combustion air after the air preheater.

Determination of boiler efficiency

Standards

There are two main standards used for definition of boiler efficiency. Of those, the German DIN 1942 standard employs the lower heating value (LHV) of a fuel and is widely used in Europe. The American ASME standard is based on higher heating value (HHV). However, this chapter calculates the efficiency according to the DIN 1942 standard. [1]

It should be marked that with the DIN standard it is possible to reach boiler efficiencies over 100 %, if the condensation heat of the flue gases is recovered.

Major heat losses

Heat loss with unburned combustible gases

The typical unburned combustible gases are carbon monoxide (CO) and hydrogen (H2). In large boilers usually only carbon monoxide can be found in significant amounts in flue gases. Assuming that flue gases contain only these two gases, the losses [kW] can be calculated as:

$$\phi_{L1} = \dot{m}_{CO} \cdot H_{l,CO} + \dot{m}_{H_2} \cdot H_{l,H_2} \tag{9}$$

where $\dot{m}_{CO}$ is the mass flow of carbon monoxide [kg/s], $\dot{m}_{H_2}$ the mass flow of hydrogen, $H_{l,CO}$ the lower heating value (LHV) of carbon monoxide (10,12 MJ/kg), and H_{l,H_2} the lower heating value (LHV) of hydrogen (119,5 MJ/kg). If a relevant amount of some other flue gas compound can be found in the flue gases, it should be added to the equation.

Heat loss due to unburned solid fuel

Unburned fuel can exit the furnace as well as bottom ash or fly ash. The heating value of ashes can be measured in a specific laboratory test. The losses [kW] of unburned solid fuels can be calculated as:

$$\phi_{L2} = \dot{m}_{ubs} \cdot H_{l,ubs} \tag{10}$$

where $\dot{m}_{ubs}$ is the total mass flow of unburned solid fuel (bottom ash and fly ash in total) [kg/s], and $H_{l,ubs}$ the lower heating value (LHV) of unburned solid fuel (fly ash and bottom ash in total) [kJ/kg]. Some estimates of the losses with unburned solid fuels are presented in table 1:

Table 1: Estimates of losses with unburned solid fuel.

Boiler type	Heat loss per heat input of fuel
Oil fired boiler	0,2 - 0,5 %
Coal fired boiler, dry ash removal	3 %
Coal fired boiler, molten ash removal	about 2 %
Grate boiler	4-6 %

Heat loss due to wasted heat in flue gases

Flue gases leave the furnace in high temperature and thus they carry significant amount of energy away from boiler process. To decrease flue gas losses, flue gas exit temperature should be decreased. However, the acid dew point of flue gases restricts the flue gas temperature to about 130-150 °C for sulphur containing fuels. The losses caused by the sensible heat of flue gases can be calculated as:

$$\phi_{L3} = \dot{m}_{fuel} \cdot \sum_i \frac{\dot{m}_i}{\dot{m}_{fuel}} \cdot h_i \qquad (11)$$

where $\dot{m}_{fuel}$ is the fuel mass flow [kg/s], $\dot{m}_i$ the mass flow of a flue gas component, and h_i the specific enthalpy of a flue gas component (e.g. CO_2) [kJ/kg].

Heat loss due to wasted heat in ashes

Ash can exit the furnace either as bottom ash from bottom of the furnace or as fly ash with flue gases. The losses related to the sensible heat of ash can be calculated as:

$$\phi_{L4} = \dot{m}_{ba} \cdot c_{p,ba} \cdot \Delta T_{ba} + \dot{m}_{fa} \cdot c_{p,fa} \cdot \Delta T_{fa} \qquad (12)$$

where $\dot{m}_{ba}$ is the mass flow of the bottom ash [kg/s], $c_{p,ba}$ the specific heat of the bottom ash [kJ/(kgK)], ΔT_{ba} the temperature difference between the bottom ash temperature and the reference temperature [°C], $\dot{m}_{fa}$ the mass flow of fly ash, $c_{p,fa}$ the specific heat of fly ash, ΔT_{fa} the temperature difference between the fly ash temperature and the reference temperature [°C]. Usually the reference temperature is 25 °C.

In recovery boilers the bottom ash is removed as molten ash in temperature of about 700-800 °C. In addition, the amount of bottom ash divided by the amount of fuel is about 40 %. The loss of sensible heat of ash is therefore of great importance in recovery boilers.

Losses due to heat transfer (radiation) to the environment

The main form of heat transfer from boiler to boiler room is radiation. It is proportional to the outer surface area of the boiler and is usually 200-300 W/(m2K) for a well-insulated boiler having its outer surface temperature below 55 °C. Another possibility to determine the heat transfer losses to the environment is to use a table from the DIN 1942 standard, presented in table 2.

Table 2: Estimations of heat transfer losses by radiation. [1]

	Combustion method	Mass flow rate of steam [t/h]									
		10	20	40	60	80	100	200	400	600	800
Loss [%]	Pulverized firing	-	1,3	1,0	0,9	0,75	0,7	0,55	0,4	0,35	0,3
	Grate	1,5	1,1	0,9	0,7	-	-	-	-	-	-
	Oil/gas fired boiler	1,3	0,9	0,7	0,6	0,55	0,4	0,3	0,25	0,2	0,2

Losses of blowdown, sootblowing and atomizing steam

Blowdown water from the steam drum and sootblowing steam (used to remove soot from heat exchanger surfaces within the boiler) use a part of the steam produced by the boiler. This lowers the boiler efficiency. In addition, steam is sometimes also used to atomize fuel in the burners. The losses can be calculated as:

$$\phi_{L6} = \dot{m}_{bd} \cdot h' + \dot{m}_{sb} \cdot h_{sb} + \dot{m}_{atomizing} \cdot h_{atomizing} \tag{13}$$

$\dot{m}_{bd}$ is the mass flow of blowdown water [kg/s], h' is the specific enthalpy of saturated water (blowdown water from steam drum) [kJ/kg], $\dot{m}_{sb}$ is the mass flow of sootblowing steam, h_{sb} is the specific enthalpy of steam used for sootblowing (when leaving the boiler), $\dot{m}_{atomizing}$ is the mass flow of atomizing steam, and $h_{atomizing}$ the specific enthalpy of steam used for atomizing the fuel (when leaving the boiler) [kJ/kg].

Internal power consumption

The power plant itself consumes a part of the electricity produced. This is due to the various auxilary equipments required, like feedwater pumps, circulation pumps and air/flue gas blowers. In forced circulation boilers the share of electricity consumed by the circulation pump is about 0,5 % of the electricity produced by the plant.

Normally the internal power consumption is about 5 % of the electricity produced by the power plant. Since the power used is electrical (and taken from the grid), the internal power consumption share is reduced from the final boiler efficiency in boiler calculations.

Calculating boiler efficiency

There are two different means of calculating the boiler efficiency: The direct method and the indirect method.

Direct method

In the direct method, the boiler efficiency is directly defined by the exploitable heat output from the boiler and by the fuel power of the boiler:

$$\eta = \frac{\phi_{output}}{\phi_{input}}$$

(14)

where ϕ_{output} is the exploitable heat output from boiler, and ϕ_{input} the fuel power of the boiler.

Indirect method

Indirect method determines the efficiency of a boiler by the sum of the major losses and by the fuel power of the boiler:

$$\eta = 1 - \frac{\phi_{losses}}{\phi_{input}}$$

(15)

where ϕ_{losses} is the sum of the major losses within the boiler, and ϕ_{input} is the fuel power of the boiler.

The indirect method provides a better understanding of the effect of individual losses on the boiler efficiency.

References

1.   DIN 1942. "Abnahmeversuche an Dampferzeugern".