

Combustion of Waste in Combined Heat and Power Plants

TOBIAS RICHARDS, PHD

INTRODUCTION

Combustion was first a method used for minimizing solid waste. The idea was that combustion reduced the amount of solids (on both a volumetric and a mass basis), leaving room for more waste. It was thereby possible to reduce the volume by up to 90% and the mass by 80%. However, it did not take long before new features as well as risks were discovered. New features included the ability to destroy toxic materials and thus avoid their release into the environment and to utilize the heat that was released to produce steam. The risks that were discovered were associated with the materials produced, both solid and gaseous: the solid material formed (i.e., ash) could contain material that was readily soluble when it came into contact with water (such as rain) and therefore be released into, and transported by, water systems. This release could contain not only relatively harmless materials (such as sodium and potassium ions) but also harmful heavy metals. It is possible that unburned material in the gases formed may result in emissions of chlorinated compounds (such as dioxins and furans) together with catalysts (such as copper). Uncontrolled combustion, with areas of relatively low temperatures and a low concentration of oxygen, leads to the emission of dioxin and other toxic materials—a common problem is emission of vaporized mercury, which was not properly addressed initially. However, much has happened since the early days of waste combustion: new, modern boilers have high degrees of efficiency and they simultaneously radically reduce the amount of unwanted emissions produced. It has also become obvious that the alternative of using landfill sites, irrespective of the fact that land is scarce, is not a sustainable option; it is, in fact, prohibited in many countries (e.g., in the European Union) to send organic material to these sites. One of the main reasons for this ban is the uncontrolled formation of

methane gases that results from landfills; methane is a highly potent greenhouse gas that should be avoided, as it contributes to raising the global temperature.

WASTE MATERIALS FOR COMBUSTION

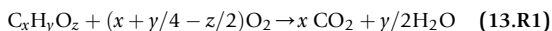
Waste that is combusted generally comes from two very different sources: municipal solid waste and industrial waste. Both these fractions have a rather wide span in composition. Industrial waste that is to be combusted could, for example, contain wood from demolition sites, waste from the pet food industry, fiber sludge, and various kinds of plastics. Such waste generally has a high heating value and low moisture content. Municipal solid waste differs in composition depending on the location and varies between countries as well as within each country. This leads to differences in heating values, and one major impact is the content of food and garden wastes in the waste collected, as these wastes have a high moisture content. A country that implements presorting of food waste will thus have waste with a higher heating value, which is easier to handle in most boilers and could, in most cases, also increase the overall efficiency of the boiler, as the heat loss in the flue gas will be reduced.

A difference between waste and other fuels is the relatively high concentration of alkali (sodium in particular), sulfur, and chlorine. These chemical species undergo many chemical reactions that could eventually lead to deposits and corrosion on the heat transfer surfaces in the boiler. The formation of a deposit will reduce the effective heat transfer and require a more frequent cleaning schedule. Corrosion will eventually reduce the strength of the piping, which could lead to the formation of holes and the subsequent shut down of the operation. In addition to these issues, others are present. Of special importance is the presence of heavy metals such as zinc, lead, and mercury because

they have a low melting point and may be vaporized; if they are vaporized, they might react with the available chlorine and increase both corrosion and the formation of deposits. Iron and copper act as catalysts in the formation of dioxin in the temperature range of 400–250°C.

COMBUSTION

The purpose of combustion is to convert all the material in the fuel into a fully oxidized product that is generally gaseous. In the case of waste combustion, this means that the incoming carbon content should produce carbon dioxide and any hydrogen should yield water (i.e., steam). The basic reaction of organic material with no inorganic content is shown in [Reaction \(R1\)](#).



However, the mechanism is a little more complex and occurs in different steps. The first step is drying, whereby the water in the fuel is released as steam; this occurs practically without any other chemical reaction and is a part of the heating process. Drying is an endothermic process, meaning that heat is required. Drying is followed by pyrolysis, which is a heat-induced cracking reaction that leads to the release of gaseous products from the solid, such as carbon oxides and various hydrocarbons of different molecular weights. No oxygen is needed, therefore, to be present during pyrolysis and, depending on the chemical composition, pyrolysis could be either slightly endothermic or slightly exothermic. The solid that remains after pyrolysis is composed of inorganic material, along with the char formed. The char has a high content of carbon, as well as some hydrogen and oxygen. The higher the temperature of pyrolysis, the higher the fraction of carbon present. The final step is reaction with oxygen, which is exothermic and provides the high temperatures in the boiler; it could occur with both the gaseous species that forms and the remaining solid material.

It is important that the heat and mass transfer inside a boiler is good to provide not only efficient and rapid heating during the initial phases but also good mass transfer, which will ensure good contact between the reacting species and oxygen. All gases must have passed through a zone with a temperature of at least 850°C for a minimum period of 2 s [1].

BOILER TYPES

Two main types of boilers are used in waste-to-energy applications: stoker (grate) and fluidized bed. Several

other options are, however, used for more specific fractions [2]. Rotary boilers, for example, are commonly used for combusting hazardous materials, but they are not included here.

A stoker boiler has a bed (often on a moving grate to ensure continuous transport) through which the primary air passes; the species being formed is thereby initially swept away and, in the final section, the remaining solids are burned. Secondary air is used above the grate to provide good mixing and thus good contact between oxygen and the gases formed. The stoker boiler is the most common type of boiler used, mainly based on its reliable operation and the large number of reference cases from around the world. Although it has minimum requirements for the fuel being pretreated, it is more difficult to operate properly if the fuel input is nonuniform. This could lead to higher emissions of carbon monoxide, which is an indication that the conditions within the boiler vary and that mixing is nonuniform.

A fluidized bed boiler has an inert bed of fine particles (often with quartz sand). The fuel is fed into the boiler, which is fluidized with air and recirculated flue gases. Once the fuel is in the fluidized bed, the bed itself ensures efficient mixing in terms of both mass and heat transfer, creating a uniform concentration and temperature. Secondary air is introduced above the bed in the “freeboard” for the final combustion and to ensure a sufficiently high temperature. This type of fluidized bed is known as the bubbling fluidized bed and is used for moderate-sized boilers in the order of 20 MW_{th}. Larger fluidized bed boilers generally use a circulating fluidized bed that has a higher power production per unit of cross-sectional area unit. The fuel used in a fluidized bed boiler requires a higher degree of pretreatment than that used in a stoker boiler to maintain the high mixing properties, which is done mainly by size reduction. In contrast to the stoker boiler, a fluidized bed does not contain any moving parts, which reduces the cost of the plant. On the other hand, the running costs are greater due to the fuel requiring extended pretreatment, the addition of sand, and more material being collected in the ash-handling system.

PARTS OF A BOILER

After collection, the solid waste is transported to a temporary storage facility where there is the possibility of subjecting it to pretreatment. This is especially important for fluidized bed boilers because it is preferable that the size of the material be reduced. There are several different options for size reduction, with the most

common being the hammer mill. Although this mill is efficient, it requires substantial maintenance, which increases the cost of operation. However, when pretreatment has been carried out, the fuel is much more mixed than the initial waste that was collected, and operation will therefore be easier. After pretreatment, the waste is transported to the fuel bin; from here, the operator can control the feed input so that it matches the requirements of the production and also achieves as even combustion properties as possible. A typical result of rapidly changing the fuel's properties can be seen as spikes of carbon monoxide, indicating the need for more oxygen to achieve complete combustion. Another result would be a rapid change in temperature, either an increase or a decrease, indicating an input of fuel with a different heating value.

Combustion Section

Inside the boiler, the material is combusted. A high combustion temperature will lead to a high formation of NO_x , which is undesirable. Regulations nevertheless demand a minimum temperature of 850°C [1], which provides the operating window that can be controlled in several ways: by decreasing the amount of fuel input, by changing the amount of primary and secondary air, or by changing the amount of recirculated flue gases. In a stoker boiler, the walls are constructed of boiler tubes, where water at high pressure is evaporated. This increases the heat transfer from the flue gases, which occurs mainly by radiation from the combustion flame. In a fluidized bed boiler, it is common that at least the fluidization zone is made of ceramic to prevent possible erosion of the water tubes. This induces higher recirculation of flue gases with respect to the heat load in order to control the temperature.

During combustion, it is essential that the level of oxygen present is controlled. If all oxygen is present at the same position, a very rapid reaction would occur, with high temperatures and a great risk of uneven mixing; some parts would be left very hot and others rather cold, moreover with no access to oxygen. A way of preventing this would be to run the boiler with a high amount of excess air, but this will result in low energy efficiency because the flue gases leave the boiler at an elevated temperature. Several levels of air "intake" are used instead, ensuring better and more homogeneous combustion as well as distribution of the temperature profile. For both the fluidized bed boiler and the stoker boiler, the definite minimum amount of primary air is controlled by the content of organic carbon in the ash.

The flue gases formed after combustion contain some inorganic material because of either evaporation

(as fumes) or entrainment (as small particles). This could cause several different issues in the following equipment, with the two most severe being corrosion and deposits. It should also be noted that the higher the temperature of these inorganic particles, the greater the risk of deposits forming, as they melt at elevated temperatures. One possible solution for reducing the magnitude of these problems is to include an "empty draft" after combustion—a passage with a large open space and planar heat exchangers with the purpose of decreasing the temperature of the flue gas sufficiently so that the particles become solid. Combining this with a return shaft (in practice, this is a U-bend) allows a substantial amount of particles to be removed from the flue gas.

Heat Exchangers

Proceeding further in the boiler is the majority of the heat exchangers. Traditionally, in power boilers, the first heat exchanger section is known as the "superheater section" because it has the biggest driving force for transferring heat; the difference in temperature between the hot and cold sides in the heat exchanger is greatest in this section. This gives a heat exchanger with the smallest area possible, and thus the lowest cost. However, this is only possible when the risks of corrosion and erosion are low enough without jeopardizing operation and this, unfortunately, is not the situation in the case of waste combustion. In particular, the presence of alkali (sodium and potassium) together with chlorine is highly corrosive, and other species are also present that could enhance corrosion. Therefore the maximum temperature of superheated steam in waste combustion is often limited to slightly above 400°C , whereas it is at least 100°C higher for ordinary biomass. In addition, heat exchanger sections could also be arranged in such a way that the highest temperatures are prevented from occurring simultaneously at the hot and cold sides. Fig. 13.1A represents the traditional setup with a minimum heat exchanger area, whereas Fig. 13.1B represents the modified setup for a corrosive environment. Here, the penalty is a heat exchanger with a larger area, although this will prolong the operating time before replacement is necessary.

Another aspect of the combustion of municipal solid waste and the amounts of inorganic materials contained in the flue gases is the large amount of deposits that occur, some of which end up on the surface of the heat exchangers. An increase in pressure drop results if the deposits are not removed. A high pressure drop leads to either the fan before the chimney requiring

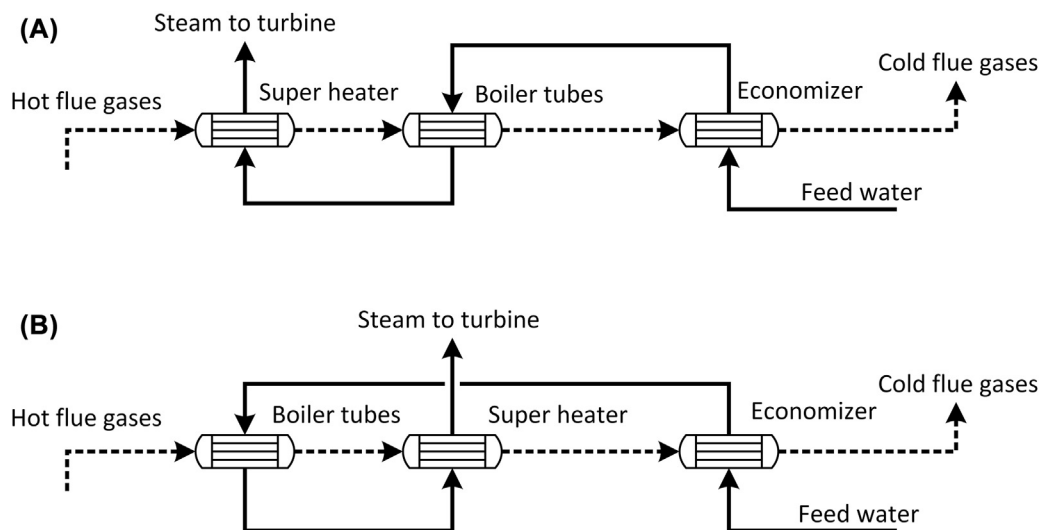


FIG. 13.1 Heat exchangers in the Rankine cycle. (A) An arrangement to minimize the surface area of the heat exchanger. (B) A setup often used in waste combustion.

more power or the combustion zone having a higher pressure. The former leads to higher internal use of electricity, whereas the latter demands a greater control, and more costly construction, of the boiler because, for safety reasons, it operates at a slightly decreased pressure (subatmospheric). Where deposits occur depends on several factors, of which the three most important are composition, the temperature of the tube walls, and the temperature of the flue gas. The composition and the temperature of the flue gas determine the degree of “stickiness” of the particles (i.e., their ability to adhere to other surfaces) and is related to the amount of smelt. The temperature of the surface determines whether the particles stick to it or fall off.

Some manufacturers of waste power boilers employ heat exchangers in a horizontal alignment. Such boilers have a larger footprint than those with a vertical alignment but have the advantage that they are easier to both handle and replace, when required.

When a circulating fluidized bed boiler is used, a cyclone is added before the heat exchangers to remove the bed material; in a bubbling fluidized bed boiler, the cyclone is more often placed after the boiler tubes and superheaters. This difference in position is due to the amount of bed particles present in the flue gas. Grate boilers do not need a cyclone.

Cleaning

The final cleaning is done using an electrostatic filter in combination with some kind of textile filter or a flue gas condenser. It is also important to handle the sulfur oxides (waste contains generally 0.1%–0.4% sulfur) and the acid gas (hydrogen chloride) formed during combustion [3]. This is most commonly done by mixing the flue gases with lime (calcium oxide) or slaked lime (calcium hydroxide), resulting in the formation of gypsum (calcium sulfate) and calcium chloride. This could be carried out (1) in a dry system, where powdered lime hydrate reacts mainly on a textile filter; (2) in a semidry system, where a slurry is sprayed into the flue gases for immediate reaction; or (3) in a wet system, where the flue gases pass through a scrubber system. In the dry and semidry systems, activated carbon is often used in combination with lime, as this would also capture heavy metals and dioxins.

A flue gas condenser may be introduced into a waste boiler that produces both heat and power. It will also serve as a cleaning device because most of the particles (even the smallest ones) can then be removed. However, the condensed water has a low pH and must therefore be neutralized and cleaned before being released. A flue gas condenser could increase heat production by approximately 15% of the fuel heating value,

depending on the fuel being used and its moisture content.

Other substances found in the flue gases include various nitrogen oxides (NO_x). During combustion, the substance found is, to a large extent, nitrogen oxide (NO), although this compound oxidizes in the atmosphere over time to form nitrogen dioxide (NO_2). As mentioned earlier, it is preferable that the concentration of oxygen is kept low during combustion, especially during the initial fuel-rich phase to minimize the formation of NO_x . Moreover, it is preferable that the temperature is kept below 1300°C to prevent the formation of thermal NO_x . These two ways are referred to as primary measures. Secondary measures include two different reduction methods, namely, selective noncatalytic reduction (SNCR) and selective catalytic reduction (SCR). In the SNCR method, either ammonia or urea is injected into the upper part of the combustion chamber, where the targeted temperature of the flue gases is $850\text{--}950^\circ\text{C}$ [4]. This method makes it possible to reduce the content of NO_x by 60% without allowing any significant amount of ammonia or urea to pass through unreacted. In the SCR method, more than 90% of the NO_x can be removed but, as it requires a catalyst, it increases costs. On the other hand, the reaction is highly efficient, as almost no unreacted ammonia or urea is present [5]. The sensitivity of the catalyst means that this reactor is placed at the end of the gas cleaning stage, so the flue gases may have to be reheated to reach the optimal reaction temperature.

The Rankine Cycle

A combined heat and power boiler is equipped with the Rankine cycle to produce electricity. This cycle is composed of four key parts: the generation of high-pressure steam, a turbine, a condenser, and a pump. Steam is generated in the boiler and then transferred to the turbine. Depending on the production setup (i.e., the preferred outcome and local restrictions, such as the cooling sources available), the back-end pressure of the turbine may vary between locations and individual plants. A lower pressure means a higher production of electricity but at the expense of less usable heat from the condenser. In systems with heat production, the back-end pressure of the turbine is around 1 bar, which would generate a water temperature close to 100°C . When the initial temperature and pressure of 420°C and 40 bar, respectively, are used, the theoretic power output for a given heat input would decrease by 28% if the condenser temperature is changed from 30 to 100°C (although, in reality, the

decrease is smaller as the efficiency of the turbine drops when a humid area is encountered).

EFFICIENCY OF A COMBINED HEAT AND POWER PLANT

There are many ways of assessing and measuring efficiency. One of the most obvious method is measuring the energy efficiency, which is basically the amount of energy transferred from the original feedstock to the desired products. In the case of a combined heat and power plant using waste as the feedstock, the energy efficiency may be described as

$$n_{\text{eff}} = \frac{\text{Electricity} + \text{heat}}{\text{Heating value of waste}}$$

The commonly used term heating value is actually the lower heating value, which originates from the time before flue gas condensers existed. However, the addition of flue gas condensers allows the energy efficiency, in some cases, to exceed 100%, and it is, therefore, more relevant to use the higher heating value. In the energy balance, the internal use of electricity should also be considered, which, in a heat and power plant, would be mainly by the pump in the Rankine cycle and the fan for extracting the flue gases. These normally consume less than 1% of the power produced in the turbine and are often neglected. The remaining energy losses are found to be due to the housing (construction and pipes) and emissions via the stack of flue gases (with temperatures up to 200°C). Minimizing heat losses would obviously increase the levels of energy efficiency.

Another option is to evaluate the exergy efficiency. In this case, the amount of energy as well as its quality are evaluated. Normally this is defined as the theoretic ability to perform work. The theoretic ability to perform work possessed by a heat flow is given by the Carnot efficiency (temperatures are given in K).

$$n_{\text{Carnot}} = 1 - \frac{T_{\text{surrounding}}}{T_{\text{gas}}}$$

This means that gas at a high temperature has a greater theoretic ability to perform work, and a gas flow at the same temperature as the surrounding has no possibility of performing work because there is no driving force to be utilized. It is possible to use this concept for even more complex materials, and it is often divided into three parts. The first part is the consideration of the kinetic and potential energy, together with the temperature; the second part is the possible reaction needed to form the chemical species that are present naturally in the surrounding (requiring a definition

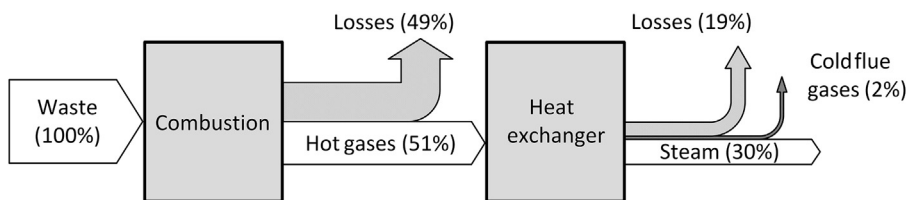


FIG. 13.2 Exergy flow in a combustion plant.

for each compound); and the third part is the mixing work related to different concentrations of the reacted species on entering the surrounding, as well as separating the species from the surrounding, which may be necessary for the chemical reaction to occur. When considering turning waste into energy, the third part is very small in comparison to the other two parts. Furthermore, the kinetic and potential energy in the combustion and flue gas sections can often be neglected, as they are much smaller than both the exergy from the chemical reactions and the temperature. Although energy efficiency does not distinguish between heat and power, exergy efficiency does. About 1 kW of electricity has the exergy value of 1 kW but 1 kW of district heating water at 100°C only has an exergy value of 0.23 kW (using a standard surrounding temperature of 15°C). Considering the loss of exergy in combustion, the majority occurs within the actual combustion process: about 49% is lost when energy stored chemically is transformed into fully oxidized flue gases at 850°C (Fig. 13.2). An additional 21% of the initial amount is lost in the heat exchanger when producing steam at 420°C and 40 bar, provided that the cold flue gases go directly to the chimney. It should be noted that this example does not consider any heat loss due to the lack of insulation to prevent other leakages from occurring, and the only energy loss is through the chimney (the cold flue gases), accounting for about 20%. The fuel composition used here is on a dry basis: 48% C, 6.3% H, 26% O, and 18% ash, with the remainder comprising N, S, and Cl. The heating value is 11,500 kJ/kg as received and the moisture content is 35%.

WASTE COMBUSTION IN A CIRCULAR ECONOMY

Waste combustion has been considered as being the last resort for the collected material; the primary reason for utilizing combustion has been to reduce mass and volume. However, it is important to understand that waste materials have substantial values in addition to their energy content that is already being utilized. These other

values are found in the solid residue, i.e., ash. Bottom ash from the combustion section contains much of the iron and copper present in the waste fuel and can be separated by using magnet or eddy current separators. The remaining ash (the fraction with a low concentration of heavy metals) is often used as construction material for roads and to cover landfills. In countries with subsequent treatment (e.g., plasma melting), the remaining ash has been sintered to form an almost impermeable product with low leachability [6] that can be used in construction work close to habitation.

Along with these simple metals, other metals are also present. These are often bound chemically to the ash particles and mean that more advanced methods for separation must be used. Success has been achieved in the removal of, for example, zinc, which is enriched in the fly ash and could be removed by leaching. Many metals, including zinc, copper, lead, and cadmium, are released during a leaching cleaning system, where recirculated acid flows from a wet flue gas. The leaching stage is able to release almost all the cadmium (above 85%), over 60% of the zinc, and lesser amounts of copper and lead [7–9]. The next step is purification of the solution; although this can be performed by several methods, the most promising one appears to be electrolysis. The economics of the process depends on both the concentration of zinc in the fly ash and the current price of the recovered metal, which varies between different countries.

Another promising material suitable for recovery is phosphorus. This is a metal that is vital for plant growth and is present in fertilizers. Phosphorus enters into the system via food waste but the main source is, in fact, sewage sludge. Extensive research and trials have been undertaken to distribute the sludge, after subjecting it to some conditioning, directly on farm land, but the risk of spreading toxic matter, hormones, pesticides, and unused medicines is substantial. Thermal treatment is necessary here, but then problem arises if the phosphorus has not been recovered. Phosphorus is a natural resource of significant importance, and it is also limited and becoming rather scarce. Another problem is that new discoveries of phosphorus contain high

concentrations of cadmium, which is a heavy metal that should be avoided by farmers because it is taken up by plants and then accumulates in the human body (primarily in the kidneys, where it generates reactive oxygen species and activates cell death pathways [10]). Phosphorus is a stable metal with a low vapor pressure even at elevated temperatures. Most of it is, therefore, found in the bottom ash (i.e., the ash in the combustion zone) and has thus been separated early on from many of the heavy metals. In principle, it is possible to use this ash as part of a fertilizer, provided that the concentrations of heavy metals are sufficiently low. The concentration of phosphorus depends very much on the feedstock, and dedicated campaigns where such a fuel is used could be of great benefit. It is important that the behavior in the boiler is monitored and estimated before a large amount of sewage sludge is added; both the composition and chemistry of the ash will change, which could cause severe agglomeration and large lumps in stoker boilers.

IMPROVING WASTE COMBUSTION

The combustion of waste material has the potential of increasing its efficiency as well as increasing the recovery of material. Increasing energy efficiency may be done by employing primarily two different measures. The first measure is to include flue gas condensers wherever possible. This could add an additional 10%–15% to the boiler effect. However, to utilize a flue gas condenser, the condensation temperature has to be higher than the return temperature of the district heating network. This generally implies temperatures above 70°C, and more likely higher. Not all the water is condensed at these temperatures, so a substantial amount of water remains—saturated air at 80°C contains 558 g of water per kg of dry air but is reduced to 281 g/kg when the temperature is decreased to 70°C. An extra option is to add a heat pump and reduce the temperature to about 30°C and then the content will be only 28 g/kg. This, however, requires heat to raise the temperature to the necessary levels. The second measure is basically to lower the temperature of the flue gas; e.g., lowering the temperature, as mentioned earlier, from 200 to 150°C reduces the energy loss from 22% to 19%. However, reducing the temperature may cause low-temperature corrosion because salt solutions could be formed from, for example, alkali chlorides and sulfuric compounds [11]. In addition, it is important that condensation in the chimney is avoided; low temperatures may also reduce the natural draft and result in the stack fan (should there be one) requiring more power.

The exergy efficiency can be improved in several ways. One option is to improve the efficiency of the Rankine cycle, which would increase the electricity production per mass of waste fuel. This, however, can never go beyond the exergy content of the steam. Measures that can be taken here are (1) improving the design of feed water heaters (an increase in both their number and temperatures may increase the steam flow for a given heat load), (2) reducing the temperature in the condenser (operating the district heating network at a lower temperature would give a lower back-pressure in the turbine), and (3) reheating the steam at a medium pressure from the turbine (a costly way of improving the efficiency of the turbine and avoiding condensation in it).

Another option is to enhance the properties of the steam while simultaneously avoiding severe corrosion, especially in the superheaters. A plant in Lahti (Finland) uses pregasification and then removes the alkali in a high-temperature filter before the gas is burned in a gas boiler. In this way, the steam's properties are increased to 540°C and 121 bar. There are also ways of making improvements to an existing boiler, e.g., sulfur recirculation can be utilized, yielding high concentrations of sulfur inside the boiler. The sulfate thus formed will compete with chloride to combine with alkali metals, thereby reducing corrosion. This could be used to either increase the properties of the steam or reduce costs by using less expensive material in the heat exchangers. It will, however, require a wet cleaning system and the addition of hydrogen peroxide, but it is not expected to increase emissions of sulfur from the stack [12].

CONCLUSIONS AND PERSPECTIVES

The combustion of waste is currently an excellent option for sustaining progressive work with respect to the environment. There are several reasons for this: fewer landfill areas are necessary, the amount of emitted greenhouse gases is reduced, toxic materials are destroyed, more material is recovered, and waste is converted into valuable products. The reduction in the amount of greenhouse gas emitted is primarily due to the combustion of organic material that would otherwise form methane gas, which has a much higher environmental impact than carbon dioxide. Examples of toxic materials are different chemicals, medicines, and pesticides, all of which should not be released into the environment; these substances react completely at high temperatures when oxygen is present. Furthermore, it is possible to recover metals from the ash that remains after combustion. This has been used

mainly for the recovery of iron and copper, although today other options include zinc and phosphorus. The main products of combustion are power and heat, both of which originate from high-pressure steam.

There are some features that are specific to waste when it is used as a fuel. Primarily, waste has a high inorganic content, especially the contents of alkali metals and halogens. These substances form salts that are corrosive and could cause deposits. Both corrosion and deposits will result in the electric efficiency being relatively low because the properties of the steam must be reduced to ensure a sufficiently long life span of the heat exchanger tubes. In addition, the composition of waste varies, making it difficult to operate the combustion unit properly. An airflow that is too high would increase the formation of NO_x and too low an airflow would not ensure complete combustion, so the concentration of carbon monoxide will increase. Moreover, there is the requirement of keeping the temperature above a minimum value. Failing to adjust the airflow correctly would impact all these conditions. Finally, cleaning the flue gas must be done appropriately. Sulfur, for example, must be separated from the flue gas or it will be released as sulfur dioxide, which will react in the atmosphere and cause acid rain. Dioxins and furans are very toxic substances that are formed during poorly controlled combustion operations or in specific temperature intervals when catalysts such as copper are present, and they must be removed from the flue gases.

Future Perspectives

Waste combustion is currently used in many countries; with respect to its generation of organic waste, Sweden is one of the countries with the highest capacity for combustion. In 2017, more than 7.6 million tons of waste was used as fuel in combustion facilities [13]. Of this, 6.1 million tons was used in dedicated waste combustion units with energy recovery [14] and the remainder was used in industrial units. This high capacity is a result of the overall high degree of energy efficiency of the combined heat and power combustion facilities in question. In Europe, the total amount of waste used for energy recovery is 105 million tons, with 196 million tons being sent to landfill [15]. There is an obvious need to minimize the amount of waste going to landfills, from both a local and global environmental perspective. The global perspective is largely associated with landfill emissions of greenhouse gases, whereas the local perspective is associated with the requirement of space, as well as the risk of substances leaking out that could contaminate water and soil.

It is important to strive after a better economy with the resources available, be it energy or materials. Many countries are now discussing and initiating the implementation of a circular economy with a higher degree of material utilization to reduce the amount of waste that is being created. This, in turn, will alter the composition of the waste available for combustion; in particular, plastics and textiles, with their high heating values, will be separated to a larger extent. An increased circular economy, which implies increased recycling of materials, will not remove the need for combustion completely because increased recycling means that harmful substances will accumulate in the materials. A function capable of removing such substances is therefore necessary and combustion is one such function, which also takes care of materials that are unsuitable for further recycling. The life span of, for example, paper and textile fibers is shortened each time they are subjected to mechanical recycling and, eventually, they become too short to function properly. In the final stage, combustion can utilize the energy content in the production of heat and power.

One of the biggest problems of modern waste combustion is the solid that remains, i.e., the ash, which is often 15%–20% (on a weight basis) of the initial amount of waste. It is composed of different fractions: the bottom ash is often regarded as being nonhazardous and used in some construction work, mainly on landfills, whereas the fly ash contains most of the heavy metals and is currently sent to landfill sites. These landfills will, however, eventually be full to capacity and alternatives are therefore necessary. It is possible to utilize these ashes for the further recovery of material: one option is to select the fuel in such a way that the resulting ash can be used for other purposes. This would, for example, allow nutrients from sewage sludge to be made available as fertilizers without risking the spread of undesirable substances such as pathogens and heavy metals. Another option is to utilize these ashes as construction material other than in landfills, provided that the chemical composition and leaching properties are within acceptable ranges.

The combustion of waste has been used very successfully in the production of district heating, as mentioned earlier; however, it is not certain that this demand will remain at the same level in the future. It has to compete with other technologies (such as heat pumps) and, as new houses are also increasingly better insulated, the demand for district heating will decrease. Moreover, waste heat from industries is also competing within the existing district heating network. Increases in demand will be from new building constructions and

from more efficient electric appliances. The introduction of district cooling as a parallel network will also increase in demand, especially when the requirement for heating is relatively low, i.e., when temperature outdoors is high. This can be of importance to other countries too.

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