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Heat Exchangers in Boilers

Sebastian Teir, Anne Jokivuori

Helsinki University of Technology

Department of Mechanical Engineering

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Table of contents

Heat transfer surfaces

The primary elements of a boiler are the heat transfer surfaces, which transfer the heat from the flue gases to the water/steam circulation. The objective of the boiler designer is to optimize thermal efficiency and economic investment by arranging the heat transfer surfaces and the fuel-burning equipment.

Heat transfer surfaces in modern boilers are furnaces, evaporators, superheaters, economizers and air preheaters. The surfaces cover the interior of the boiler from the furnace (or inlet in a HRSG) to the boiler exhaust.

The main means of heat transfer in a furnace is radiation. Superheaters and reheaters are exposed to convection and radiant heat, whereas convectional heat transfer predominates in air heaters and economizers.

Flue gases exiting the boiler can be cooled down close to the dew point (t=150-200 °C). Air preheaters and economizers recover heat from the furnace exit gases in order to reduce to preheat combustion air (thus increasing efficiency) and use the heat to increase the temperature of the incoming feed water to the boiler.

Every heating surface cannot be found in every boiler. In industrial systems where saturated steam is needed, there are no superheaters. Superheaters are built when superheated steam is needed (mainly at electricity generation in order to reach high efficiency and avoid droplets in the steam turbine). Figure 1 gives and example of the physical arrangement of heat transfer surfaces in a boiler with two-pass layout.

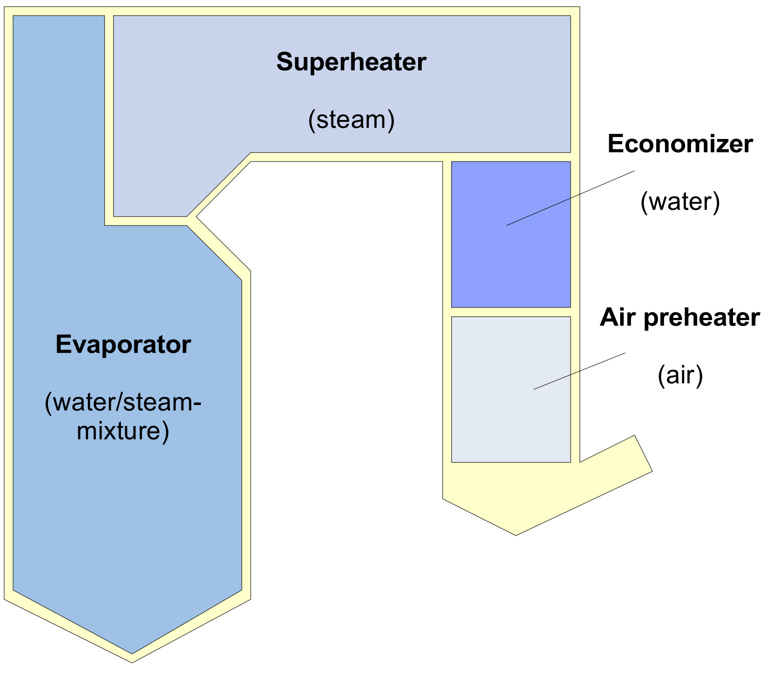

Figure 1: Physical locations of heat transfer surfaces in a boiler with two-pass layout.

Arrangement of heat transfer surfaces (furnace-equipped boiler)

According to the second law of thermodynamic heat transfer cannot occur from a lower temperature level to a higher one. That's why the flue gas temperature has to be higher than the temperature of the heat absorption fluid (working fluid). The temperature of flue gas leaving the furnace is 800-1400 °C and it cools down to 150-200 °C in the air preheater (figure 2). The right arrangement of heat transfer surfaces have an effect on durability of material, fouling of material, temperature of steam and final temperature of flue gas.

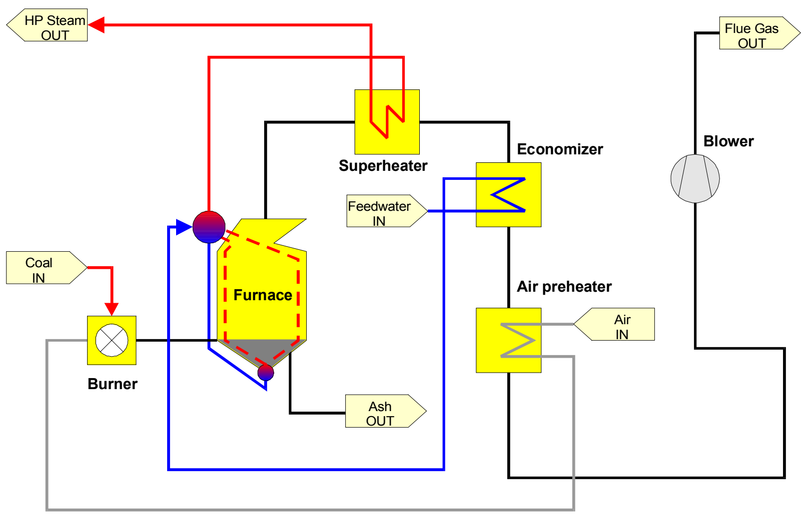

Figure 2: Process drawing of the arrangement of heat transfer surfaces in a furnace equipped boiler

The evaporator is generally built into the furnace. Moving through the flue gas path in a boiler the heating surfaces are found in the sequence shown in figure 1: furnace, superheaters (and reheaters), economizer and air preheater.

Table 1 presents and example of changes of stream temperatures in heat exchanger surfaces of a boiler, where the steam pressure is about 80-90 bar.

Table 1: Typical stream temperature changes in heat exchanger surfaces of a boiler.

Boiler surface	Working fluid temperature [°C]	Flue gas temperature drop [°C]
Furnace	290->300	1400->1000
Superheaters	300->600	1000->600
Economizer	105->290	600->300
Air preheater	20->200	300->150

The heat transfer in the furnace results in a phase change of the working fluid (water to steam). The small water/steam temperature rise is due to the fact that the water enters the furnace slightly sub-cooled (not saturated). These temperatures are only examples. They can be at various levels at different types of boiler, but the heat load graph look practically the same. The heat load graph, constructed from the table above, can be found in figure 3.

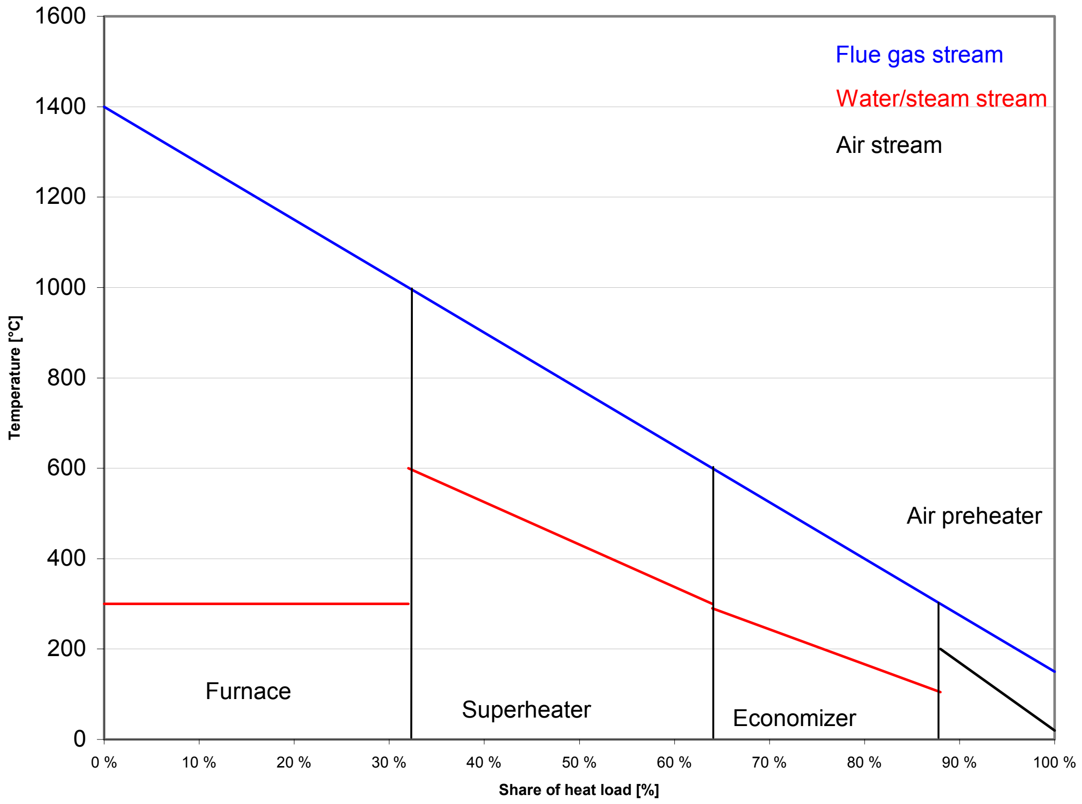

Figure 3: Example of a heat load graph for a furnace equipped boiler.

Furnace

General

The furnace is the part of the boiler where the combustion of the fuel takes place. The main role of the boiler furnace is to burn the fuel as completely and stably as possible. Leaving unburned material will decrease the heat efficiency and increase the emissions. Combustion must be performed in an environmentally sustainable way. The emissions from the furnace must be as low as possible.

The furnace walls of a modern boiler consist of vertical tubes that function as the evaporator part of the steam/water cycle in the boiler. The boiler roof is usually also part of the evaporator as well as the flue gas channel walls in the economizer and the air preheater parts of the boiler. Figure 4 shows a photograph from the inside of a recovery boiler furnace.

Adequate furnace cooling is vital for the boiler. However, when burning very wet fuels as wood chips, some parts of the furnace should not be cooled in order not to remove too much heat from furnace. Thus a part of the furnace of boilers using such fuels consists of a refractory material, which reflects the heat of combustion to the incoming wet fuel.

If the flue gas temperature after furnace is too high, the smelting of ash can occur such problems as ash deposition on superheater tubes. High temperature corrosion of superheater tubes can appear as well. Figure 5 presents an example of a temperature distribution in a two-pass boiler.

Figure 4: Inside a recovery boiler furnace [Andritz].

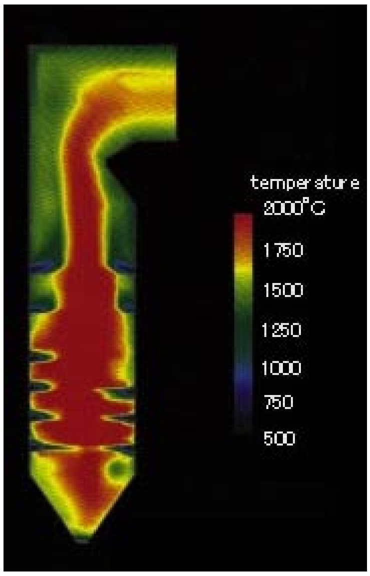

Figure 5: Furnace temperature distribution (IHI).

Membrane wall

Nowadays, the furnace is generally constructed as a gas-tight membrane wall. The membrane wall construction consists of tubes, which have been welded together separated by a flat iron strip, called the membranes. The membranes act as fins to increase the heat transfer. They

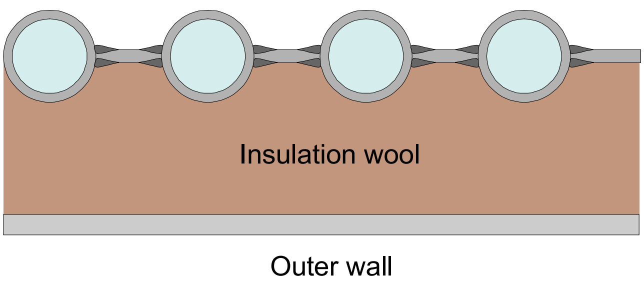

Figure 6: Modern gas-tight membrane tube wall construction. Unfinned wall tubes are welded together with metal strips.

also form a continuous rigid and pressure tight construction for the furnace. The most common furnace tube used is a finned carbon steel tube that forms the membrane wall. A drawing visualizing a typical membrane tube wall can be found in figure 6.

Convection evaporators

In boilers with low steam pressure, the share of the heat needed for evaporation is bigger than when considering a high-pressure boiler. Thus the furnace-wall evaporator cannot provide enough heat for evaporation process in low-pressure boilers. Convection evaporators supply the supplementary heat needed for complete evaporation. They are normally placed after the superheater stage in boiler process. Convection evaporators can cause local tube overheat problems with partial loads.

Boiler generating bank

A boiler generating bank is a convection evaporator that uses two drums: one on the top of the evaporator tubes, and another in the bottom. A boiler generating bank is usually used in parallel with the natural circulation based evaporator/furnace, as in figure 7. Boiler generating banks are less common nowadays and are nowadays typically used in low pressure and small boilers.

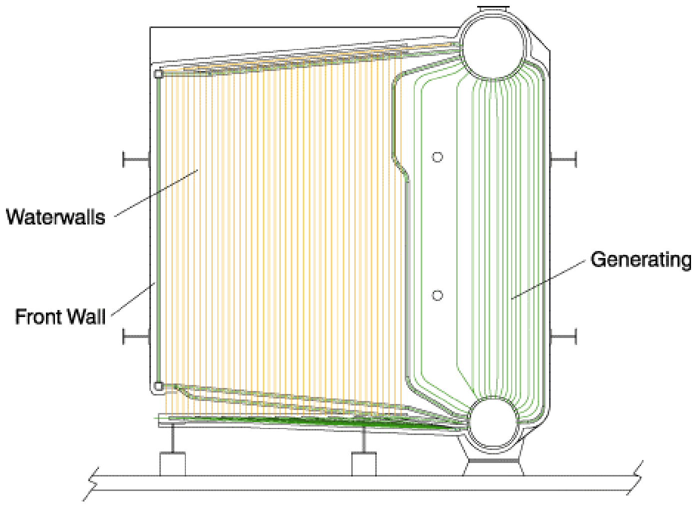

Figure 7: Boiler generating bank (marked with green colour).

Economizer

After the feedwater pump, the water has the required pressure and temperature to enter the boiler. The pressurized water is introduced into the boiler through the economizers. The economizers are heat exchangers, usually in the form of tube packages.

The purpose of economizers is to cool down the flue gases leaving the superheater zone, thus increasing the boiler efficiency. The limiting factor for cooling is the risk of low temperature corrosion, i.e. dew point of water. Economizers are placed after the superheater zone in the flue gas channel. They are usually constructed as a package of tubes fastened on the walls of the flue gas channel.

Figure 8: Economizer tube banks prior to installation (Andritz).

Flue gases are cooled down with feedwater, which gets preheated up to its saturation temperature. In order to prevent the feedwater from boiling before it has entered the furnace/evaporator, the temperature of the feedwater exiting the economizer is usually regulated with a safety margin below its saturation temperature (about 10°C). The heated water is then led to the steam drum.

The economizer shown in figure 8 consists of two long-flow, vertical sections. Each economizer section is comprised of straight vertical finned tubes, which are connected in parallel to one another. The tubes are connected at the top and bottom to larger headers. The bundles are placed in the second pass of the boiler, behind the superheaters. Here, the water is utilizing the heat of the flue gases that is left from the superheaters, before the flue gases leave the boiler. The flue gas temperature should always stay above the dew point of the gases to prevent corrosion of the precipitators and ducts.

Superheater

General

The superheater is a heat exchanger that overheats (superheats) the saturated steam. By superheating saturated steam, the temperature of the steam is increased beyond the temperature of the saturated steam, and thus the efficiency of the energy production process can be raised. Superheated steam is also used in facilities that don't produce electricity.

The benefits of using superheated steam are:

- Zero moisture content
- No condensate in steam pipes
- Higher energy production efficiency

The superheater normally consists of tubes conducting steam, which are heated by flue gases passing outside the tubes. The tubes are usually connected in parallel using headers, with steam entering from one header and exiting in another header. There can be several superheater units in the same boiler, as well as reheaters, which is a superheater for heating external steam (steam already used in a process outside the boiler).

Figure 9: Panel superheaters in production (Andritz).

Types of superheater surfaces

Superheaters can be divided into convection based and radiation based superheaters.

Radiation superheaters

Radiation based superheaters are used to gain higher steam temperatures and the heat is mainly transferred by radiation. These superheaters have to be placed within reach of the flame radiation. Thus radiant superheaters are usually integrated as tubes in the boiler-walls or built as panels hanging from the boiler roof. The radiation superheater is located in the top of the furnace, where the main means of heat transfer is radiation.

Convection superheaters

Convection superheaters are the most common superheaters in steam boilers. Convection based superheaters are used with relatively low steam temperature, and the heat from the flue gases is mainly transferred by convection. They are placed after the furnace protected from the corrosive radiation of the flames. This type of superheater can also be protected from radiation by a couple of rows of evaporator tubes. Convection based superheaters can hang from the boiler roof or they can be placed in the second pass of the boiler (in a two-pass design), and are called back-pass superheaters.

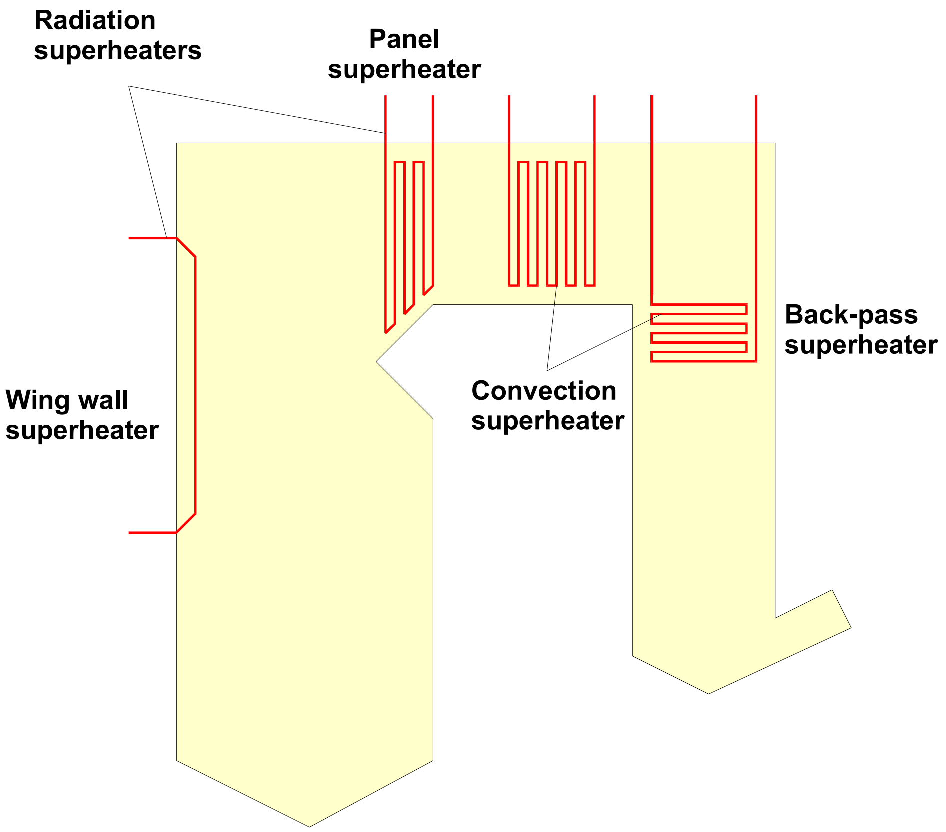

Figure 10: Arrangement of various types of superheater units.

Panel superheater

The panel superheater (shown in figures 9 and 11) functions on both radiation and convention heat transfer, depending on its location in the boiler. It consists of tubes that are tightly bundled in thin panel walls, which hang from the roof in the exhaust of the furnace. The distance between the panels is usually about 300-500 mm. The tubes are laid out according to the inline arrangement. This kind of superheater can be located e.g. first in the flue gas stream after furnace in which coal with low heating value is burned (brown coal). The panel superheater is resistant to fouling and can withstand high heat flux.

Figure 11: Panel superheaters installed (Andritz).

Wing wall superheater

The wing wall superheater is a kind of panel superheater that extends from a furnace (figure 10). The bank of tubes, which are welded together, is usually built in the front wall of boiler. It has become popular especially in CFB applications. The tube is often made of carbon steel. The wing wall superheater receives heat mainly through radiation.

Back-pass superheater set

Convection superheaters located in the flue gas channel (figure 10 and 12), where the flue gas starts flowing downwards, are called back-pass superheaters. In large CFB, coal and oil boilers horizontal tube arrangements are commonly used. Back-pass superheater tubes hang from the back-pass roof.

Figure 12: Back-pass superheater.

Reheater

A reheater is basically a superheater that superheats steam exiting the high-pressure stage of a turbine. The reheated steam is then sent to the low-pressure stage of the turbine. By reheating steam between high-pressure and low-pressure turbine it is possible to increase the electrical efficiency of the power plant cycle beyond 40%. The reheat cycle is used in large power boilers since it is feasible economically only in larger power plants. Reheater design is very much similar to superheater design because both operate at high temperature conditions. The effect of the reheater in a T-S diagram is plotted in figure 13.

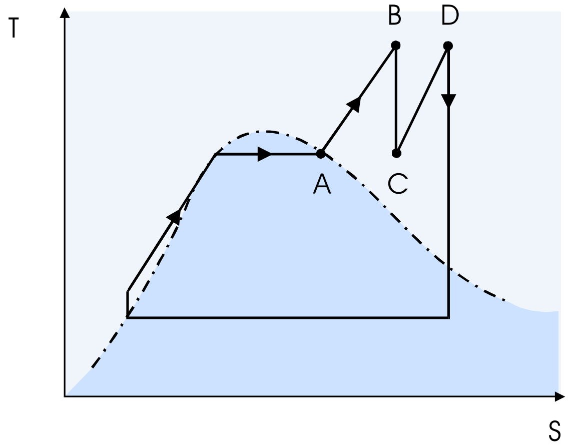

Figure 13: The reheater (line C-D) in a power plant cycle, plotted in a T-S diagram for steam/water.

Connections of superheater elements

Superheater elements are usually connected in series, e.g. first convection stage and then radiant stage. The steam temperature that can be reached with convection type superheaters is significantly lower than that reached with radiant type superheaters. Thus, boilers having high live steam temperature use radiant type superheaters as final superheater.

The small amount of saturated water still remaining in steam evaporates in the first superheater section, which make solid impurities of boiler water stick on inner surface superheater tubes. This decreases the heat transfer coefficient of the tubes. Superheater stages are therefore placed in counter-current order, i.e. the first superheater stage is situated at the lowest flue gas temperature.

However, the superheater situated at the hottest spot within the boiler (normally convective superheater) is not usually the final superheater because of the possible overheating problems. Thus, the convective superheater is connected in forward-current order in relation to flue gas flow to provide enough cooling for superheater tubing.

The superheater banks are connected to proceeding banks by interconnecting piping, i.e. pipes connect each ends of an outlet header to the opposite ends of the next superheater's inlet headers, as shown in figure 14. This cross-over of steam flow assures even distribution of steam circulation through the entire superheater system and minimized temperature variations from one side of the boiler to the other.

Air preheater

Regenerative air preheaters

In regenerative air preheaters (also called Ljungstrom® air preheaters) no media for heat transfer is used - they use the heat accumulation capacity of a slowly rotating rotor for transferring the heat. The rotor is alternately heated in the flue gas stream and cooled in the air stream, heat-storage being provided by the mass of the packs consisting of closely spaced metal sheets (figure 15), 0.5-0.75 mm thick, which absorb and give off heat on both sides. The rotor is divided into pie-shaped 'baskets' of theses metal sheets, which in turn pick up heat from flue gases and release it into the combustion air, as shown in the drawing in figure 16.

Regenerative air preheaters occupy little space, about 1/4 or 1/6 of the space required by recuperative air preheaters and can be produced cheaply. Without exaggeration it can be claimed that they have rendered possible the low flue-gas exit temperatures achieved today. Their reduced tendency to dew point corrosion should also be stressed, in particular where sulphur-containing fuels are used. Moreover, any sheet metal packs that have become corroded can be replaced easily and quickly. They can also be cleaned easily by playing a jet of steam over the gaps in the packs of sheet metal.

The Ljungström air preheater has acquired exceptional importance; since the last war it has found wide acceptance in Europe. The Rothmuhle is another type of regenerative air preheater, where the duct rotates around the battery of plates, which is fixed.

Figure 14: Cross-connections of superheater headers (Andritz).

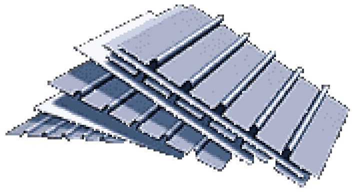

Figure 15: Heat transfer surfaces of the rotor (Alstom).

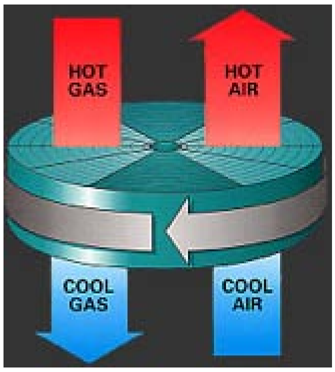

Figure 16: The heat-transfer principle of a regenerative air preheater (Alstom).

Figure 17: A photograph of a Ljungstrom air preheater (Alstom).

The problem of regenerative air preheaters is the gas leakage from one side to another. This can cause fires due to air leakage if flue gases contain high amount of combustibles (due to poor combustion). A photograph of a regenerative air preheater can be found in figure 17.

Recuperative air preheaters

In a recuperative air heater the heat from a high-temperature flowing fluid (flue gas) passes through a heat transfer surface to cooler air. The heating medium is completely separated at all times from the air being heated. The recuperative principle implies the transfer of heat through the separation partition, with the cool side continuously recuperating the heat conducted from the hot side. Thus, the advantage of recuperative air preheaters in general is the lack of leakage because the sealing is easier to implement here than in the regenerative type. The separating surface may be composed of tubes or plates. The rate of flow is determined by temperature differential, metal conductivity, gas film conductivity, conductivity of soot, and ash and corrosion deposits. The cumulative effect of these factors may be large. There are two types of recuperative heat exchangers: tubular and plate preheaters.

Tubular recuperative air preheater

Tubular air preheater is comprised of a nest of long, straight steel or cast-iron tubes expanded into tube sheets at both ends, and an enclosing casing provided with inlet and outlet openings. If the tubes are placed vertically, the flue gases pass through or around them. If the tubes are placed horizontally, the flue gases only pass around them. The design, which usually provides a counter-flow arrangement, may consist of a single pass or multiple passes with either splitter (parallel to tubes) or deflecting (cross-tube) baffling. Traditionally the tubes were made of cast iron for good corrosion resistance. Thus the whole preheater was heavy and needed massive foundations.

Plate recuperative air preheater

The newer alternative design is the plate-frame type recuperative air preheater. It offers the same heat transfer capacity with reduced unit weight and size. Plate air preheater consists of a series of thin, flat, parallel plates assembled into a series of thin, narrow compartments or passages, all suitably cased. Flue gas and air pass through alternate spaces in counter-flow directions. The plate air preheater may be arranged more compactly than the tubular type. Because of cleaning difficulties, however, its use is diminishing.

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