by **Paul Darley**

MSW – problem or opportunity?

Energy recovery from municipal solid waste

The design and operation of the equipment used in energy from waste plants, to recover and utilize the valuable energy content of municipal solid waste as heat and electricity, has evolved to cope with the particular problems associated with the fuel and achieve the desired reliability and plant life.

One can visit any country in the world and be told: 'we have a problem with our waste disposal here.' Yet municipal solid waste (MSW) contains valuable energy which, if recovered, could reduce our dependence on fossil fuels for power generation. Nevertheless, the separation of reusable materials and the utilization of the energy from MSW have rarely been viable on economic grounds if the waste disposal is taken in isolation from a wider economy and without considering the impact on the total environment. However, this is changing as environmental issues become increasingly political and, as a result, it becomes more commercially attractive for those who invest in waste disposal facilities to recover energy from the waste.

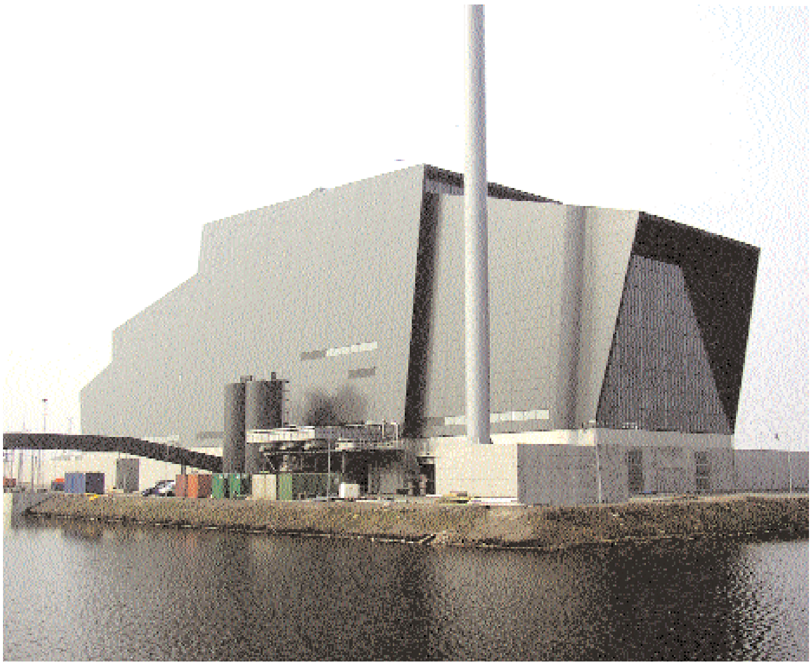
The disposal of MSW should therefore be viewed as an opportunity to be seized, with the undoubted technical and economic difficulties being solved carefully, as is now possible, rather than cited as reasons for failing to recover the available energy.

While the heat from the combustion process can be used in a variety of ways, by far the most common use is to raise steam, and by far the most common use of this steam is to generate electricity.

The history of energy from waste

Since the earliest days of the waste disposal industry, combustion has been one of the methods employed to dispose of waste, or at least to reduce its bulk.

Although an MSW incinerator with energy recovery was built in Nottingham, UK, as early as 1874,[1] only five of the 40 plants operating in the UK by the early 1970s included energy recovery. Major problems with the boilers of these five energy from waste (EfW) plants had to be overcome over a period of years before they could be considered to



Incinerator plant in Denmark: the disposal of MSW represents a chance to recover the energy available in it. PHOTO: BABCOCK & WILCOX VØLUND APS

operate with an acceptable reliability and life. Some boilers blocked completely in weeks, while others corroded seriously in months. The high cost of some manufacturers' attempts to find solutions affected their trading position just as seriously.

Plants on mainland Europe had a more successful record, and their continuing development is one reason for more plants being built there than in the UK. Problems with other steam cycle components were less dramatic, but efficiency improvements resulting from their development have been no less significant.

The benefits of energy recovery in EfW plants

The boiler is employed to cool the flue gas or syngas coming out of the thermal treatment process by generating and superheating steam. This can be used to generate electricity and usable heat as described below. The boiler is also a valuable operating tool to indicate the actual heat load in the thermal treatment process at any given instant.

The absence of any direct cooling of the flue gas by air injection or water quenching results in high boiler efficiency (typically 85%) and a minimum plant operating cost. However, the boiler should be designed for maximum reliability and not for maximum heat recovery.

EfW plants must be planned, designed, built and operated to the same high standards as other process plants

The problems for energy recovery in EfW plants

The heterogeneous nature of MSW, together with the character of some of its components, tends to cause corrosion, erosion and fouling problems in the steam generators of incineration plant. An emphasis on environmental issues may have often overshadowed all other aspects of developing technologies at recent conferences and in publications, but the old problems of boiler corrosion and fouling have not gone away.

A comprehensive knowledge of the causes of corrosion and fouling has been gained in recent years and if such knowledge is taken into account in the design, construction and operation of new plants, it is possible to keep the difficulties within tolerable limits.

The combination of cooling flue gas from the thermal treatment of MSW (whether by combustion, gasification or pyrolysis) and generating steam makes special demands on the equipment, which cannot be satisfied from conventional boiler-making experience alone. The special problems that may arise for a boiler cooling the flue gas or syngas from MSW thermal treatment are:

- very high flue gas or syngas temperature
- high dust content in the gas, with possibly molten particles leading to fouling and erosion
- corrosive components in the gas
- the need to prevent the formation of dioxins as the gas cools
- variations in the heat load arising from the heterogeneous fuel and its batch feeding.

Despite all these difficulties, EfW plants must be planned, designed, built and operated to the same high standards as other process plants. For safety as well as for economic reasons, such plants must achieve high reliability and availability.

Steam generation

The design and construction of the steam generator (boiler) must be tailored to the specific plant requirements and local conditions, taking the following into consideration:

- the composition of the waste
- emission requirements
- required equipment life
- required duration between shutdowns
- any height and space restrictions at the site
- the value of electricity.

Fluidized-bed combustion plants and the waste heat boilers in gasification and pyrolysis plants generally have the steam

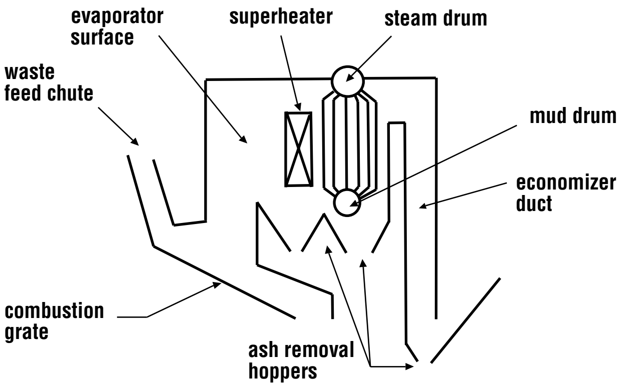


FIGURE 1. **Typical bi-drum boiler configuration**

generator separate from the chamber in which the MSW is thermally treated and the configuration may vary considerably from that of a boiler in a conventional combustion plant as described below. The issues to be addressed to ensure successful boiler operation and longevity are nevertheless the same.

Almost all boilers in MSW combustion plants have a radiation section above the combustion grate using membrane walls (gas-tight tube–web–tube fabrications with water in the tubes). In the past, subsequent boiler passes were often of a bi-drum design (the upper one being the steam drum and the lower one being called the 'mud drum'). In this design, more or less vertical tubes join the upper and lower drums, and the flue gas passes the water-filled tubes horizontally (see Figure 1).

The old problems of boiler corrosion and fouling have not gone away

More recently, and in many continental (European) plants, the convection section of the boiler comprises a row of tube bundles in a horizontal duct (see Figure 2), with the flue gas typically entering at 550°C with the radiant section fully clean, and 650°C with it fouled. Many modern EfW steam generators, however, consist of largely vertical passes (see Figure 3). The flue gas flows up the first (radiant) pass above the grate, through a tube screen into a second pass, down the second pass over an evaporator bundle, and up the third pass over superheater and economizer tube banks. There may also be a vertical fourth pass before the boiler exit.

A typical modern steam generator arrangement

In a typical modern steam generator, the gas passes are constructed from 'membrane walls' (tube–web–tube) which form part of the evaporator surface for heat transfer. The second and any subsequent passes have evaporator tube bundles in them.

The large empty first pass allows sufficient time to complete combustion at high temperature. The lower part of the first pass is lined with a refractory (silicon carbide) to avoid corrosion and to provide thermal insulation in the grate area. The gas is cooled to approximately 650°C before it leaves the first pass and reaches the convection heat transfer surface in the second pass. The first convection surface is a superheater arranged in parallel flow to cool the gas to approximately 600°C; the next is a further superheater arranged in counter-current flow. Here, the flue gas temperature is reduced further to approximately 450°C.

The lower end (exit end) of the final pass contains economizer bundles, which cool the flue gas to approximately 230°C before it leaves the boiler. Feedwater enters the lower end of the economizer and passes through it in counter-current flow before being fed to the steam drum.

The water/steam circuit

Deionized water is used as boiler feedwater. All dissolved gases are removed in a de-aerator, which operates slightly above atmospheric pressure. From the de-aerator, the boiler

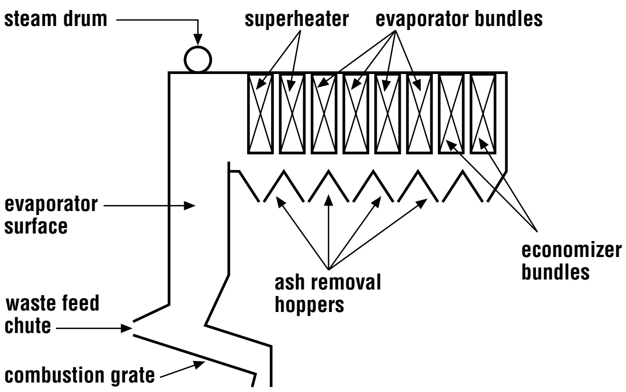


FIGURE 2. **Typical horizontal boiler configuration**

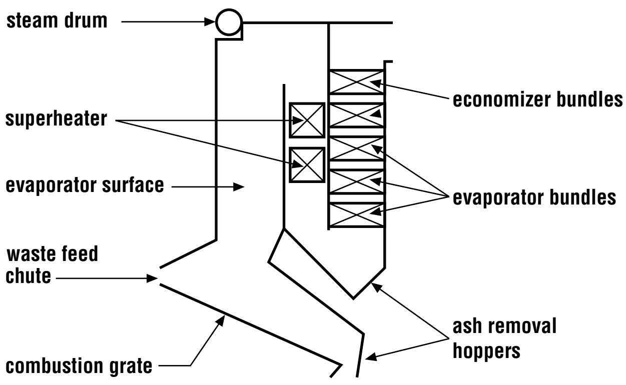


FIGURE 3. **Typical vertical boiler configuration**

feedwater is pumped via the economizer into a steam drum mounted on the boiler roof, which operates at the boiler operating pressure (generally a maximum of 40 bar). Continuous blowdown from the steam drum avoids salts accumulating in the water system.

The most serious fouling is caused by ash constituents that undergo sublimation, as this requires out-of-service cleaning

The water is circulated from the steam drum through the evaporator panels and tube banks back to the steam drum by natural circulation. If the fluctuations in heat load are rapid and relatively high compared with the total boiler capacity, part of the boiler may be operated with forced circulation.

The steam leaving the steam drum is passed through the primary and secondary superheaters. A spray injection cooler is located between the two superheater stages in order to control the steam temperature.

There are many special conditions to be accommodated in the design of a steam generator in an EfW plant. The potential hazards and some solutions are described below.

Boiler fouling

The flue gas or syngas entering the boiler downstream of MSW thermal treatment will have a high dust content. This can cause fouling of the heat transfer surface, thus reducing the heat transfer and the amount of steam generated, and increasing the exit temperature of the boiler gas. The options for cleaning heat transfer surfaces, which are explained below, are:

- steam or compressed-air soot blowers
- mechanical rapping
- shot blasting
- sonic devices.

A boiler is provided with a spacious vertical radiation chamber in which much of the particulate matter will fall back down rather than be carried over in the gas stream or stick to the heat transfer surfaces. However, some dust will adhere, and as the first passes become fouled, the amount of gas cooling in the front of the boiler is steadily reduced, and the later passes remove more heat from the gas. Cleaning of the heat transfer surfaces is thus always necessary.

The boiler design must ensure that the gas cools before it reaches the convective heat transfer surfaces so that no sticky deposits build up on the tubes. The most serious fouling is caused by ash constituents that undergo sublimation as this necessitates out-of-service cleaning. The products of sublimation (also known as sublimates) have a very fine crystalline structure and tend to form deposits that bond intimately to the tube surface and act as an insulator, thus reducing heat transfer. The lower furnace tubes are protected by a refractory, which has gas-side temperatures too high to permit such fouling.

To minimize fouling and corrosion, the membrane walls and tube banks should be arranged so that the tubes are parallel to the gas flow. The main fouling and increased gas-side pressure drop generally occur in the evaporator panels of the second pass; hence the use of platen-type tube

ABOVE EfW plant at Long Beach in the US state of California. PHOTO: MONTENAY POWER (ONYX) **BELOW** The MKVA Krefeld plant, Germany **FACING PAGE** Waste incineration plant in Tuas, Singapore bundles parallel to the gas flow. To prevent blocking of the gas path in the third pass, a tube pitch of 300 mm in the final stage superheater and 150 mm in the primary superheater is advisable.

Gas-side cleaning of the heat transfer surface during operation is carried out with steam or air soot-blowers. Retracting and rotating steam soot-blowers have proved most successful.

Mechanical rapping is used in many plants, but often fails to produce the desired effect because of its low energy potential.[2] On some horizontal-pass steam generators equipped with rapping gear, the exit gas temperature, which indicates the degree of fouling of the heat transfer surfaces, rises by as much as 50°C within a few days despite continuous rapping. In these cases, the only ways to reduce the gas temperature are to run at minimum load or to cool down the steam generator keeping the rappers in continuous operation. This also explains why other cleaning systems such as shot blasting and sonic cleaning – with their low energy potential – have generally not proved satisfactory. Steel shot cleaning has only been used in the economizer area, where it occasionally causes the fine ash layer to consolidate on the tubes.

A typical regime is to clean a boiler on-line with steam lances three times a day for 30 minutes each time using some 4 tonnes of steam. There is also usually a scheduled shutdown every 4000 hours for manual cleaning. It is sometimes preferable to shut down more frequently to provide an opportunity for an effective programme of preventive maintenance with early identification and remedy of damage or defects.

Boiler erosion

The particulate matter in the gas is extremely hard and can cause erosion of the heat transfer surface. This must be taken into account when selecting the gas velocity and the material type and thickness, especially where the gas changes direction in the boiler. The gas velocity should not exceed 4 metres/second in the radiant section and 8 metres/second in the convective sections. If the velocity is too low, however, fouling and dioxin formation will be increased.

Boiler corrosion

The corrosion rate depends largely on the tube wall temperature. During operation, therefore, the heat transfer surface temperature must be kept between 170°–320°C in order to avoid both low-temperature and high-temperature corrosion.

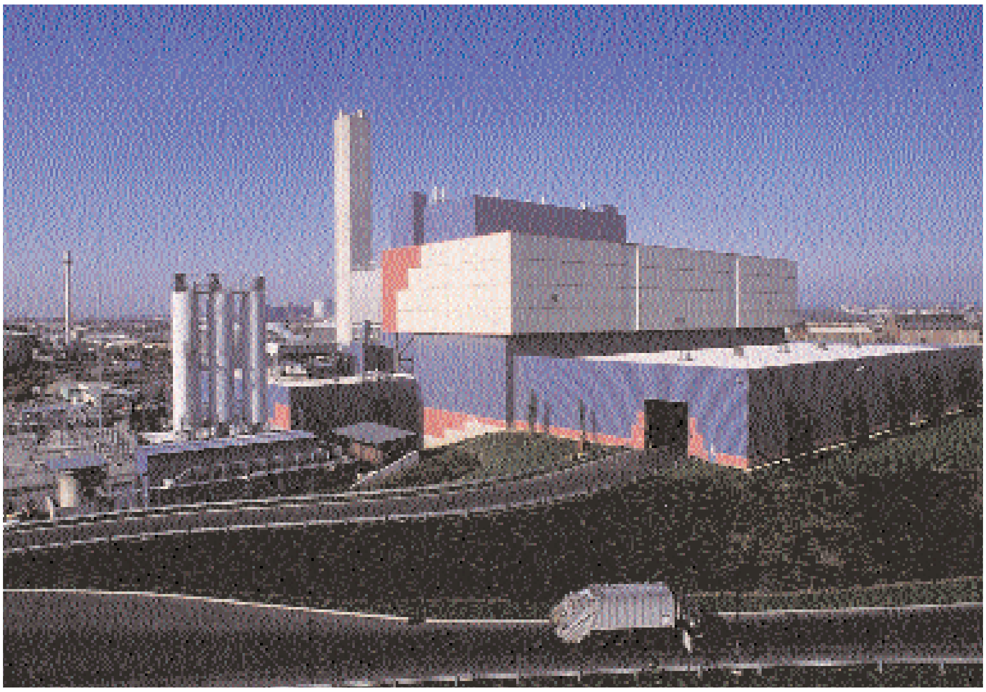
Below 130°–160°C – the region below the dew points of hydrochloric acid and sulphuric acid – electrochemical corrosion (acid corrosion) becomes perceptible. These acidic gases are produced from the inevitable inclusion of materials containing chlorine and sulphur in the waste. The need to avoid such corrosion dictates the minimum heat transfer surface temperature and thus the minimum gas exit temperature from the boiler.

Above 340°–370°C, high-temperature corrosion occurs, which increases in intensity with temperature and with the concentration of chlorine and sulphur compounds.[3] Hence, it is not possible to use the high steam temperatures generated in EfW utility boilers.

Selection of the steam conditions is critical to avoid metal temperature levels at which accelerated high-temperature corrosion takes place. The optimum steam conditions are a maximum of 40 bar and 400°C. In addition, potentially vulnerable tube areas can be protected with replaceable sleeves. The use of corrosion-resistant alloys or coatings can also extend the useful life of components to some degree, but this alone is rarely successful. Component life can be extended by providing increased corrosion allowance through the selection of tubing with thicker walls than the design code requires. But because corrosion is temperature dependent, the accompanying rise in metal temperature may offset any increase in component life. Fouling also leads to elevated local metal temperatures and subsequently to an increased corrosion rate.

Preventive maintenance minimizes corrosion and damage due to fouling. Ideally, the boiler should be shut down regularly for cleaning and inspection.

Heat transfer surface temperature must be kept between 170°–320°C in order to avoid both low- and high-temperature corrosion



An EfW facility in Essex, New Jersey, US.
PHOTO: AMERICAN REF-FUEL

Dioxin and furan formation

A major concern these days is the formation of dioxins and furans by *de novo* synthesis as the gas is cooled in the steam generator. This reaction can take place on the surface of fly-ash particles (especially those containing organic carbon and copper which act as catalysts) if the flue gas contains chlorinated organic compounds or metal chlorides and is cooled slowly in the range 450°–200°C in an oxygen-rich environment.[4,5,6] It is therefore vital that the thermal treatment process is efficient to minimize the presence of free carbon particles or hydrocarbon chains in the gas.

The boiler design should ensure that gas does not remain in the 450°–200°C zone any longer than necessary.[7,8] This can be achieved by a number of design features.

- An economizer or evaporator tubes should be positioned in the part of the boiler where the flue gas cools through the *de novo* synthesis temperature range. These should have a suitable steam pressure such that the heat transfer surface temperature is minimized (170°C for reasons of corrosion) and the gas therefore cools as rapidly as possible.
- The boiler passes can be designed so that the gas velocity increases through the boiler and is at a maximum (limited partly by the danger of erosion) through the *de novo* synthesis temperature range.
- The boiler should be designed to prevent pockets of stagnant gas or areas where the gas velocity or temperature will be locally reduced.
- The gas flow rate and regime must not allow a boundary layer along the heat transfer surface which will result in the gas remaining in the critical temperature range for too long.

Plant operation is also a key factor in the formation of dioxins and furans. The boiler heat transfer surface must be cleaned regularly to limit the dust surface on which *de novo* synthesis could take place.

Steam use

The options for energy use are:

- steam generation alone for process use or district heating
- power generation alone
- cogeneration (combined heat and power – CHP)
- trigeneration (combined heat, power and refrigeration).

Electricity generation is the most common use of the steam, but this does not preclude some of the energy being available for other potential uses.

While exporting all the steam produced to a process plant would eliminate the need for a turbine generator, it is rare for any process plant operator to be willing to be dependent on an EfW facility for steam. In addition, the value of steam is low compared with the value of electricity. The difference usually justifies the cost of a turbine generator and its ancillaries.

Condensing steam turbines for power generation alone

When the aim is solely to produce electricity, steam is expanded through a condensing steam turbine to as low a vacuum as is practical in order to convert as much as possible of the energy in the steam into electricity (see Figure 4). Some steam is bled from the turbine for the de-aerator and feedwater heating.

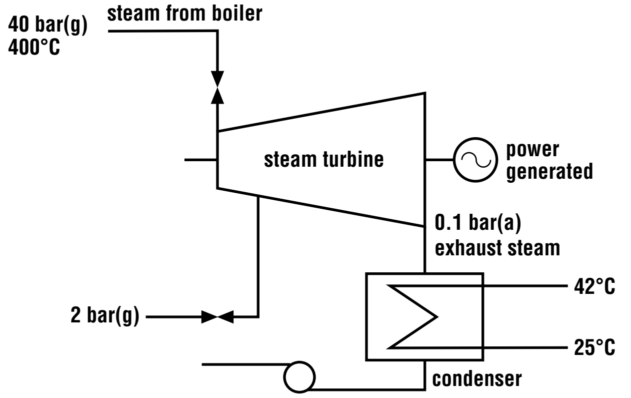


FIGURE 4. Typical turbine arrangement for power generation alone

Condensers can be either water-cooled (seawater or freshwater) or air-cooled. If water is available, this route provides a lower cost and more efficient solution. The vacuum is limited by two considerations.

- The temperature difference between the cooling medium leaving the condenser and the saturation temperature at the turbine’s exhaust pressure, which for all practical purposes is rarely less than 3°C.

- The exhaust wetness, which can be up to 15% if an appropriate materials are used for the turbine blade base construction and leading edge coating. If the wetness of the steam exceeds the design conditions, turbine blade erosion may occur.

The disadvantages of an increased vacuum are:

- the steam turbine must handle the large volumetric flows, which has an associated cost because the final blades and exhaust casing are larger
- the condenser increases in size and cost
- the cooling medium flow is increased.

Combined heat and power (CHP)

In a condensing turbine as described above, about two thirds of the energy in the steam is lost to the cooling medium. However, it is possible to increase plant efficiency considerably by recovering the lower-grade heat. This is achieved by raising the exhaust pressure of the turbine by passing the steam leaving the turbine through a heat exchanger to produce hot air, hot water or low-pressure stream for process use or space heating (see Figure 5). A steam turbine exhausting at a positive pressure is called a back-pressure turbine.

Developers of EfW plants should involve both the boiler designer and the steam turbine designer at an early stage

Extraction steam turbines are available with either uncontrolled or controlled extractions as required. Steam for de-aerators and feed-heaters is usually provided from an uncontrolled bleed in which the bleed pressure varies in proportion to the downstream flow, and the flow varies as the load fluctuates. This pressure variation can be overcome by designing the bleed at a pressure higher than required to allow for these fluctuations.

Controlled extraction turbines provide steam at a constant pressure by having one or more valves part way down the machine to control the flow to the low-pressure section of the turbine. The turbine governor monitors and controls the extraction steam pressure.

Efficiency and availability considerations

The steam turbine designer must take into account the following:

- efficiency
- availability
- ease of maintenance
- economy of manufacture.

A 5 MW turbine-generator will be a very different in concept as well as size from a 500 MW set. To maximize efficiency, a 500 MW set will:

- be coupled directly to the generator
- have one high-pressure, one intermediate-pressure and two low-pressure cylinders, with reheat between the high and intermediate pressures
- have several extractions for feed-heating.

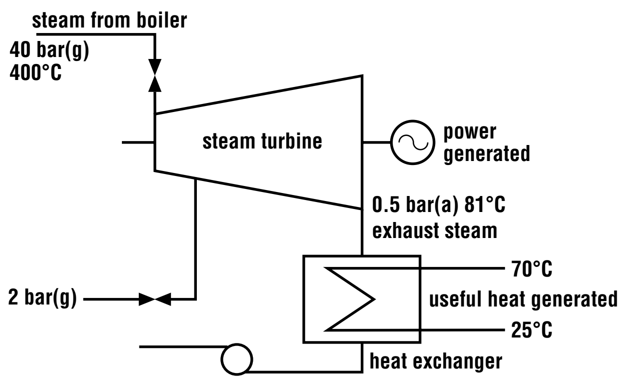


FIGURE 5. Typical turbine arrangement for CHP

MSW – an opportunity to be seized. PHOTO: ISWA

Such complexity is impractical and uneconomic for a 5 MW turbine. For an EfW facility, it is also important to design all the components with a wide operating range. A steam turbine principally designed for utility power application may not provide optimum availability when used with the inevitably varying steam flow from an EfW plant.

It is very easy to follow the route to maximum efficiency at the expense of both practicality and overall cost. Developers of EfW plants should involve both the boiler designer and the steam turbine designer at an early stage, as changes to steam turbine design parameters may have an impact on the boiler and vice versa.

Steam is most commonly used for electricity generation

Steam turbines are designed with certain basic frame sizes. If steam or power parameters require a turbine frame that is at the bottom of its range, the equipment will have a considerably higher specific cost than if the top end of a frame size can be used. Only by a site-specific study can the system and its key equipment components be optimized and thus economic viability determined.

Conclusions

The problems associated with energy recovery in EfW plants can be minimized and controlled by consistent application of the knowledge and experience that have evolved regarding their design and operation. To maximize its viability, it is necessary to consider fully all aspects of equipment design, plant operation and potential revenue streams at the earliest stage of a project. Any of the many aspects to be considered could cause a project to fail, so it is wise to involve experts early on – and preferably those who are not promoting a particular technology.

For the steam generator, the optimum operating parameters are a maximum of 40 bar steam pressure and 400°C steam temperature. While higher pressures and temperatures improve system efficiency, the anticipated economic benefits should be evaluated against the increase in maintenance costs. It is essential to ensure that the design and quality of all steam/water cycle components are optimized both individually and as a whole system, and that their design is appropriate for an EfW facility. If they are not, its life, reliability and/or availability may be disappointingly poor. If they are appropriately designed and optimized, overall plant availability need not be adversely affected by the energy recovery equipment.

For the steam use, there are many options besides power generation alone. A full analysis of these may bring two commercial benefits: increased plant efficiency and an additional revenue stream.

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