HEFAT2008
6th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
30 June to 2 July 2008
Pretoria, South Africa
Paper number: K9

EFFECTIVE UTILIZATION OF HEAT IN WASTE AND BIOMASS PROCESSING

P. Stehlík.
Institute of Process and Environmental Engineering
Brno University of Technology,
Brno, 616 69,
Czech Republic,
E-mail: stehlik@fme.vutbr.cz

ABSTRACT

Effective utilization of heat in thermal processing of waste and biomass plays an important role since it contributes to environmental and economic optimization of the processes and equipment. In case of utilizing energy released during thermal oxidization (incineration) of municipal solid waste (MSW) or of hazardous waste for generation of process steam or for co-generation (combined heat and power systems - CHP) we can consider the thermal processing as a certain kind of recycling. Since waste has sufficient heating value, it belongs to renewable energy sources which enable to save fossil fuel as a primary energy source. Then we speak about waste to energy systems (WTE). In addition to environmental benefit, effective utilization of released energy has a positive impact on economics of the process including reduced operating costs. WTE can partially or completely compensate costs of waste treatment (costs of auxiliary fuel for incineration of low calorific industrial and/or hazardous waste) and it can even bring profit to the operator in case of waste with high calorific value.

Typical examples of units for the thermal processing of both MSW and hazardous waste are shown with the objective to evaluate main factors influencing energy balance of the processes, while taking into account various regimes of operation. Basic rules of selection of the systems for efficient heat utilization including CHP are summarized and illustrated on concrete industrial examples. Conventional methods of energy availability are discussed and analyzed. Heat flows in the incineration plant are evaluated as well as factors like plant efficiency and/or energy utilization rate.

A novel and original technology for combustion of various types of biomass and fytomass consisting of a feeding system, boiler, heat recovery system and flue gas cleaning system (in case of contaminated biomass) is presented.

Moreover, it is necessary to take into account specific features of flue gas (and/or off-gas) as a process fluid. For an optimum design of heat exchangers as equipment and integrated items it is necessary to follow a top-down approach "process – heat recovery system – heat exchanger" while respecting specific features of the concerned process. A combination of intuitive design, know how and sophisticated approach based on up-to-date computational tools with emphasis on computational fluid dynamics (CFD) is shown in the paper.

After selecting a convenient process for the given type of waste and/or biomass, the available energy for heat recovery is evaluated and a heat recovery system is designed. Novel design of air pre-heaters, heat recovery steam generators and special heat exchangers (e.g. those for sludge pre-heating) is shown. This approach always respects the primary role of the process, while stressing also the importance of analysis aimed at selection of heat exchangers and their design including specific features and fouling problems.

INTRODUCTION

Heat recovery in units for the thermal processing of various types of waste i.e. waste to energy systems as well as in those for biomass combustion can be without any doubt considered as one of the most important parts of these processes. Design of equipment for utilization of energy contained in flue gas (and/or off-gas) from the thermal treatment of waste i.e. incineration and the placement in the process is one of key factors in these technologies. Heat recovery represents one of subsystems which enables to consider incinerators not only as units for the treatment of waste but as energy sources. This is generally supported in valid environmental regulation within European Union. In the design and operation of heat recovery systems it is necessary to take into account the characteristics of heat transfer equipment and/or heat exchangers and their specific features as well as those of process fluids.

A unit for the thermal processing of waste has primarily to be considered as a process. This is the first step in plant design (see Figure 1) based on selecting an optimum technology using heat and mass balance calculations. In the second step we can divide the process into subsystems like the combustion chamber (kiln), heat recovery system and off-gas cleaning system and optimize these subsystems. Heat recovery subsystem usually consists of air pre-heaters, heat recovery steam generators (HRSG) or various types of heaters. In some cases HRSG can be substituted by heat exchangers with heating fluids (e.g. thermo-oil). Only afterwards we can make the third step and design those pieces of equipment.

Optimum design of both the equipment and the process is a combination of intuitive design, know how, practical experience and sophisticated approach based on modeling, simulation and CFD approach.

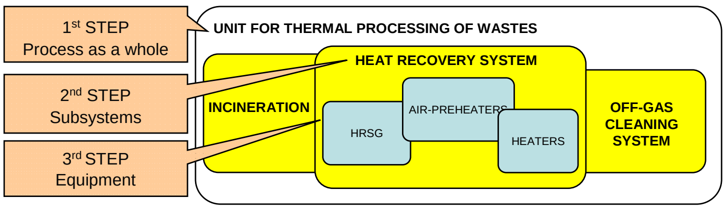


Figure 1 Hierarchy in design of unit for thermal processing of waste

Specific features of process fluid

Combustion of waste (incineration) produces both gas products and solid residues. Solid residues are divided into ash (slag, cinder and/or sinter) and fly-ash. Off-gas from waste incineration is a multi-component mixture of chemical species. It contains harmless components like nitrogen, carbon dioxide and water vapor, but also harmful components like nitrogen oxides and sulfur oxides, carbon monoxide, hydrogen chloride and fluoride, dust, heavy metals and their chemical compounds, phosphoric compounds and organic compounds like hydrocarbons. Note that harmful compounds of acid character are present in the gas phase. Hydrogen chloride produced by thermal decomposition of chlorinated plastics is the dominating acid gas. Sulfur dioxide, heavy metals (Cd, Hg, Cr, Zn, Cu, Pb) and dust also belong among the main harmful pollutants. Further to that, the group of persistent organic pollutants (POP), like polycyclic aromatic hydrocarbons (PAH), polychlorinated biphenyls (PCB) and polychlorinated dibenzodioxins and dibenzofurans (PCDD/F) are extremely harmful compounds contained in emissions. However, the most important primary criterion of combustion efficiency is given by CO and NO_x concentrations.

From the characteristic features of off-gas described above it follows that the off-gas composition and properties differ significantly from those of flue gas in conventional combustion chambers, furnaces, boilers etc. Therefore in units for the thermal processing of waste it is necessary to apply a specific arrangement. Fouling obviously represents a serious problem.

HEAT RECOVERY IN THERMAL PROCESSING OF WASTE AND BIOMASS

Waste incineration in up-to-date facilities is a complex process. From the time when first incineration plants were put into operation, the technologies have undergone a large progress. They have developed from simple units designed only for waste disposal into complex systems, where waste is thermally destroyed and energy is efficiently utilized, while the negative impact on the environment is minimized. Waste processing is described in many papers and monographs (e.g. [1-3])

Let us only briefly mention typical waste processing technologies according to the waste type and origin, namely municipal solid waste incinerators (MSWI) and hazardous waste incinerators (HWI).

Municipal solid waste incineration

A typical unit for municipal solid waste (MSW) incineration is displayed schematically in Figure 2. Waste incineration is performed in a combustion chamber equipped with a moving grate and followed by a secondary combustion chamber (SCC) under temperatures ranging between 850 and 1000°C. The heat released in this process is utilised in a heat recovery steam generator (HRSG), most often for the production of superheated steam. The flue gas is cooled down to approximately 250 to 280°C in the boiler together, while separating a major part of fine fly ash particles (carried by flue gas from the combustion chamber). Mechanical cleaning of flue gas that collects the remaining particulates is performed in electrostatic precipitator (ESP).

A part of flue gas (and/or off-gas in terms of incineration terminology) leaving this equipment may be recycled back to the combustion chamber. This is a feature of up to date incinerators since recycling contributes to decreasing exhaust emissions. Thus based on the lower off-gas flow rate, size of equipment forming the final part of the off-gas cleaning system is decreased as well. The remaining part of flue gas enters the off-gas cleaning system, comprising a wet scrubber, and a system for final gas cleaning. This step may include the catalytic reduction of nitrogen oxides (SCR) and destruction or removing the persistent organic pollutants (POP), especially polychlorinated dibenzodioxins and dibenzofurans (PCDD/F). Our experience shows that a very efficient way for the destruction of dioxins and furans is catalytic filtration in a dioxin filter.

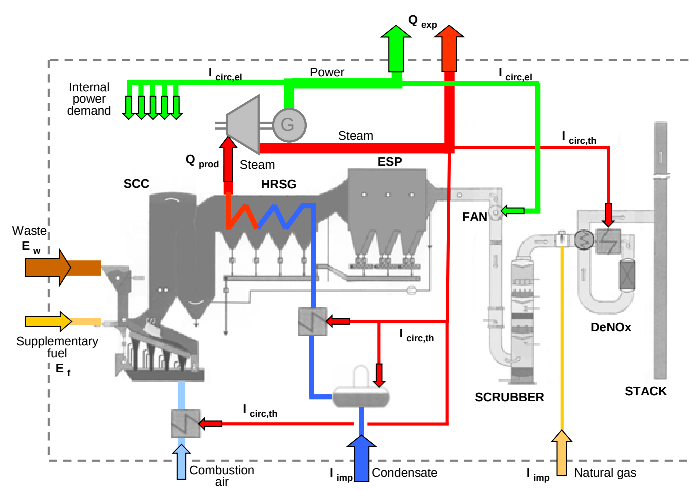


Figure 2 Main energy streams in case of municipal solid waste incineration

Hazardous waste incineration

In order to achieve a perfect combustion in thermal treatment of industrial and hazardous waste, two-stage incineration is the most common approach. A typical arrangement of unit for the thermal treatment of solid and liquid waste is shown in Figure 3.

Rotary kiln is usually used in the first stage of incineration. Combustible portion of the waste burns in oxidizing atmosphere and the heat releasing process is virtually completed in the kiln. Thermal decomposition and oxidation of harmful compounds however continues in the secondary combustion (after-burner) chamber, where temperature of flue gas is increased to the required level by means of burners firing auxiliary (gaseous) fuel.

Cooling of flue gas is partially carried out in the air pre-heater, and particularly in the waste heat boiler and/or heat recovery steam generator (HRSG). Steam can be used for the incineration plant itself, for power generation, heating purposes etc.

Cooled off-gas is mechanically and chemically cleaned so that fine solid particles and harmful products of the thermal decomposition (namely HCl, sulphur oxides, emissions of heavy metals etc.) are removed down to levels required by emission regulations.

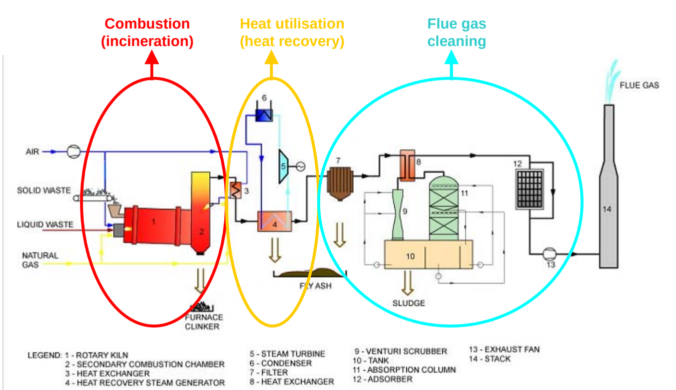


Figure 3 Typical configuration of industrial waste incinerator with rotary kiln

Apart from this common technology we can meet with a number of other special incinerators. An example is an incineration plant of industrial and hazardous waste discussed in [4].

Rules for the design of efficient WTE systems

It can be stated that in most of the applied technologies there is a number of similar items. It can be clearly seen that the above described MSW and IHW incinerators differ only by the thermal system – the remaining parts are more or less identical. However, in most cases it is necessary to "hand-tailor" the technology from case to case. These specific features as well as different position of every piece of equipment integrated within the technology have strong influence on the process energy demand and the way of energy utilization, which is performed in the heat recovery system. The more and more sweeping environmental limits mean that the number of devices (not just in the off-gas cleaning systems) is rising. Energy demand increases (power for fan driving, plant heating up to the operating temperature during start-up, etc.). The integration of every single apparatus in the unit thus becomes increasingly important. For better understanding to the highly efficient waste to energy systems it is vital to analyze heat fluxes in the unit (see Figure 2).

Regarding energy distribution it is obvious that heat recovery system represents the "heart" of the unit, i.e. the place where energy is produced (usually in the form of steam) and afterwards supplied as circulated energy (I_{circ}) for on-site consumption or exported (Qexp) to other consumers. Therefore sophisticated design of heat recovery systems plays a key role.

To compare the effectiveness of energy production in different incineration plants several criteria have been developed by several institutions [5-7]. Their names are very similar – plant efficiency factor, plant efficiency, energy efficiency, energy utilization rate. Their common feature is their purpose – to describe the relationship between energy outputs (produced or exported energy) on one side and energy demand on the other.

As an example the criterion called Plant Efficiency Factor defined in the CEWEP can be used. It defines the ratio between energy produced by incinerating the waste and energy consumed by the process itself:

$$Pl_{ef} = \frac{Q_{prod} - (E_f + I_{imp})}{E_f + I_{imp} + I_{circ}}.$$

The meaning of particular symbols is evident from Figure 2. A comparison of the efficiency of energy utilization according to this criterion gives [8]. In this comparative study were included 97 European waste-to energy units. The resulting weighted average, which accounts not only for the number of the incinerators but also heating value of the waste and the plant capacity is 4.08 , with minimum value of 0.04 and maximum equal to 21.08. The threshold (minimum) value that identifies a plant as a waste-to-energy system is set at 1.0.

The basic rule for efficient operation of a process with a high degree of energy utilization is based on the principle of self sufficiency and may be formulated as follows: **To minimize the amount of imported energy while maximizing the amount of exported energy.**

Concrete ways of achieving this objective are summarized below:

1. Process optimization and the selection of technology aiming to decrease or to completely eliminate consumption of external imported energy, which is however generally hard to be substituted by energy generated in the heat utilization section. This concerns mainly additional fuel (E_f) consumed in secondary combustion chamber.

   The combustion system has to be designed and operated in a way that minimizes the temperature of gaseous products downstream the last air inlet. This temperature is specified by regulatory limits and differs according to the type of combusted waste (see Table 1).

Type of waste	Required temperature T_{min} [°C]
Hazardous waste containing more than 1 % of halogenated organic substances	1,100
Other waste	850

Table 1 *Minimum temperature required in combustion chamber [9]*

If heat released by waste combustion is not sufficient to meet the threshold temperature, additional energy has to be supplied into the system (pre-heating of combustion air I_{circ}, possibly combustion of auxiliary fuel E_f). This situation occurs usually during combustion of low-caloric waste which is for example industrial sludge and waste water treatment sludge [3].

2. Identification of energy-saving measures leading to the decrease of energy consumption directly in the process. This consumption is covered by the so-called circulating energy (I_{circ}) and in case of need also by imported energy (I_{imp}).

   One of the possibilities is the efficient utilization of waste heat and low-grade heat. Widely used, simple and popular tool that allows to analyze energy flows inside the process and to identify the ways of maximum waste heat utilization is Pinch analysis. The results must however always be checked for realizability constraints of technological and space nature.
3. Design of the heat utilization section in a way that secures internal plant energy requirements while maximizing energy export. Example using an air preheater is provided in the following chapter.
4. The highest degree of energy utilization is achieved by applying the cogeneration approach, i.e. production of heat and electricity. Systems with a steam turbine are the most frequently used methods of excess steam utilization for heat or power production. However it is possible to design various combinations and arrangements for specific applications with the aim of maximum energy utilization.
5. The highest efficiency expressed in saving of primary energy sources is reached when backpressure turbine is applied. In this case all the steam going through the turbine and used for power generation is then utilized for heating purposes, which results in higher efficiency. However the disadvantage of this system is the direct dependence of the incinerator on the grid conditions, to which steam is distributed. Suitable consumers of heat for this application are for example industrial processes with steady heat consumption.
6. When stable demand for heat throughout the year is not secured, the owner must seek other solutions. A very flexible solution for such unsteady heat consumption is application of bleeding condensing turbine, where excess steam is utilized for power production. The turbine can then accommodate varying demand for heat by working either in backpressure mode or condensing mode.
7. However the consequences of so-called summer operation mode with a reduced heat output and increased power output on plant performance is evident - the efficiency of the cycle as well as primary energy savings are considerably lower.
8. When the structure of heat consumers allows it, it is advantageous to perform expansion in the turbine with minimized outlet pressure and to export the steam of the lowest possible grade, or to export hot water.

   Lower grade of the exported steam enables to increase the enthalpy gradient in the turbine and so to achieve maximized electrical power output. Similar effect is obtained by decreasing pressure losses of the steam system after the turbine.
9. When the steam bleeding from the turbine matches internal energy consumption, it is important to check parameters of the low-pressure steam, whether they are sufficient for heating of internal flows (e.g. air preheating). When the required steam parameters are higher than the threshold values of steam for export, it is advantageous to consider a turbine with several bleeding stages. The application of a by-pass for these purposes may negatively influence the energy utilization rate.
10. In the absence of heat consumers, it is necessary to generate only electricity and to waste the remaining heat in a condenser. The efficiency of electricity generation is however relatively low even though several approaches are available to increase it (heat regeneration, re-heating of steam etc.).

Biomass combustion

A considerable decrease of greenhouse gases (GHG) released to the atmosphere is not possible without a substitution of fossil fuels by renewables. Biomass has the largest potential from all the presently available renewable energy sources.

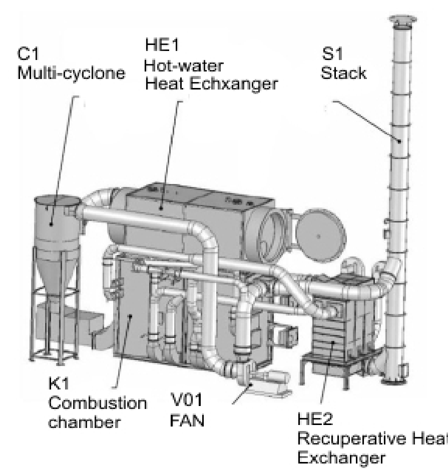


Figure 4 Novel technology for biomass combustion

Figure 4 shows a realistic model of a technology for combustion of various types of biomass and phytomass. In spite of the fact that similar technologies are commonly used it is necessary (like in the case of incinerators' heat recovery systems – e.g. flue gas recycle, air pre-heating) to solve heat transfer problems. In this case the heat exchanger for air preheating represents the main concern because its design has to be resistant to fouling caused by tarry products on flue gas side.

Characteristic features of the developed prototype unit are as follows:

- An effort to integrate field proven state-of-the-art technologies into one unit. This includes measures contributing to high performance and operation flexibility (e.g. flue gas recirculation or air preheating).
- The possibility to combust various types of biomass from saw dust and wood chips to fast-growing energy crops (e.g. amaranth). Naturally, not all types of fuel can be processed in one unit. Especially straw fuels require a different boiler design or co-firing in a mixture.

The fuel feeding system consists of two separate paths for wooden biomass and for phytomass. The combustion process takes place on an inclined hydraulic grate and is completed in a secondary combustion chamber. The products of combustion then flow through a tube bundle in the heat exchange section of the boiler (HE1 in Figure 4). The fly ash contained in the gas is removed in the multi-cyclone (C1). Induced draft fan is situated downstream the multi-cyclone (V01) and it is the only driving equipment of the flue gas stream from the combustion chamber to the stack (S1). Controlled amount of flue gas is extracted in a splitter situated downstream of the fan. Using this recycled stream, part of the flue gas is brought back to the combustion chamber. The rest of flue gas continues to special recuperative heat exchanger "flue gas – air" (HE2), where its sensible heat is used for preheating primary and secondary combustion air. The aim is to cool down the flue gas as much as possible and thus eliminate the stack losses. On the other hand, excessive fouling caused by condensation of tarry compounds has to be avoided. Flue gas cooled in the exchanger than goes to the stack (S1).

Specific systems

A typical problem concerning design of heat exchangers in the field of biomass processing is given by the fact that most applications are custom-made and therefore we face demand for specific types of equipment. One such application is demonstrated below. There is shown a special compact unit for the thermal processing of gas waste consisting of a combustion chamber placed inside heat exchanger. Heat recovery requires new ideas for optimum design of heat exchangers, discussed in the following chapter.

HEAT EXCHANGERS AS EQUIPMENT AND INTEGRATED ITEMS

The processes displayed in Figures 2 to 4 show subsystems for heat recovery and waste heat utilization. The pieces of equipment where heat transfer plays a predominant role include: air pre-heater, HRSG and condenser in the steam turbine system.

Other applications in different technologies include e.g. utilization of waste as alternative fuel in cement or lime production. In that case, heat exchanger "off-gas/oil" can be inserted into the existing technology with the aim to utilize waste heat from cement works for drying of sewage sludge (from waste water treatment plants, WWTP) that may be used as alternative fuel. Case study published in [11] has analyzed the potential of such heat-exchanger application.

Air pre-heaters

Air preheating is the most frequently used method of heat utilization for internal plant consumption. It includes

- Preheating of primary air brought to under the grate with the aim to enhance combustion processes
- Preheating of combustion air for burners installed in the secondary combustion chamber which leads to fuel consumption reduction.

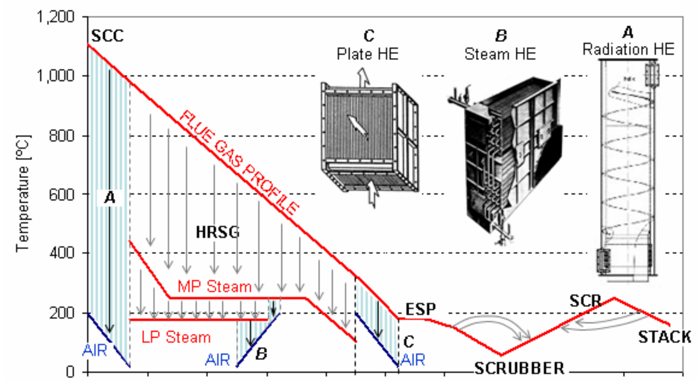


Figure 5 Typical temperature profiles, heat transfer between hot and cold streams and feasible integration of air-preheaters in waste processing technology

The required amount of heat in the air preheater (circulated energy I_{cicr}) is the result of heat and mass balance calculations of the whole process as well as single pieces of equipment. A number of possible solutions can be applied (see Figure 5). When making the final decision it is necessary to respect the main technological parameters related to the process and to the heat transfer equipment (e.g. temperature of flue gas leaving the thermal system, target temperature of air preheating, flue gas temperature at the HRSG outlet, amount of produced steam, parameters over the turbine). Each technique has its advantages as well as weak points.

- Usually the air preheating exchanger is placed downstream the waste heat boiler (heat recovery steam generator, HRSG), i.e. where combustion gases lost most of their heat. However, the temperature of hot stream (in this case flue gas) has to be sufficient for the target temperature of air (to ensure adequate temperature gradient). Conventional types of plate heat exchangers can be used and optimized with the help of optimization procedures [12].
- In some cases it is more advantageous to break thermodynamic principles and place the exchanger upstream the heat recovery steam generator. In technologies for industrial and hazardous waste incineration, raw combustion gases leaving the combustion chamber have a characteristically high temperature, which often exceeds 1000°C, at which temperature they contain melted and sticky fly ash. In such cases, solution may be a radiant air preheater.

Off-gases are there cooled down and partly cleaned of solids at the same time, which eliminates the otherwise excessive fouling on boiler walls, thus leading to a reduction in heat transfer, reduced boiler output and increased frequency of shut-downs.

- Heating by steam. In cogeneration systems, where low pressure steam is taken from the turbine outlet, it can be used advantageously to serve for air preheating. This solution maximizes power production. If steam parameters are too low, it is necessary to by-pass the turbine and utilize steam directly from the boiler. Combination of afore mentioned, i.e. initial heating by low-pressure (LP) steam and final heating by higher-grade steam from the by-pass is possible in specific cases (e.g. in Figure 5 MP, medium-pressure steam).

Air-preheating of combustion air in a biomass-unit

The following example shows a dedicated recuperative heat exchanger designed for air preheating in an experimental unit for biomass utilization for energy production. This device ensures high efficiency of the process. The objective is to cool down the flue gas as much as possible and thus eliminate the stack losses. On the other hand excessive fouling caused by condensation of tarry compounds has to be avoided. These influences can be minimized by a suitable design of all parts. The flow among the tubes as well as inside them has been investigated with the help of modeling by computational fluid dynamics (see Figure 6).

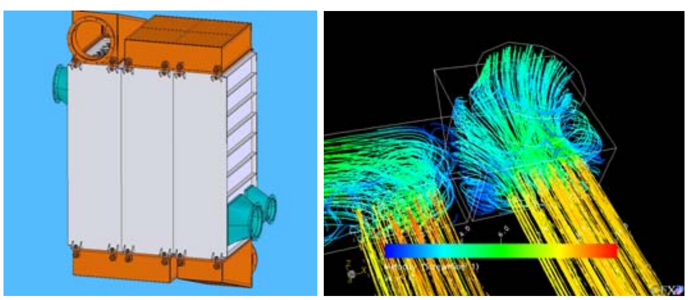


Figure 6 Illustration of computational support in the modeling of inlet and outlet chambers of a recuperative heat exchanger

Waste heat boilers and heaters

Selection of a convenient type of heat recovery steam generator (HRSG) depends on operating conditions and capacity of incinerator (throughput of waste). In case of flue gas with high propensity to fouling it is better to use a fire-tube boiler which provides easy access for a mechanical cleaning. Fire-tube HRSGs are also preferred for incinerators with lower throughput of waste (approximately of 0.5t/h and less). When production of steam is not required, then this equipment actually represents a heat exchanger like e.g. that in Figure 7 (details of its application will be described later). This heat exchanger is provided with a bellows compensator in a shell for compensating thermal expansion.

Figure 7 Industrial fire-tube exchanger

For incinerators with higher waste treatment capacity, conventional water-tube HRSG (see e.g. [13]) are used. However, various types and arrangements are preferred in industrial practice - depending on the specific application and know-how [7]. For a preliminary design and simulation calculations of HRSGs, consisting of several sections (superheater, evaporator and economizer) a computational tool has been developed as reported by [14]. This tool enables versatile and fast preliminary design of boiler temperature profile and its basic geometrical characteristics.

Specific applications

As described in section 2 a novel design of heat exchangers is necessary in some cases. Let us demonstrate it on a process of waste to energy where sludge coming from waste water treatment plants (WWTP) is disposed and at the same time used as a fuel.

A potential application of heat exchangers in sludge utilization for power production is in flue gas stream after the sludge utilization technology. Energy contained in the flue gas produced by combustion of WWTP sludge may be used to pre-heat the sludge before de-watering. The underlying idea consists in assumption that preheating sludge before de-watering may increase the attainable water extraction rate. The expected improved de-watering of sludge would provide a more profitable energy balance of the combustion process, possibly even self-sustained sludge combustion. Schematic drawing of this technology is shown in Figure 8.

For the research and development of a new type of heat exchganger it is necessary to select a convenient procedure. In the first phase there has been proposed a special heat exchanger “water-sludge” (see Figure 9), the concept of which is based on two counter-current helical channels with rectangular cross-section. Equations for thermal and hydraulic calculation will be obtained by corrections applied to plate-type heat exchanger, validated on a pilot-scale model. The experimental heat exchanger will also serve in the investigation of sludge de-watering temperature dependence. Should the investigation confirm the expected positive influence of increased temperature on sludge de-watering efficiency, a new heat exchanger “flue-gas – sludge” will be implemented.

The main difference between the two systems (“water-sludge” and “flue-gas – sludge”) is the heat capacity of the heat carrier medium. Other changes include different flow velocities and fluid properties. Due to that it is necessary to consider modifications to the heat exchanger design. The main two advantages of the proposed design are simple geometry, enabling easy cleaning of heat-exchange surfaces and low pressure drop for sludge pumping. The sludge contains approximately 5 % of dry matter and will thus flow easily through the helix. Therefore sludge transport will require low investment and operating costs (we can avoid using sludge pump).

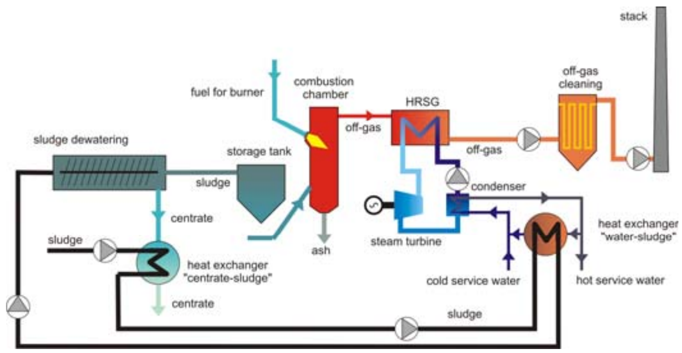


Figure 8 Process for thermal treatment of sludge with utilization of off-gas heat

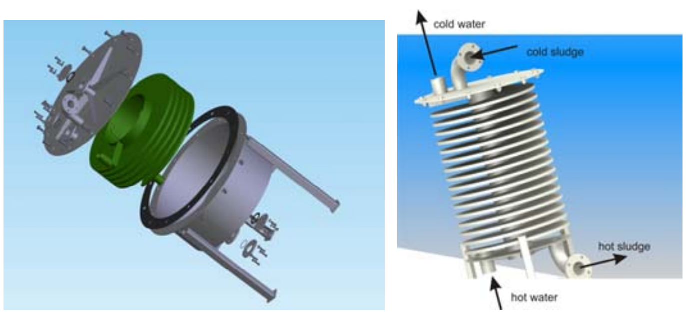


Figure 9 Heat exchanger "water-sludge"

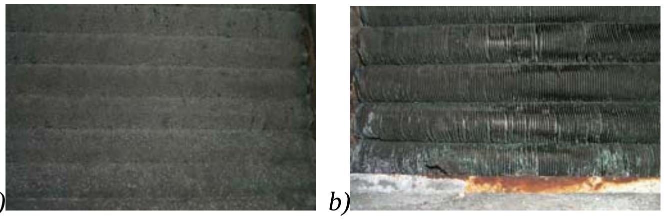
Fouling in heat recovery systems for the thermal treatment of wastes applications

Fouling represents a very important and complex problem in waste and biomass processing applications. Fouling of a surface takes place as a result of the complex processes (mechanisms) that cause deposits to form on process surfaces. A quite large number of parameters influence development of fouling, including: flow velocity, surface temperature, exposed surface material/finish, surface geometry and fluid properties [15]. Based on results of numerous present research studies, fouling can be classified according to the principal process: precipitation fouling, particulate fouling, chemical reaction fouling, corrosion fouling, bio-fouling, freezing fouling, and crystallization. In most thermal treatment of wastes applications, more than one type of fouling will occur simultaneously. Moreover, the form and structure of a fouling deposit is influenced by type of burned fuel and incinerated waste. Generally the most troublesome deposits are formed when solid or liquid type of waste and fuel are processed. Deposit thickness is difficult to predict, however, thickness is extremely important in determining density and distribution of the various constituents in the deposit.

Various reviews have been attempted describing the attachment/formation process, however this is still not a very well understood process in industrial applications of thermal treatment of wastes. First results of our current research show that it is possible to develop mathematical models, based on broadly recognized method of balance of forces acting on an elementary particle. Moreover, the model considers that particle is drifted by flue gas and getting in the contact with heat transfer area. Developed model allows determining so called critical flow velocity, strictly speaking the theoretically determined minimum flow velocity that avoids particulate fouling (particles with given size). Obtained results were compared with experimental data obtained from worldwide available literature and very good agreement was found. Mathematical model is suitable for preliminary analyzing of fouling tendency and also for prevention in design and operation of tubular heat transfer equipment. Designer obtains from results of the model clear idea about interdependence between heat exchanger arrangement and fouling propensity. Thus, complex evaluation of optimum tubular heat transfer equipment with respect to fouling, requires technical-economic optimization taking into account investment, operating and maintenance cost and based on the character and constitution of deposit.

If fouling cannot be prevented, it is necessary to make some provisions for periodical removal of deposits. The removal of created deposit involves a combination of dissolution, erosion or spalling of the deposited material. On some heat transfer equipment (for example different types of tube banks placed in flue gas channels) in thermal treatment plant can be applied several methods of surface cleaning for deposits removal during equipment operation ("on-line" cleaning), like for example soot blowers. However, frequently removal of fouling deposits cannot be performed online and fouling formation can be controlled only by adhering to proper operating conditions. In such case the periodical removal of deposits when equipment is shut down is the only possible way. Periodic cleaning removes deposits by chemical or mechanical means. Mechanical methods include steam, high-pressure jets, brushes or water guns. Chemical cleaning is designed to dissolve deposits by a chemical reaction with the cleaning fluid. Hardly accessible areas may be cleaned using this method. Mechanical methods of cleaning are expensive and also tend to erode the heat transfer surface.

It is often noted in boiler-related literature that 2mm deposit will effectively increase fuel consumption by approximately 5%. Thus, because fouling is very important problem in heat transfer equipment placed in thermal waste treatment applications, it is necessary to use only smooth surfaces for the heat transfer areas. Such configurations allow easy cleaning on both outer and inner heat transfer surfaces. This restriction strongly limits possible configurations of heat transfer equipment. Any offence against this constraint can lead to large losses. Figure 10 demonstrates unsuitable application of extended surface (finned tube bank) in heat transfer equipment.



a) b)

Figure 10 Fouled (a) and cleaned (b) finned tube bank

COMPUTATIONAL SUPPORT FOR EQUIPMENT DESIGN AND OPERATION

Improved or even optimum design of heat exchangers can be obtained most conveniently through a sophisticated approach based on simulations and modelling. Computational support in this sense may be divided into the following areas: (i) simulation based on energy and mass balance, (ii) thermal and hydraulic calculation of heat exchangers, (iii) computational fluid dynamics (CFD) approach, (iv) optimization, and (v) heat integration.

Simulation (energy and mass balance)

Design of equipment for heat exchange typically consists of the following steps: mass and energy balances, preliminary design, and detailed design.

The first step (process heat and mass balance calculations) is necessary for evaluation of all process parameters for further calculation of heat exchangers (values of process fluids' temperatures, flow rates, properties etc.). Various software packages for simulation exist, however, for special areas like thermal processing of waste including energy utilization a creation of own software packages proved to be the preferable solution. Currently there is an ongoing development of a new integrated simulation system WTE (Waste-to-Energy), first introduced by Pavlas et al. in [16], which takes up on the TDW system see [17, 4]. Besides plant design support in the area of waste and biomass utilization, the WTE system enables also a complex evaluation (i.e. economic and environmental analysis) of a given problem with the objective of maximum waste heat utilization.

Thermal and hydraulic calculations

A wide range of existing heat exchangers can be used for various purposes. Let us focus on the field of thermal processing of waste and waste to energy systems.

When the character of application allows it, it is preferable to use conventional shell-and-tube heat exchangers or compact (plate type) heat exchangers. Manufacturers mostly have at their disposal a commercial software package (e.g. HTRI or HTFS) enabling reliable design calculations of those heat exchanger types.

However, in real applications of units for the thermal treatment of waste, it frequently is necessary to design special types of heat exchangers for which no reliable design methods exist. It is the responsibility of the general contractor to provide manufacturers with detailed documentation. Such custom-made designs have to be carefully investigated and new design calculation methods must be developed. An example of solution approach in such kind of problem is shown in the next chapter.

A correct selection of convenient type of heat exchanger is important especially in case of so called hot gas applications especially in the case of heat recovery system in waste processing units. Energy contained in the flue gas is utilized for air pre-heating, steam generation, water heating or technological purposes. Without taking into account specific features of the process fluids, serious operation problems can occur (e.g. excessive fouling, damage caused by thermal expansion). These and other reasons gave impetus to the development of a multi-purpose computational system with a database for hot gas applications (HGA) where data concerning both the common and specific types of heat exchangers are collected. Conventional heat exchangers are preferred; however in some cases there it is profitable to propose a new type of heat exchanger [18, 19].

Characteristics of the HGA approach are as follows:

– Use of elimination strategy based on AHP method [20] for selection of potential candidates in the first stage, based on main process characteristics (process fluids, temperatures, pressures, fouling propensities etc.). Screenshot of the HGA database software enabling selection of candidate heat exchanger type is presented in Figure 11.

– Simplified preliminary design calculations to narrow the range of possible solutions.

– Preliminary rough estimate of investment and operational costs and selection of optimum candidate.

– Final design check and summary of design data, required for making enquiries to heat exchanger manufacturers or alternatively to design of a new type of heat exchanger.

– Modules for selecting, costing and design/rating calculations of heat exchangers are independent and can be used separately, based on actual requirements of the designer.

– HGA database is an open system prepared for further extensions.

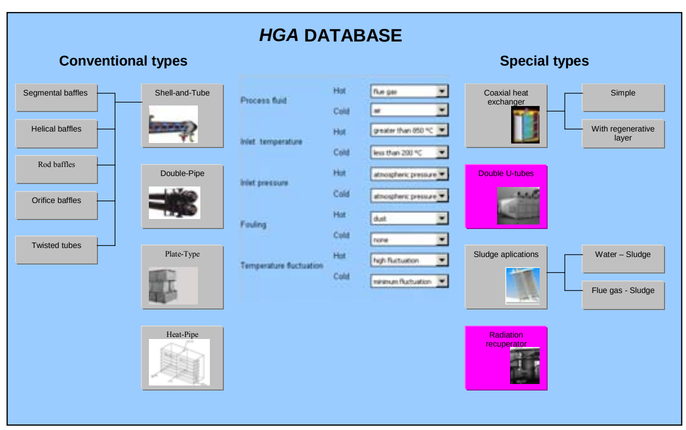


Figure 11 Main window of HGA database for selection of suitable heat exchanger type

CFD approach

Simulations of fluid flow and heat transfer in various pieces of equipment within waste-to-energy plants may provide very useful information both in the design phase and in troubleshooting. The CFD methodology itself is a very broad field so here we rather focus on a recent specific application, relevant to the topic of the present paper. The main candidates for CFD modeling among devices in thermal waste treatment units include secondary combustion chamber, flue gas ducts, low-NO_x burners, filters, wet scrubbers and heat exchangers. In the following we briefly present a case study related to a heat recovery system.

Flue gas duct optimization

Uniformity of flow across tube banks and/or bundles is a common objective in many heat exchanger applications. Methods of computational fluid dynamics are well-suited for studying the flow inside of an exhaust duct of a waste sludge incineration plant (see Figure 12). The flow pattern in this duct leads to fouling in a connected heat exchanger. CFD analysis is used to find what causes the fouling and to optimize the duct design in order to eliminate the undesirable phenomena.

Previous work on this application has been performed using software STAR-CD (product of CD-adapco Group), as documented by Hájek et al. [21]. The analysis has been however recently re-simulated in FLUENT (product of ANSYS, Inc.) software and the optimization has been taken one more step further, using a geometry optimization software SCULPTOR (product of Optimal Solutions Software, LLC), coupled with FLUENT. This enabled a rigorous optimization of geometry that has been previously identified by an intuitive trial-and-error approach. The number of degrees of freedom thus could have been increased as compared to the manual approach.

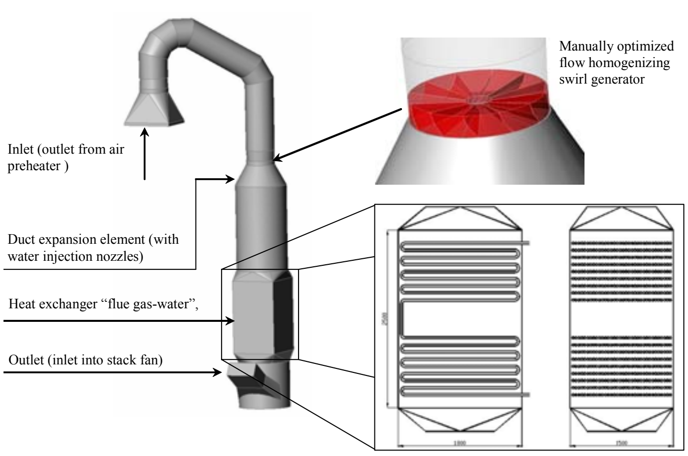


Figure 12 Geometry of exhaust duct with heat exchanger

To briefly introduce the previous results, let us firstly inspect the overall geometry and setup in Figure 12. Based on experience from operation and complex analyses it was decided to install a convenient water-tube heat exchanger instead of the fire-tube one. The previous work has focused on several flow homogenizing measures in the form of vanes and swirl generators. Figure 12 shows the selected insert as well as its location in the overall duct geometry. It is a swirl generator, which produced the best results of all considered alternatives.

Alternative designs were compared using two objective functions, based on the distribution of velocity magnitude in a horizontal cross-section of the duct located just above the heat exchanger. The first measure of flow homogeneity was defined as ratio of minimum to maximum velocity in the reference cross-section. The second measure was the maximum velocity magnitude in the same cross-section. Both objective functions however led to the same optimum.

Examples of the geometry modifications performed during the automatic re-shaping optimization process are displayed in Figure 13. The optimization process is controlled by the SCULPTOR code, which performs re-shaping of the concerned geometry and of the computational grid, calls the CFD solver FLUENT and after receiving results of the simulation, evaluates the objective function.

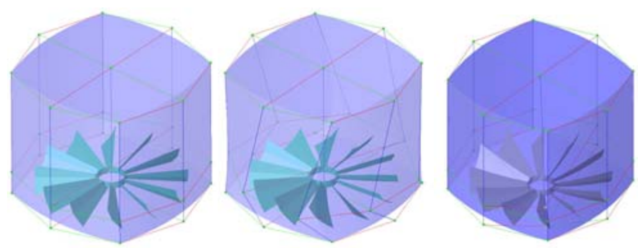


Figure 13 Original swirl generator and two examples of geometrical modifications (from left to right)

An improvement of about 10% in terms of maximum velocity magnitude has been obtained with the automatic optimization approach. The analysis has been recently described in more detail in [22].

Optimization of plate type air pre-heater

Plate type air pre-heaters [23, 24] are widely used in WTE applications.

The design of these heat exchangers is usually realized with the aid of CAD methods using either commercial software packages available at the market or in-house software products. However, the final solution (even if technically correct) can be sometimes far from the optimum design. It was found that the heat exchanger configuration and geometry significantly influences capital cost and operating costs of heat exchangers [25, 26].

Since the costs of heat exchangers represent an important issue [26, 27], a new optimization algorithm was developed with the aim to achieve minimum total annual cost of air pre-heaters [12]. Pressure drop and heat transfer are interdependent and both of them strongly influence capital and operating costs of any heat transfer system. During the design process of a heat exchanger it is necessary to determine optimum dimensions of the equipment, connected with its operating conditions.

The total annual cost consisting of fixed and variable costs was selected as an objective function, which is to be minimized. If we consider a heat exchanger system for a gas-gas application in general (Figure 14), we can specify the major cost components as follows: capital, operating and maintenance costs of gas 1 and gas 2 fans, and capital and maintenance costs of the heat exchanger.

Capital cost of any process equipment can be estimated with a reasonable accuracy using relations which take into account installed cost as a function of characteristic equipment parameters. The maintenance cost is assessed as a percentage of capital cost. Operating cost can be predicted as a function of power consumption for overcoming the pressure drops.

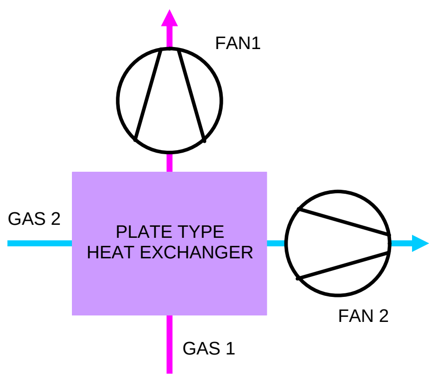


Figure 14 Heat exchanger system for „gas/gas" application

Considering several relations (concerning heat transfer, pressure drop, investment costs, operating costs etc.) we obtain the total annual cost as a function of heat transfer coefficient. Thus it is possible to obtain optimum values of both heat transfer coefficients and consequently optimum values of pressure drops. By a convenient re-arrangement of equations relating heat transfer and geometry, relations were obtained, which provide the possibility to calculate optimum dimensions of a heat exchanger.

For an improved and economic design of plate type heat exchangers we recommend firstly to apply the above optimization approach [12] and utilize the results of calculations as input data to a commercial and/or an in-house design calculation software package which provides the final results.

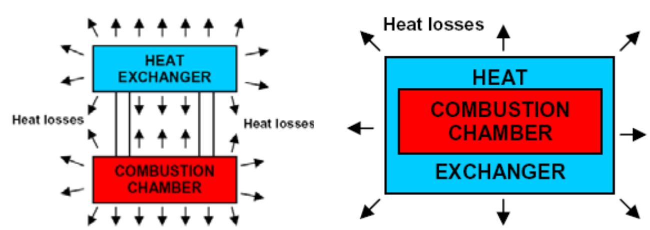
This methodology has been developed mainly for grassroots design of plate type heat exchangers. It can be however adapted also for specific situations and constraints required at retrofit cases (space limitations, pressure drop allocations).

Heat integration

In order to design a highly efficient, optimised heat utilization process for incinerators, it does not suffice to design highly efficient individual heat exchangers. It is always necessary to consider heat exchangers also as elements of the overall process. Principles of process integration reviewed by [27] should be used wherever possible. Unfortunately there is frequently not enough space for this approach in units for thermal processing of waste. In this area, heat integration usually means integration of the heat produced in incineration plant into the local utility networks. The specific way of utilisation of produced heat (typically in the form of steam) will be different according to local conditions (climatic as well as legislative). Basic rules of selection and integration of the systems for energy utilization including CHP (Combined Heat & Power) ones have been specified, analyzed and illustrated by examples in [28].

INTEGRATED EQUIPMENT FOR GAS WASTE TREATMENT

Research and development of a novel unit for thermal (and/or catalytic) treatment of waste gases contaminated mainly by VOC (Volatile Organic Compounds), HOC (Halogenated Organic Compounds) or CO was initiated by more and more sweeping environmental regulations. This equipment has considerable advantages compared with commonly used arrangement (combustion chamber (catalytic reactor) - pipeline - heat exchanger) shown in Figure 15a. It is very compact since the combustion chamber, catalytic reactor and heat exchanger are integrated into one unit (Figure 15b). Maximum re-use of heat lost in the combustion chamber and catalytic reactor is achieved.



a) Two independent pieces b) Fully integrated compact unit

Figure 15 Comparison of a conventional and compact unit

As mentioned above the novel and original design is based on integration of several pieces of equipment into one unit, which has several advantages. It is characterized by a cylindrical combustion chamber placed inside a heat exchanger – polluted air preheater (see Figure 15). This cylindrical preheater consists of several concentric stainless sheets. Both flue gas from the combustion chamber and polluted air (which is heated by flue gas) flow in the spaces between each couple of cylindrical sheets. Narrow strips helically placed between the sheets form helical rectangular ducts. This results in counter-current flow of process fluids. In specific cases, the combustion chamber can be extended by a catalytic reactor as shown in Figure 16. Catalytic treatment is more suitable for waste gas with small concentrations of pollutants.

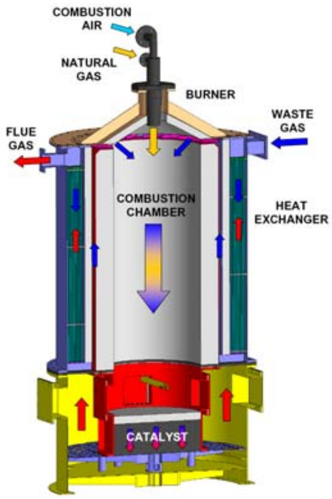


Figure 16 Compact unit

The unit can be used in various branches of industry such as paint shops, refining plants, sewage treatment plants, food processing industry, pharmaceutical industry, processing and transporting of crude oil or natural gas, etc.

Basic process parameters of the experimental equipment were evaluated with the aid of software for simulation of processes for the thermal treatment of wastes. Additionally, sophisticated computational support based on CFD proved to be a very efficient approach and resulted in an optimized design and elimination of bottlenecks [22].

Thermal and hydraulic calculations

Equations for the thermal and hydraulic calculation of a heat exchanger and relationships for its sizing form the core of its mathematical model. In the present specific case, general equations for heat balancing were used as in any other case. However, the specific design has to be reflected by the mathematical model as well. This means that we need equations for the evaluation of heat transfer coefficient h and friction factor f. Unfortunately no formulae existed for the new heat exchanger. Therefore, a tentative mathematical model containing an approximate description of transfer phenomena had to be created in order to provide design guidelines for construction of an experimental equipment. Equations have been selected from reputable literature, namely [26], [29], [23], considering geometrical and hydraulic similarity with other heat exchanger types. Experience from the research of segmentally baffled shell-and-tube heat exchangers [30, 31] were utilized..

New equations for calculation of heat transfer and pressure drop were derived both for laminar and turbulent flow and can be found in [32, 18]. The equations are based on measurements at the experimental unit.

Experimental facility

In the frame of research, a full-scale experimental facility for thermal and catalytic treatment of waste gases polluted by VOC has been designed. The main objective of this facility is validation of mathematical design models by measured data such as inlet and outlet pollutants concentration in processed gas, temperatures and pressures in various parts of unit, flow rates of waste gas, flue gas and natural gas, etc.

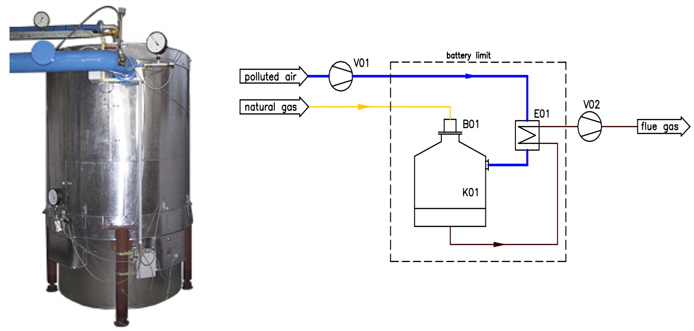


Figure 17 Photo and simplified flow sheet of the facility

Table 2 Technical specification of the experimental facility

Flow rate of waste gas	m_N^3/h	500 ÷ 1600
Type of pollutants	-	VOC (HOC)
Volume of pollutants in waste gas	ppm	to 5000
Type of catalyst	-	Pd/Al_2O_3 (CHEROX 40-31)
Height of catalytic reactor	m	0.2
Diameter of catalytic reactor	m	0.6
Volume of catalyst	m^3	0.0565
Weight of catalyst	kg	36
Space velocity VHSV	$m_N^3/m^3.h$	8850 ÷ 28320
Operating temperature in catalytic reactor	°C	250 ÷ 400
Max. burner duty	kW	160
Excess of combustion air	-	1.05
Consumption of electric power	kW	3 ÷ 6
Consumption of natural gas	m_N^3/h	0 ÷ 10
Pressure drop of equipment	kPa	6

The experimental facility displayed in Figure 17 contains the combustion chamber and catalytic reactor K01, burner B01, heat exchanger E01 (these three parts are integrated into one unit), waste gas fan V01, flue gas fan V02 and the control panel. The unit has also automatic data acquisition and control system, which measures various values and feeds them into a computer. Sophisticated processing of the data enables to investigate the operation of the whole integrated unit in a number of operating modes. Based on evaluation of operating data, the unit can be further optimized. Technical specifications of the experimental unit designed for catalytic treatment of waste gases are shown in Table 2.

Practical industrial applications

Requirements coming from the industrial practice influence the further development of the equipment and give rise to various modified units based on the new equipment. Two examples of application are shown in Figures 25 and 26.

The first is a unit for the thermal treatment of waste gas from a chemical plant (see Figure 18). Waste gas with flow-rate of 2200 m_N^3/h and concentration of volatile organic compounds (VOC) of 26.4 g/m_N^3 is pre-heated to a sufficient (yet safe) temperature in the heat exchanger. Then the pre-heated waste gas enters the combustion chamber where volatile organic compounds are burnt so that the concentration of pollutants falls well below the allowable limit. Flue gas produced by combustion enters the heat exchanger only in such amount that is required for pre-heating counter-currently flowing waste gas. The remaining flue gas flows through a bypass. This bypass is controlled by a pneumatically operated valve. Flue gas leaves the unit with temperature ranging from 500 to 750 °C, which provides a possibility for further heat recovery.

Another industrial application is a unit for thermal treatment of waste gas having high heating value together with waste vapours as a part of process for drying and cleaning natural gas (see Figure 19).

Figure 18 Compact unit for thermal treatment of waste gas (Courtesy of EVECO Brno Ltd)

Figure 19 Unit for thermal treatment of waste gases (Courtesy of EVECO Brno Ltd)

CONCLUSIONS

It has been shown that heat exchangers, heat recovery steam generators, and many other heat-transferring devices play a key role in processes for the thermal treatment of wastes and thermal processing of biomass. Secondly, it may be concluded that efficient application of waste-to-energy systems requires systematic analysis of various options in the design phase and integration of individual devices by rigorous methods like the Pinch analysis. Specific properties of process fluids and other constraints encourage the development of non-traditional and innovative solutions and designs of heat transfer devices. Several examples and case studies are included in the text to illustrate the discussion of general principles.

ACKNOWLEDGEMENTS

A number of people have contributed either directly or indirectly to this paper. Gratitude is expressed to Jiri Hajek, Martin Pavlas, Radek Dvorak, Jaroslav Boran, Lucie Houdkova and Zdenek Jegla from the Institute of Process and Environmental Engineering for their assistance and valuable contributions as well as to Jaroslav Oral, director of EVECO Brno Ltd, and other specialists from this company for providing results of practical applications.

REFERENCES

[1] Ludwig Ch., Hellweg S., Stucki S., 2003, Municipal Solid Waste Management, Springer-Verlag, Berlin, 2003, ISBN 3-540-44100-X

[2] Brunner C.R., 1996, Incineration Systems Handbook, ICI, USA

[3] Santoleri J.J., Reynolds J., Theodore L., 2000, Introduction to Hazardous Waste Incineration, Second Edition, Wiley-Interscience, New York

[4] Oral J., Stehlik P., Sikula J, Puchyr R., Hajny Z. and Martinak P., 2005 Energy Utilization from Industrial Sludge Processing, Energy, 30, pp. 1343 – 1352

[5] CEWEP, 2005, Discussion paper on criteria for energy recovery in waste incineration plants, Brussels, URL: <http://www.cewep.com/energy/energy_recovery> [cit 2006-2]

[6] Commission of the EC, 2005, Proposal for a Directive of the European Parliament and of the Council on the Waste, Brussels, COM(2005) 667, 2005/0281 (COD), URL: <http://europa.eu.int/comm/environment/waste/pdf/directive_waste_en.pdf > [cit 2006-2]

[7] European Commission, 2005, Reference Document on the Best Available Techniques for Waste Incineration, Brussels, URL: <ftp://ftp.jrc.es/pub/eippcb/doc/wi_bref_0705.pdf>, [cit. 2006-2]

[8] Reimann D. O.: CEWEP Energy Report (Status 2001-2004). Result of Specific Data for Energy, Efficiency Rates and Coefficients, Plant Efficiency factors and NCV of 97 European W-t-E Plants and Determination of the Main Energy Results, Bamberg, Germany, Updated July 2006

[9] Council Directive 2000/76/EC of the European parliament and of the council of 4 December 2000 on the incineration of waste, Official Journal of the European Communities, 28 December 2000

[10] Boráň, J.; Houdková, L.; Ucekaj, V.; Stehlík, P.; Thermal Processing of Sewage Sludge II. Applied Thermal Engineering, 2008, (accepted for publication)

[11] Šťasta, P., Boráň, J., Bébar, L., Stehlík, P., Oral, J. Thermal Processing of Sewage Sludge. Applied Thermal Engineering, 2006, roč. 26, č. 9, s. 1420-1426

[12] Jegla Z., Stehlik P. and Kohoutek J., 2004, Alternative Approach in Optimization of Plate Type Heat Exchangers, Heat Transfer Engineering, 25, pp. 6 – 15

[13] Ganapathy, V., 1991, Waste Heat Boiler Deskbook, The Fairmont Press, Inc., Lilburn, USA

[14] Sponar, M., Stehlik, P., Bebar, L., 2004, Simple mathematical model of heat recovery steam generator, 16th International Congress of Chemical and Process Engineering CHISA 2004, Proceedings on CD-ROM, Prague, Czech Republic

[15] Kukulka, D. J., Baier, R. E., Mollendorf J. C., 2004, Factors Associated with Fouling in the Process Industry, Heat Transfer Engineering 25, no. 5, pp. 23-29

[16] Pavlas M., Stehlík P., Oral J., 2005, Computational approach for efficient energy utilization in process industry, 8th Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction Press 05, Proceedings on CD ROM, Giardini di Naxos-Taormina, Italy

[17] Stehlik P., Puchyr R. and Oral J., 2000, Simulation of Processes for Thermal Treatment of Wastes, Waste Management, 20, pp. 435-442

[18] Stulir R., Stehlik P. and Oral J., 2003, Efficient Equipment with Special Heat Exchanger for Thermal Treatment of Polluted Air – Experiments, Computations, Applications, Heat Transfer Engineering, 24, pp. 60 - 69

[19] Stehlík, P. Heat Transfer as Important Subject in Waste to Energy Systems. In *Heat Transfer in Components and Systems for Sustainable Energy Technologies.* Grenoble, France: 2005. s. 11-21. ISBN: 2-9502555-0-7.

[20] Saaty T. L., *The Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process*. Series: AHP, VI, RWS Publications, Pittsburg, PA 2000

[21] Hájek J., Kermes V., Sikula J., Stehlik P., 2005, Utilizing CFD as Efficient Tool for Improved Equipment Design, Heat Transfer Engineering, 26, 5, pp.15-24

[22] Hájek J. Computational fluid dynamic simulations in thermal waste treatment technology—Design, optimisation and troubleshooting. Energy (2008), doi:10.1016/j.energy.2007.11.010

[23] Hewitt, C.H., Shires, G. L., and Bott, T. R. , 1994, Process Heat Transfer, Begell House, New York

[24] Shah, R. K., 1991, Compact heat exchanger technology and applications, In Heat Exchange Engineering, Vol. 2, E. A. Foumeny and P. J. Heggs (Eds), Ellis Horwood, Chichester

[25] Reppich, M. and Kohoutek, J., 1994, Optimal Design of Shell-and-Tube Heat Exchanger, Computers Chem. Engng., 18, pp. 295-299.

[26] Hewitt, C. H. and Pugh, S. J., 1998, Approximate Design and Costing Methods for Heat Exchangers, Proc. International Conference Heat Exchangers for Sustainable Development, pp. 801-820, Lisbon, Portugal

[27] Smith, R., 1995, Chemical Process Design, McGraw-Hill, Inc., New York

[28] Pavlas M., Bébar L.and Stehlík P., 2005, Waste-to-energy systems and their benefit, 1st International Confetrence & Exhibition on Thermal Treatment and Resource Utilization of Wastes, Proceedings on CD ROM, Beijing, China

[29] VDI, Wärmeatlas, 1984, VDI-Verlag GmbH, Düsseldorf.

[30] Král, P. Stehlík, H. J. van der Ploeg, and B. I. Master, 1996, Helical Baffles in Shell-and-Tube Heat Exchangers, Part I: Experimental Verification, Heat Transfer Engineering, 17, pp. 93-101

[31] Stehlík P., Němčanský J., Král D., and Swanson L.W., 1994, Comparison of Correction Factors for Shell-and-Tube Heat Exchangers with Segmental or Helical Baffles, Heat Transfer Engineering, 15, pp. 55-65

[32] Štulíř R., 2002, Equipment for thermal treatment of wastes – heat exchanger, Ph.D. Thesis, Technical University of Brno (in Czech)