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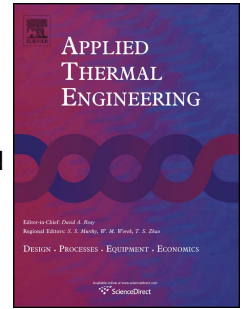
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## **Conventional versus Specific Types of Heat Exchangers in the Case of Polluted Flue Gas as the Process Fluid – A Review**

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### **Abstract**

The present contribution shows certain practical aspects of selection and design of heat exchangers for industrial applications where polluted flue gas (off-gas) represents one process fluid.

One of the key factors in designing heat exchangers for these applications is the primary selection of a suitable type. The presently available possibilities and methodologies of efficient heat exchanging device selection and supporting software do not allow covering all the needs of related industries. A concrete example of an industrial process furnace is used to demonstrate the issues of “compactness and enhancement vs. reliability” for various temperature levels of high temperature applications. Attention is also given to the specific area of fouling of the heat exchanging surfaces by flue gas.

In high-temperature applications, it is necessary to pay special attention to all phases of a solution. Heat integration of devices into the plant system and its possibilities are presented. The irreplaceable role of modelling and optimization on the design of heat exchangers and its design details is emphasized which may significantly contribute to final product quality. An important role in high-temperature applications is also played by CFD simulations.

**Keywords:**

Heat exchangers, flue gas, high temperature application, fouling, modelling

**1 Introduction**

Selection of heat exchangers represents primary importance in heat recovery systems design. It is necessary to perform the design in such a way so that we may utilize conventional types of heat exchangers with maximum degree of compactness in relation to process parameters like temperature, composition of process fluids, proximity to fouling and potential operational problems.

At present compact heat exchangers are preferred whenever and wherever possible. A graphical presentation of basic and/or typical types of compact heat exchangers versus highest allowable temperatures for their applications is shown in Fig. 1.

Fig.1 presents a simple overview of recent conventional metallic heat exchangers as the preferred heat exchanger implementation for flue gas heat recovery systems. There is, however, the possibility to use ceramic materials which have been subject to intense development in the last 40 years and they exhibit good properties at high temperatures (up to 1400°C). However, generally, these ceramic materials, if they are applicable for temperatures around 1000 °C, are too expensive. Their use for lower temperatures in flue gas (off gas) application is technically possible but obviously is economically too expensive. Therefore, most requirements for “common” high temperature flue gas industrial applications (up to 1000 °C) use metallic materials.

**1.1 Enhancement vs. compactness and heat exchanger vs. network**

Improving heat transfer performance is commonly referred to as heat transfer enhancement.

Enhancement is normally concerned with increasing the (film or overall) heat transfer coefficient [1].

Although there is an obvious relation between enhancement and compactness, there is no strict criterion for differentiation between “enhanced” and “compact” solutions. These two terms are always referred to depending on two different categories, i.e. points of view. The true difference is only in realization phase – new solutions are referred to as “compact”, improvements within reconstruction are called “enhanced” solutions which at the same time can be referred to as “compact”.

The system application of heat transfer enhancement is a very important and attractive solution for heat exchanger network (HEN) retrofit [2]. If enhanced techniques are used, the requirement of additional area retrofit design can be reduced dramatically.

Therefore we can speak about local and global heat transfer intensification [3]. The local one is considered in terms of individual heat exchangers, the global one in terms of heat exchanger network (HEN). First we should consider the overall system (HEN), i.e. heat transfer enhancement in the context of HEN [4]. As mentioned above it can be found that using enhanced heat exchangers can in fact contribute to reducing additional area in the HEN retrofit [2]. Only then we analyze possibilities of further enhancement of individual heat exchangers. In high temperature applications we have to make a technical-economic trade-off as to what type of heat exchanger can be used for the purpose.

## **2 Difficult conditions of operation in case of polluted flue gas**

Energy recovery in thermal processing of waste plays an important role since it contributes to maximum utilization of energy contained in leaving flue gas (i.e. off-gas). At the same time we can speak about probably the most difficult case in terms of operational conditions. When utilizing energy released during thermal oxidizing (incineration of municipal solid waste (MSW) or hazardous waste) for generation of process steam, for co-generation (combined heat and power systems - CHP), we can consider the thermal processing as a specific kind of recycling. Since waste has sufficient heating value,

it belongs to renewable (and/or alternative) energy sources which enable us to save fossil fuels as a primary energy source. Thus we may speak about waste to energy systems (WTE) [5].

In relation to those conditions it is very important to consider and analyse the RAMS – Reliability, Availability, Maintenance and Safety - features of heat exchangers as part of the process. The methodology and implementation into heat exchanger networks and efficient waste minimisation and management were studied by Sikos and Klemeš [6, 7].

### ***2.1 Specific constraints of flue gas high temperature applications***

Both gas products and solid residues come from combustion of waste, i.e. from incineration process. Solid residues may be classified as ash (slag, cinder and/or sinter) and fly-ash. Off-gas from waste incineration is a multi-component mixture of chemical elements and compounds. It contains harmless components such as nitrogen, carbon dioxide and water vapour, but there are also harmful components like nitrogen oxides and sulphur oxides, carbon monoxide, hydrogen chloride and fluoride, dust, heavy metals and their chemical compounds, phosphorus compounds and organic compounds like hydrocarbons present in flue gas. It is necessary to take into consideration that harmful compounds of acid character are transferred into gaseous phase. Hydrogen chloride produced by thermal decomposition of chlorinated plastics is considered a predominant one. Sulphur dioxide, heavy metals (Cd, Hg, Cr, Zn, Cu, Pb) and dust also fall into category of main harmful pollutants. Further to that, chlorinated hydrocarbons such as polycyclic aromatic hydrocarbons, 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<sub>x</sub> concentrations [8].

Main process stream of incineration (i.e. produced flue gas stream) and its thermo physical characteristics and properties from fouling point of view significantly influence operating, maintenance

and investment cost of installed equipment and its service life. Moreover, properties of flue gas can greatly vary due to large composition variety of incinerated waste, which is a very complicated factor. Thus effective utilization of heat from produced flue gas through heat transfer equipment requires consideration of the following aspects:

- Influence of radiation and convection mechanisms of heat transfer on the flue gas side during design of heat transfer equipment;
- Knowledge of flue gas properties since their ability of fouling plays a key role when considering the proper type and design of heat transfer equipment;
- Composition and temperature of flue gas since they influence the selection of proper material for heat transfer equipment;
- As mentioned earlier, composition of flue gas in various incinerator applications can greatly vary – thus the worst working conditions should be taken into account and they should also be reflected in design of heat transfer equipment;
- Above mentioned restrictions on “flue gas as a process medium” make it difficult, with respect for sustaining reliable unit operations, to transmit theoretical principles of compactness and enhancement into industrial practice. They can be applied only sporadically as will be demonstrated further on.

## ***2.2 Possibilities of industrial applications of compactness and enhancement vs. process flue gas limitations***

Possibilities of industrial applications of compactness and enhancement vs. process flue gas limitations will be demonstrated on an example coming from common practice and showing solution of process tubular furnace with combustion air pre-heating system.

Process tubular furnaces (or fired heaters) are large and complex items of process plants. Design of radiation-convection types of furnaces is currently positively preferred. Main parts of furnace are as follows: radiation chamber, convection section, burners, tubes (or the so-called tube coils) and stack (see Fig.2). It is obvious that radiation-convection furnace contains two main parts: radiation chamber and convection section [9].

Cabin furnace types, as those shown in Fig. 2, are preferred for large heat duty applications (approximately 20 MW and more) and contain horizontally oriented tubes (or tube banks) in both radiant and convection parts of furnace.

Following detailed description of individual parts of process furnace gives us an idea about possibilities of designers with respect to compactness and enhancement solutions to high-temperature applications with flue gas as a process fluid:

***Radiation (combustion) chamber.*** Combustion of fuel in burners takes place in the radiation chamber, which leads to very high flue gas temperatures (reaching 900 to 1 500 °C). Tubes, usually located close to cabin walls, are exposed to high heat fluxes and to radiation-convection mechanisms of heat transfer with dominant radiation component. These high flue gas temperatures (due to burn-off and direct effect of fouling components) do not allow applications of extended surfaces or any other techniques of heat transfer enhancement and compact solutions. The only feasible method is to use plane surfaces (i.e. plane tubes). It is possible to optimize their location with respect to economically effective utilization of released heat by tube system in radiation chamber [10].

***Crossover from radiation chamber to convection section—the shield section.*** Part of tube coil(s) which is located in flue gas stream between radiation chamber and convection section is called the shield tubes (or shield section). This part of a tube system is the most exposed part of the furnace tube system due to common action of radiation heat flux from radiation chamber as well as intensive convection flue gas



heat flux coming from radiation chamber to convection section. Flue gas temperatures at the crossover between radiation and convection sections typically range from 900 down to 700 °C; they are obviously lower than in radiation chamber. However, intensive heat transfer disables practical application of enhanced and compact solutions mostly due to heat transfer surface burn off. This section then also enables only plane surface solutions (i.e. plane tubes) [9].

**First part of furnace convection section.** First part of furnace convection section is located above the shield section in the area of flue gas temperatures reaching from 500 to 700°C. Lower values of flue gas temperature result in decreased radiating heat transfer. This section enables enhanced (compact) solutions depending on fouling and burn off properties of flue gas. If there is no risk of fouling, application of fins is feasible and achieving “compact” design is possible. If there is any chance of fouling by flue gas, lower degree of heat transfer enhancement may be used, such as studded surfaces (studded tubes) [9].

**Second part of furnace convection section.** This section is downstream of the first convection section and is located in the area where flue gas temperatures are typically 300 to 500 °C. Actual value of lower boundary of the mentioned flue gas temperature region is influenced by temperature differences between furnace inlet temperature of heated fluid (i.e. into second convection section) and furnace outlet flue gas temperature – see diagram in Fig. 3. (Typical inlet temperature of fluid heated inside furnace tubes, ( $T_{f,inlet}$ ), ranges for example in case of furnaces of petrochemical industries from 250 to 350 °C. Thus, outlet flue gas temperature from this section ( $T_{fg,outlet}$ ) reaches from 300 to 350 °C.)

We may state that in this convection section (flue gas temperature range) it is possible to utilize the potential of compact and enhanced solutions (taking into account fouling properties of flue gas). This is probably an area with the biggest potential for application of compact and enhanced solutions associated with increasing significance of heat recovery in this temperature range.

Depending on possibilities and constraints mentioned above, even higher degrees of compactness may be obtained here since burn off is no longer a problem within this temperature range. Thus, higher density of fins or studs than in the first part of furnace convection section may be applied. However, the selection of a concrete degree of compactness or enhanced solution should be supported by results of operating and technical -economic balances (optimization) [9].

**Utilization of flue gas waste heat from furnace.** Flue gas usually leaves the convection section with temperature reaching approximately 300°C. Potential of flue gas energy utilization (within the temperature range 300-150°C) greatly depends on temperature of flue gas dew-point.

Effective utilization of this type of low potential waste heat requires compact or enhanced solution depending again especially on flue gas fouling properties. This type of heat is commonly used for preheating of combustion air for furnace burners which allows reducing the amount of noble fuels [11].

Typical heat transfer equipment used in these applications with no risk of flue gas fouling is a plate type heat exchanger with plain plates [12] which falls into initial levels of compact solutions (surface density being 100 to 200 m<sup>2</sup>/m<sup>3</sup>) comparable approximately to compactness of plate and frame heat exchangers.

In case of risk of flue gas fouling, it is necessary to use plane surfaces (i.e. typically plane tubes) or surfaces with small degree of enhancement (such as studded tubes).

### **2.3 Clean vs. fouled high temperature applications**

Fouling of heat exchangers' heat transfer surfaces is a serious problem for certain process plants. Waste incineration plant is a typical example of such a process plant. As it was mentioned before, the flue gas (as main process stream of such high temperature process) and its thermo physical characteristics and properties significantly influence operating, maintenance and investment cost of installed equipment and its service life from the fouling point of view. Due to high content of solid particles in the gas, the

particulate fouling is the dominant fouling mechanism of heat transfer equipment installed in waste incineration plants, and other related applications.

Fouling of a surface takes place as a result of the complex processes (mechanisms) that cause deposits to form on process surfaces. Quite a large number of parameters influence development of fouling, including flow velocity, surface temperature, exposed surface material/finish, surface geometry and fluid properties [13]. Based on results of numerous present research studies, fouling may generally be classified according to the principal process as follows: 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. It is difficult to predict deposit thickness; however, thickness is extremely important in determining density and distribution of various constituents in the deposit.

As reported in [14] from measurement of flue gas from boiler installed in a waste incineration process plant, the flue gas commonly contains fly ash particles with sizes ranging from 1 to 450  $\mu\text{m}$ . Such a large particle sizes range is typical for the above mentioned applications and such a fouling process is accompanied with certain important phenomena, such as mechanism of sticking, sintering of layer of stick in particles and thus the change of fouled layer properties during operating time of equipment.

This fact proves previously mentioned enunciation that in process applications of highly fouling flue gas it is very difficult to transmit theoretical principles of compactness and enhancement into industrial applications. Basically, compact solutions are not applicable, only plane surfaces are used (i.e. plane tubes) which further undergo special types of enhancement. It is possible to use, for example, oval tubes [15] or special tube bank inserts for improved auto-cleaning capability, as illustrated in Figure 4.

It is often noted in boiler-related literature (for example [16]) that 2 mm deposit will effectively increase fuel consumption by approximately 5 %. Thus, because fouling is a very important problem in heat transfer equipment placed in the thermal treatment of wastes applications, it is necessary to use only smooth surfaces for heat transfer area without any extensions. This restriction strongly limits possible configurations of heat transfer equipment. Any alteration to this fact may lead to important economic losses. Figure 5 demonstrates unsuitable application of extended surface (finned tube bank) in heat transfer equipment with a consequent destruction of the fins after cleaning.

Various reviews have attempted to describe the attachment/formation process; however, this is still not a very well understood process in industrial applications of thermal treatment of wastes. One of the results of present research [10] shows that it is possible to develop a mathematical model, based on broadly recognised method of balance of power acting an elementary particle. Moreover, model considers that particle is carried by flue gas and getting in contact with heat transfer area. Developed model allows determining the so called critical flow velocity, strictly speaking the theoretically determined minimum flow velocity to avoid particulate fouling (particles of a given size). Obtained results were compared with experimental data from worldwide available literature and a very good agreement was found. Mathematical model is suitable for a preliminary analysis of fouling tendency and also for prevention in design and operating of tubular heat transfer equipment. Results give a designer of the model a clear idea about interdependence between heat exchanger arrangement and fouling influence. Thus, complex evaluation of optimum tubular heat transfer equipment from fouling point of view requires technical-economic optimisation which takes into account investment, operating and maintenance cost with respect to character and constitution of deposit [17].

If fouling cannot be prevented, it is necessary to make certain provisions for periodical removal of deposits. The removal of formed deposit involves a combination of dissolution, erosion or spalling of the

deposited material. Certain heat transfer equipment (for example different types of tube banks placed in flue gas channels) in thermal treatment plant allow for methods of surface cleaning for deposits removal during equipment operation (“on-line” cleaning), for example soot blowers etc.

However, frequent removal of fouling cannot be performed online and fouling formation can be controlled only by maintaining proper operating conditions. In such a case the periodical removal of deposits when equipment is shut down is the only possible way. Periodic cleaning removes deposits using chemical and/or mechanical means. Mechanical methods include steam, high-pressure jets, brushes and water guns. Chemical cleaning is designed to dissolve deposits via chemical reaction with a cleaning fluid which is helpful for cleaning of hard to access areas. Mechanical methods of cleaning are expensive and also tend to erode the heat transfer surface.

#### ***2.4 Suitable types of heat exchangers for specific high temperature applications***

According to the previous information it can be generally noted that for high temperature and highly fouled flue gas industrial applications heat exchangers with plain tubes or plate-types should be preferred wherever possible. These configurations allow easy cleaning on both outer and inner heat transfer areas.

Suitable types of heat exchangers for high temperature applications will be discussed using an example of efficient way of utilizing energy contained in off-gas as shown through a real industrial case [18].

Heat recovery system of a unit for the thermal treatment of sludge from pulp production (a part of a flow-sheet of the unit is shown in Fig. 6 and view of the unit is in Fig. 7) consists of fluidization and combustion air pre-heater and heat exchanger for heating water.

The amount of heat contained in flue gas can be used for various purposes and is the result of heat and mass balance calculations of the process as well as single pieces of equipment. A number of possible

heat transfer solutions can be applied, as demonstrated in Fig. 8 through a graphical representation of the available heat vs. temperature level of flue gas and other process streams.

Due to the character of flue gas (discussed in previous section) it is often necessary to break thermodynamic principles and place the air pre-heater before the heat recovery steam generator (see equipment “A” – a radiating recuperator - in Fig. 8). In the incinerator in question (see Figs. 6 to 8), the air pre-heater is located directly after the secondary combustion chamber. Off-gas from the combustion chamber enters the exchanger with temperature ranging from 1 000 °C to 1 100 °C (sometimes even higher). Due to combustion of various types of solid/liquid waste (incineration) it contains small solid particles in the form of fly ash, which may result in serious fouling hand in hand with operational regime (especially fly ash melting). Therefore a special type of radiation recuperative exchanger described in more details in [19] is used as an option where both high temperature and radiation properties of off-gas are utilized for dominant radiation heat transfer in terms of combustion air pre-heating.

In the case of low fouling applications the common method is to use a conventional plate type heat exchanger with a modular arrangement (see Fig. 9), which can be classified as a low-compact solution – area density typically ranges from 100 to 200 m<sup>2</sup>/m<sup>3</sup>. However, such an application must be designed very carefully. Author of this article has had an experience with such an application where a conventional plate type heat exchanger type was originally used for high temperature purpose. The plates were manufactured from special fireproof chrome-nickel steel. Unfortunately, this heat exchanger was not designed correctly in terms of thermal expansion and the conditions of operation specified in regulations were not respected either. A combination of these two facts resulted in distortion of plates and a complete destruction of the exchanger (see Figure 10).

A new type of the air pre-heater (see Figure 11) was designed, manufactured and successfully put into operation and has operated without any problem since then

This non-conventional design is based on using “double-U-tube” banks (Fig. 12) in a modular arrangement. Inlet and outlet air collectors can be optimized for uniform air distribution [20]. The overall design enables a potential replacement of tube bank even during operation.

For flue gas temperature ranging approximately from 1000°C down to 350°C (see Fig.8) the most heat transfer application is the heat recovery steam generator. Selection of a convenient type of heat recovery steam generator (HRSG) depends on operating conditions and capacity of incinerator (throughput of waste), propensity to fouling, production (steam or water) required, etc. [19].

Certain specific industrial applications require a novel (frequently tailor-made) design of heat exchangers. Two different industrial examples are shown and discussed.

First, let us demonstrate the case on a process of waste to energy where sludge coming from waste water treatment plants (WWTPs) is disposed and at the same time used as a fuel [5, 19]. Thus it means that first we have to start with the process design, and only then we can consider the equipment itself.

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 in this way to pre-heat the sludge before de-watering. The underlying idea consists in assumption that preheating the sludge before de-watering it may increase the attainable water extraction rate. The expected improved de-watering of sludge may provide a more profitable energy balance of the combustion process, possibly even self-sustained sludge combustion [21]. Schematic drawing of this technology is shown in Fig. 13.

Let us emphasize again that it is necessary to solve the problem as a whole, in other words to find the most efficient way to achieve sludge heating. We came to the conclusion that instead of direct sludge

pre-heating by off-gas the combined heat and power system involving heat recovery steam generator (HRSG) and “water – sludge” heat exchanger represents an effective selection (see Fig. 13).

Then it is necessary to select a convenient procedure for research and development of a new type of special heat exchanger “water-sludge” (see Fig. 14). A concept which is based on two counter-current helical channels with rectangular cross-section was proposed.

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 consist in different flow velocities and other properties. Due to that, it is necessary to consider modifications to the heat exchanger design. The main two advantages of the proposed design consist in 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 (we can avoid using sludge pump) and operating costs.

The second example of specific high temperature application derived from a specific technology in [22] which shows a dedicated recuperative heat exchanger designed for air preheating in an experimental unit for biomass utilization for energy production. This equipment ensures high efficiency of the process. Let us also mention that here we are dealing with a multi-media heat exchanger with primary and secondary air flows placed outside the tubes and flue gas in tube-side. 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. (The other constituent are minority from point of view of deposit from biomass combustion.) These influences can be minimized by a suitable design of all parts and easy cleaning inside the tubes. The flow among the tubes as well as inside them has been investigated with the help of CFD modelling (Computational Fluid Dynamics) (see Fig. 15).

As a concluding note to the above presented problems and examples of suitable types of heat exchangers for high temperature applications as well as to the industrial ways of heat transfer enhancement, it can be stated that operating conditions and properties of flue gas as a “controlling side” of the process fluid for heat transfer equipment design dominantly influence the final solution. Therefore a real design of high temperature applications can vary in a wide range, i.e. from compact equipment (e.g. plate-type air pre-heater, heat exchanger “water-sludge”) to ‘non-compact’ (and/or special) design (e.g. radiation heat exchanger, “double-U tube” heat exchanger).

### ***2.5 Certain aspects of modelling and optimization of heat exchangers for high temperature applications***

The above mentioned information demonstrates that it is necessary to work with a suitable mathematical model to design a specific heat exchanger. Different phases of the design work require different modeling and optimization design methods. All phases of design have to be closely observed and analyzed in high-temperature applications; it is necessary to pay attention to selecting a suitable heat exchanger, its integration into process, optimization and design solution including analysis of problematic parts of the equipment with help of sophisticated calculation methods such as the above mentioned computational fluid dynamics (CFD).

In other words, it is necessary to come up with a system solution, which means analyzing the overall system of heat transfer, possibilities of its improvement and only then opting and designing individual heat exchangers (see recommended steps in design in Fig. 16).

Several significant phases of solutions for high-temperature applications will be discussed now.

**Heat integration.** The aim of this phase is to find an economically optimum solution of heat transfer system and in the case of incineration plants also to minimize the amount of energy input and maximize the amount of energy output [4]. In case of retrofit of existing plants, this phase allows to identify holes (or bottleneck) in the current heat transfer system and to predict promising ways of retrofit for improving the existing production system.

Up-to-date incineration plants cannot be considered as units for waste disposal only. They are modern energy sources producing renewable and/or alternative energy (waste to energy - WTE) as well, which can partly replace conventional energy sources combusting fossil fuels. The effectiveness of utilization energy in incineration plant is evaluated by two criteria proposed by The Confederation of European Waste-to-Energy Plants (CEWEP): Energy Utilization Rate and Plant Efficiency Factor. Results of energy utilization analysis in terms of generally known composite curves for a municipal solid waste incinerator (MSW) with capacity of 96,000 t/y of waste are shown in Fig. 17 [23].

Simulations based on industrial data acquired by monitoring system were carried out and obtained results were analyzed. Using in-house software WTE [24] for solving waste to energy systems and customized software SPRINT [25] containing process integration tools and tools for total site analysis [4], both based on the Pinch Analysis [26], recent overview in [27], it was found out that the potential energy savings are available in the area of low-grade heat (see Fig. 18).

Possible improvements were proposed and discussed with the plant operators.

The integrated incineration plant in question consists of one processing line with capacity of 12 t/h which produces 2.5 MW of electricity and 24 MW of thermal energy. CHP arrangement is an important feature of the plant. There is a connection with the heating station which produces steam for district

heating. The incineration plant supplies steam and electricity to the heating plant and the heating plant provides demineralized water to the incineration plant and returns condensate from the steam.

While temperature profiles like in Fig. 8 help us indicate which types of heat exchangers can be applied for certain temperature range and part of technology, the composite curves shown in Figures 17 and 18 can be used as a valuable tool for placing them like in various processes elsewhere.

**Optimization.** The design of these heat exchangers is usually carried out 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 (including cost of installation) and operational costs of heat exchangers [28].

Plate type air pre-heaters (Figs. 8 and 9) are widely used in high temperature applications [29, 30]. Since the cost of heat exchangers represent an important issue [31, 32], an alternative 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 equipment which are connected with given conditions of the equipment operation. 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 flue gas/air application (see Fig. 19), we can specify the major cost components as follows: capital, operating and maintenance costs of flue gas and air 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.

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. Afterwards we obtain optimum values of both heat transfer coefficients and consequently optimum values of pressure drops. By a convenient re-arranging equations concerning heat transfer and geometry we obtained relations which provide us with a possibility to evaluate optimum dimensions of a heat exchanger.

For an improved efficient and economic design of plate type heat exchangers (which can be considered as compact ones) we recommend firstly to apply the above optimization approach [12] and then results of calculations utilized as input data to a commercial and/or an in-house software package which provides us with final results.

Methodology developed mainly for grassroot design of plate type heat exchangers is also adapted for specific situations and constraints required in retrofit cases (space limiting, pressure drop allocations). It was shown that reduction of total annual cost of optimized heat exchangers in case of solved industrial cases in comparison with common not optimized designs typically varies in significant range of 5 to 15 % [12].

**CFD simulation.** Simulations of fluid flow and heat transfer in various pieces of equipment within incineration and waste-to-energy plants may provide very useful information both in the design phase and in troubleshooting. The CFD methodology itself is well known and thus we will rather focus on certain recent specific applications, relevant to the topic of the present paper. Typical arrangements of unit for the thermal treatment of sludge which can be considered a waste-to-energy plant were displayed

in Fig. 6 and 7. Let us indicate which units/equipment of the system are the main candidates for modelling using CFD and potential achievements: secondary combustion chamber, flue gas ducts, low- $\text{NO}_x$  burners, filters, heat exchangers. Let us focus on examples related to heat recovery system [33].

(i) *Example 1 of CFD simulation – flue gas flow optimization.* Uniformity of flow across tube banks and/or bundles is a common objective in many heat exchanger applications. In this part, it is shown how methods of computational fluid dynamics can be utilised for studying the flow inside exhaust duct of an incineration plant (Figures 6 and 7).

The flow pattern in this flue gas duct (follow Fig. 6, 7 and 20) leads to fouling in a connected heat exchanger. CFD analysis is used to find what causes the fouling and to optimise the duct design in order to eliminate the undesirable phenomena. This step in design is very important and useful for selection of a convenient type of heat exchanger for the purpose.

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 [33]. Fig. 20 shows the resulting, manually optimized swirl generator which produced the best results out of all the considered alternatives and its location in the overall duct geometry. An improvement of about 10 % in terms of maximum velocity magnitude has been obtained with the manual optimization approach [33]. First results from the computational optimization show that further improvement by 8 % is still possible [34].

(ii) *Example 2 of CFD simulation – tube bank inserts.* The problems with heavy particulate fouling of heat recovery tube bank of an incineration plant were solved using the previously mentioned developed model [17] allowing to determine the so called flue gas fouling critical flow velocity (minimum flow velocity to avoid particulate fouling of particles of a given size).

Predictions obtained from modelling which provided necessary flue gas velocity distribution were supported by detailed CFD analysis confirming important contribution of proposed special tube bank inserts to improved auto-cleaning tube bank capability (see Fig. 4).

Illustration of CFD results is obvious from Fig. 21. Tube bank inserts were installed and successfully approved in real industrial operation. Moreover, the inserts can be moved in vertical direction which enables flexibility in changing the velocity.

*(iii) Example 3 of CFD simulation – heat exchanger chambers.* The similar approach as consulted in previous example 2 was used also during detailed design of specific dedicated high temperature recuperative heat exchanger as it was mentioned above and illustrated in Fig. 15. This heat exchanger was suggested and developed as a specific equipment for pre-heating both primary and secondary air by flue gas from combustion of various types of biomass (as a 3 streams heat exchanger). It is actually a fire-tube heat exchanger with flue gas flow inside the tubes and primary and secondary air flow outside the tubes where baffles (similarly like segmental ones in shell-and-tube heat exchangers) are applied. Here the CFD simulation helps to investigate the flow among the tubes (on the “shell-side”) and the inlet and outlet chambers (see Fig. 15). It significantly contributed to correct design of the tube bank for avoiding excessive fouling caused by condensation of tarry compounds and to minimization of fouling of inlet and outlet heat exchanger chambers. The results were approved in the operation of a reference unit [39].

All the above described cases proved useful when applying the CFD approach for selection of the most convenient type of heat exchanger. It does not depend whether it is considered as a compact one or not. Let us mention that it is not always possible to utilize all the theoretical knowledge and apply sophisticated approach in industrial practice. However, it has been proved that such approach substantially contributes to improved design.

### 3 Discussion and conclusions

As demonstrated in the text above, wide range of existing heat exchangers can be used for various purposes. Let us focus on the field of thermal processing of waste and high temperature waste to energy systems again. When using a conventional shell-and-tube heat exchanger or a compact (plate type) one these exchangers are usually purchased from a manufacturing company and based on an accepted quotation and later agreement delivered. Manufacturers mostly have a commercial software package (e.g. HTRI or HTFS) at their disposal. However, as it was shown above, in real applications of units for the thermal treatment of waste special types of heat exchangers are frequently proposed and designed when no computer codes exist. Then it is a matter of a general contractor to provide manufacturers with all the necessary parameters of geometry to be able to manufacture the exchanger.

Correct selection of a appropriate type of heat exchanger is a very important solution stage, especially in the discussed hot gas (or high gas temperature) applications in case of heat recovery system in units for the thermal processing of wastes (waste to energy systems). Energy contained in flue gas (in some cases off-gas before cleaning which contains pollutants such as solid particles) is utilized for air pre-heating, steam generation, water heating or technological purposes. Therefore without taking into account specific features of this process fluid, serious problems during operation may arise (e.g. excessive fouling, thermal expansion, leakages). These and other reasons give rise to developing of multi-purpose computational systems with databases based for hot gas applications where data concerning both the common (and/or conventional) and specific types of heat exchangers are contained. It means conventional heat exchangers are preferred; however, in some cases there is no other choice than to select a newly developed type of heat exchanger [35, 36].

Thus we can recommend the following approach for selection of appropriate type of heat exchanger:

- Using elimination strategy based on AHP (Analytic Hierarchy Process) method [37] for selection of potential candidates at first stage of choice based on main process characteristics (process fluid, temperature, pressure, fouling etc.) [38].
- Simplified preliminary design calculations to narrow the choice (also with the aid of software for thermal and hydraulic calculations).
- Preliminary rough estimate of investment and operational costs and selection of an optimum candidate (and/or candidates).
- Final design checking and obtaining data for enquiring heat exchangers manufacturers and/or design of a specific type of heat exchanger.
- Evaluation of quotations based on a sophisticated comparison of offered alternatives (practical aspects, price, meeting required parameters e.g. with simplified design/rating calculations etc.).

As discussed above, we always prefer the economically acceptable solution based on using conventional types of heat exchangers even in case of high temperature applications where hot-side fluid is flue gas (frequently heavily polluted). We prefer compact heat exchangers and enhanced surfaces wherever and whenever possible, however, frequently tailor-made heat exchangers cannot be avoided. Various aspects are demonstrated on units for thermal treatment of wastes which are characterized by the most difficult working conditions.

Most important features of these applications are discussed with respect to their specific limitations.

Several industrial units served for demonstrating of the most significant phases of the process, tools and strategies for solution and design of suitable heat transfer equipment.

Let us try to summarize a practical approach to the selection of appropriate heat exchangers:

- Analysis of the specific case of heat exchanger application.



- Checking all available types of conventional (if possible) compact heat exchangers which could meet the required process parameters (especially temperatures), and conditions of operation (e.g. propensity to fouling) and are available on the market.
- Preliminary selection of potential candidates.
- Enquiring manufacturers and repeated evaluation of quotations.
- In case no appropriate candidate is available there is a need to develop a special type of heat exchanger.

Thus we can state that there is really a challenge of continuing research and development in this field. In fact this is a “never ending story”.

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[40] **List of figures:**

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Fig. 1 Types of compact heat exchangers and their typical high temperature limits

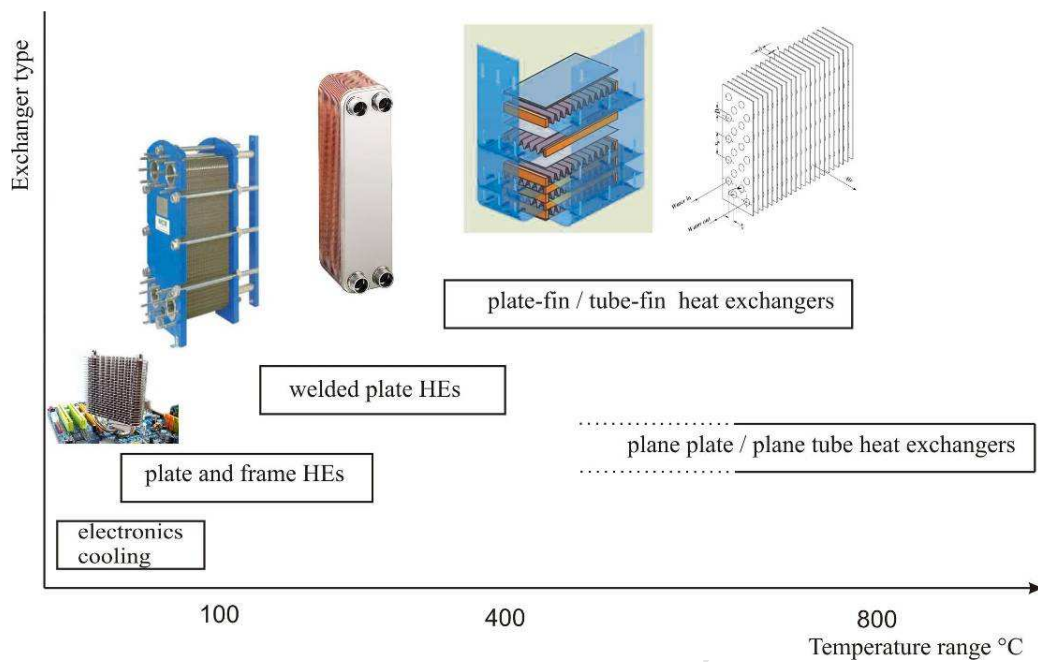




Fig. 2 Cabin type of process tubular furnace

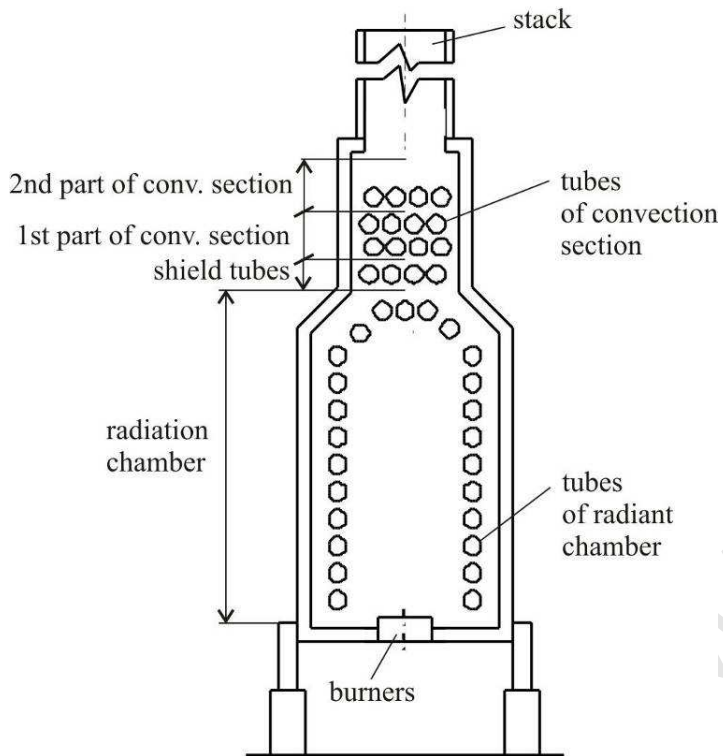


Fig. 3 Scheme of furnace and its process fluids

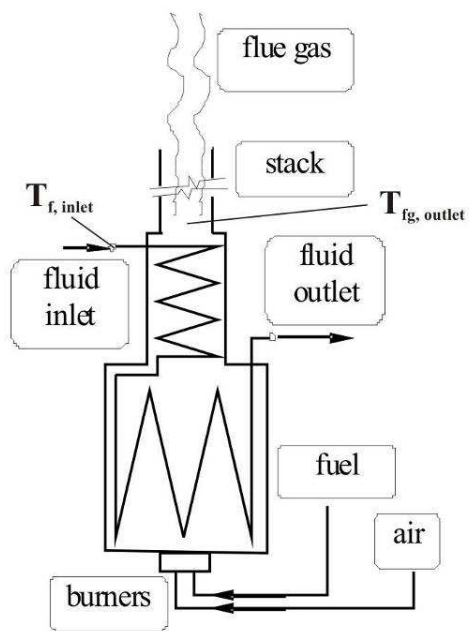


Fig. 4 Example of passive enhancement approach for improved auto-cleaning capability in applications with highly fouling flue gas containing high amounts of ash particles (Courtesy of EVECO Brno Ltd)

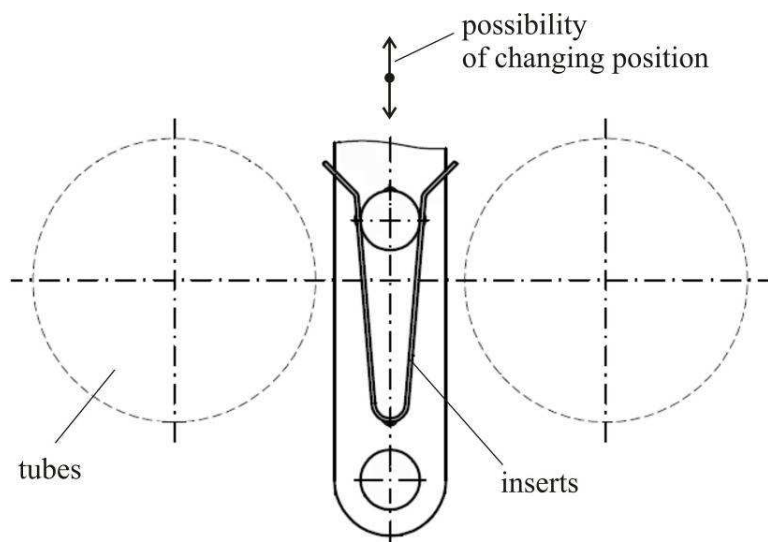


Fig. 5 Fouled and cleaned finned tube bank



a) Heavily fouled finned tube bank



b) Finned tube bank after cleaning

Fig. 6 Simplified flowsheet showing heat recovery system of unit for thermal treatment of sludge from pulp production [19]

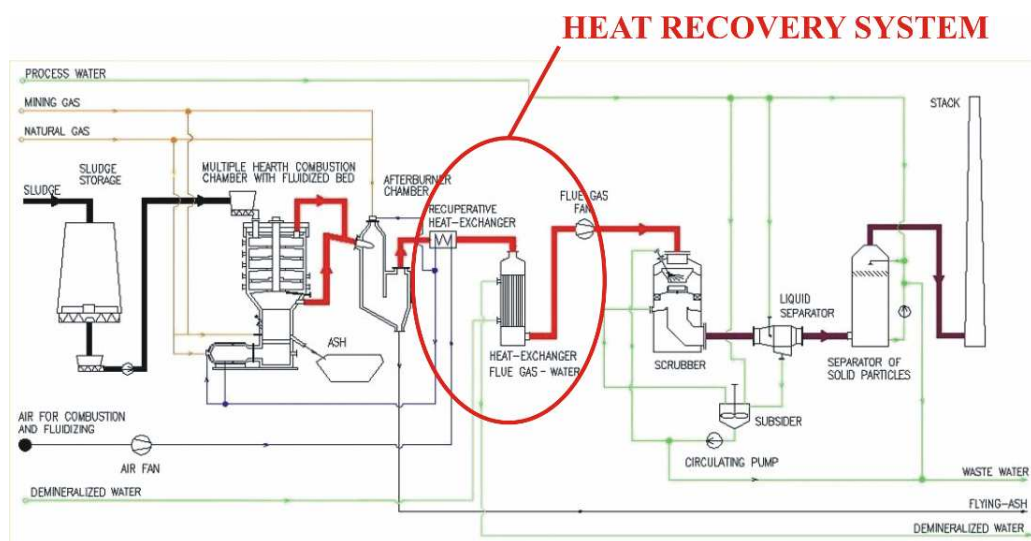


Fig. 7 View of unit for the thermal treatment of sludge with heat recovery system [19]

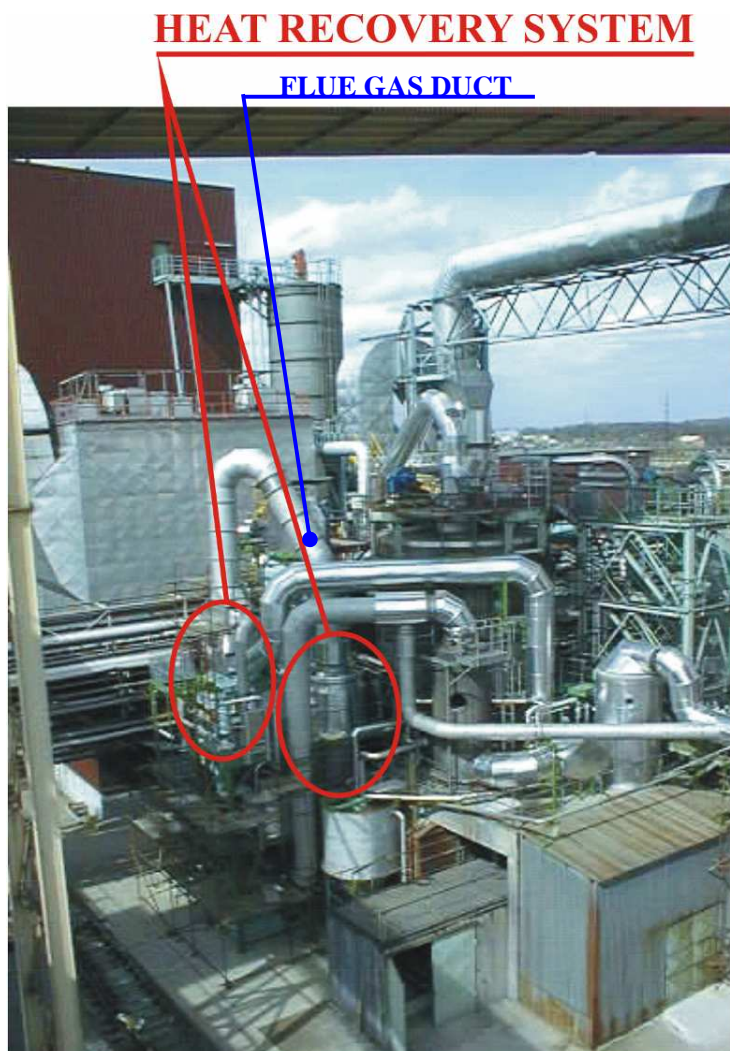
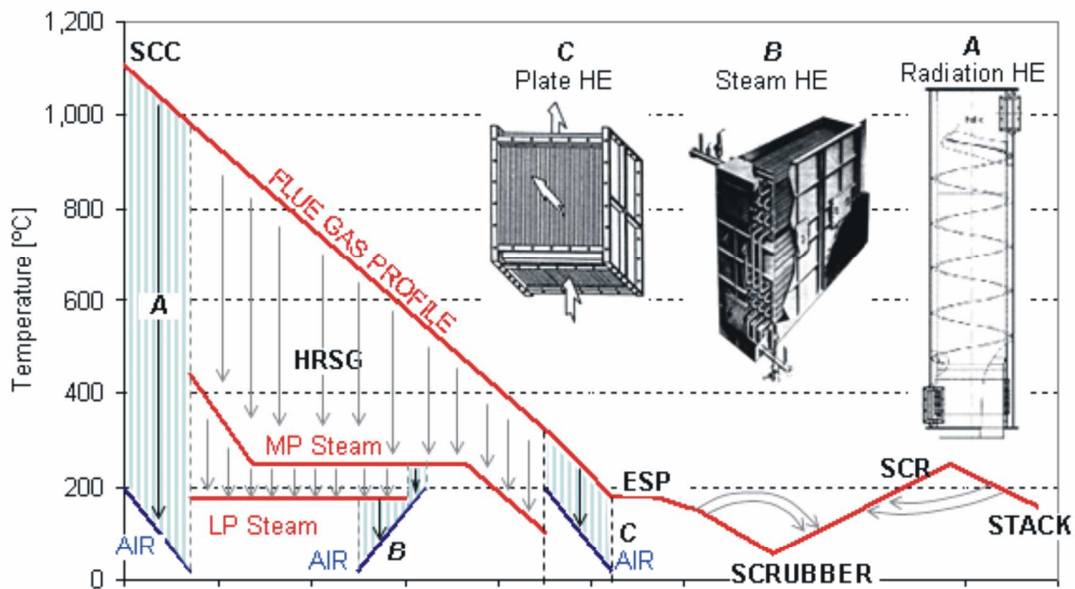


Fig. 8 Typical temperature profiles, heat transfer between hot and cold streams and feasible heat exchangers integration in waste processing technology [24]



*Abbreviations:*

- ESP - electro static precipitator
- HE - heat exchanger
- HRSG - heat recovery steam generator
- LP - low pressure
- MP - medium pressure
- SCC - secondary combustion chamber
- SCR - selective catalytic reduction

Fig. 9 Plate type heat exchanger for air pre-heating (left-look inside, right – modular arrangement)

(Courtesy of EVECO Brno Ltd)

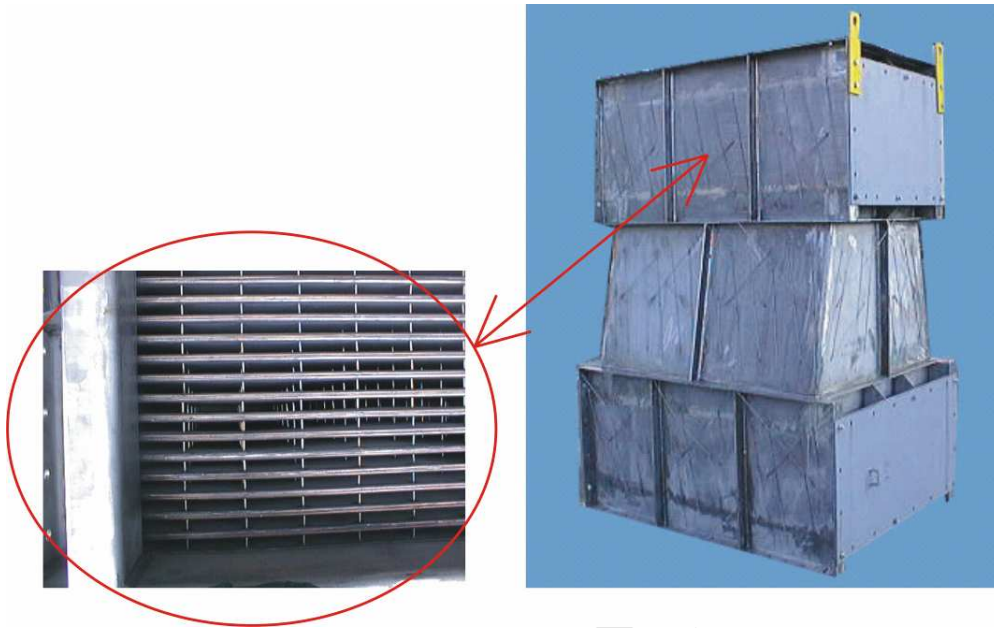




Fig. 10 Heat exchanger after operation (Courtesy of EVECO Brno Ltd)



Fig. 11 New design of “double-U tube” air pre-heater (Courtesy of EVECO Brno Ltd)



Fig. 12 Tube bank (Courtesy of EVECO Brno Ltd)



Fig. 13 Process for thermal treatment of sludge with utilization of off-gas heat [22]

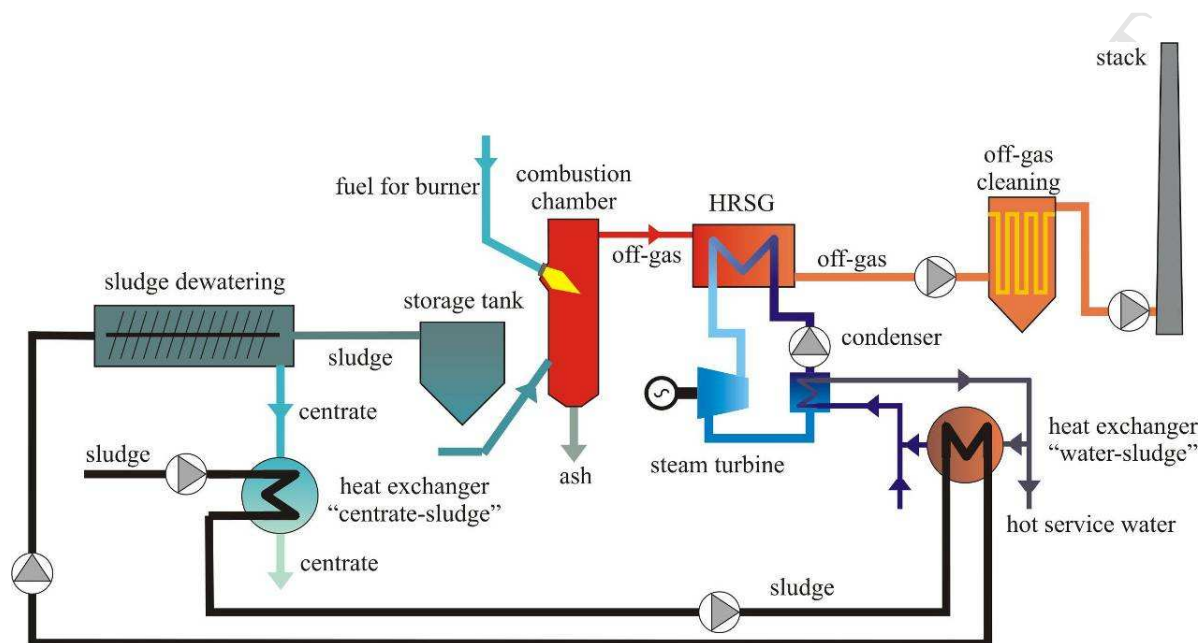


Fig. 14 Heat exchanger “water-sludge” [22]

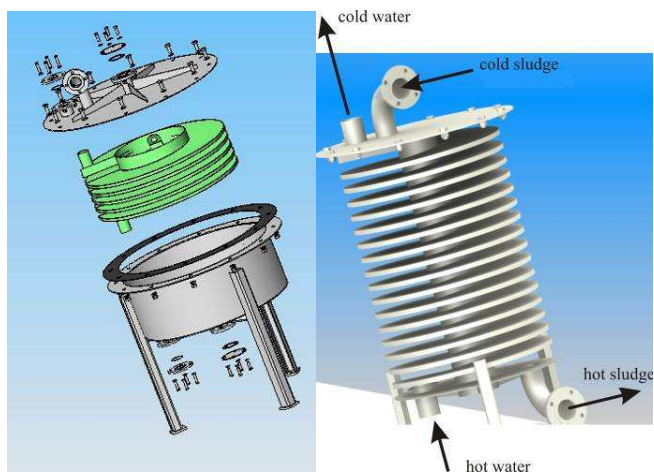


Fig. 15 Illustration of computational support in the modelling of flow in a recuperative heat exchanger

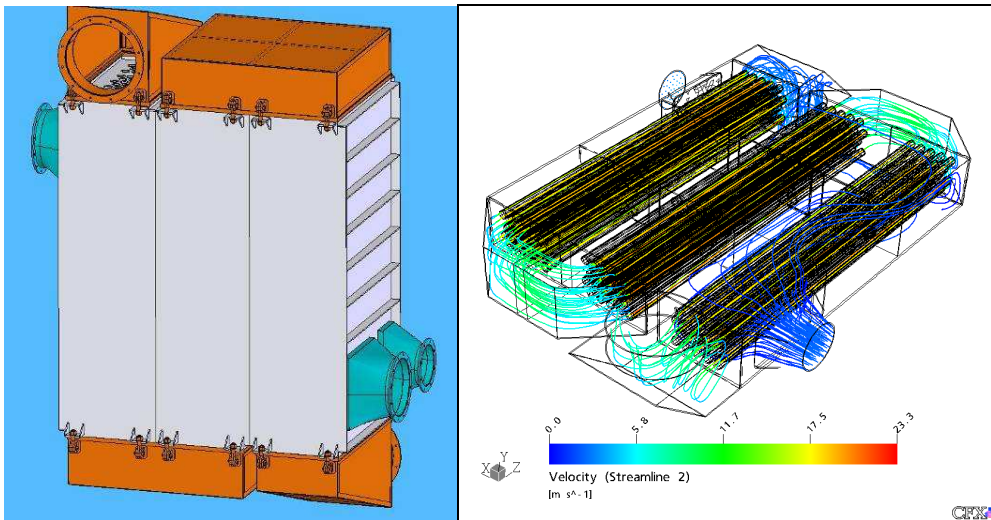


Fig. 16 Recommended steps in design

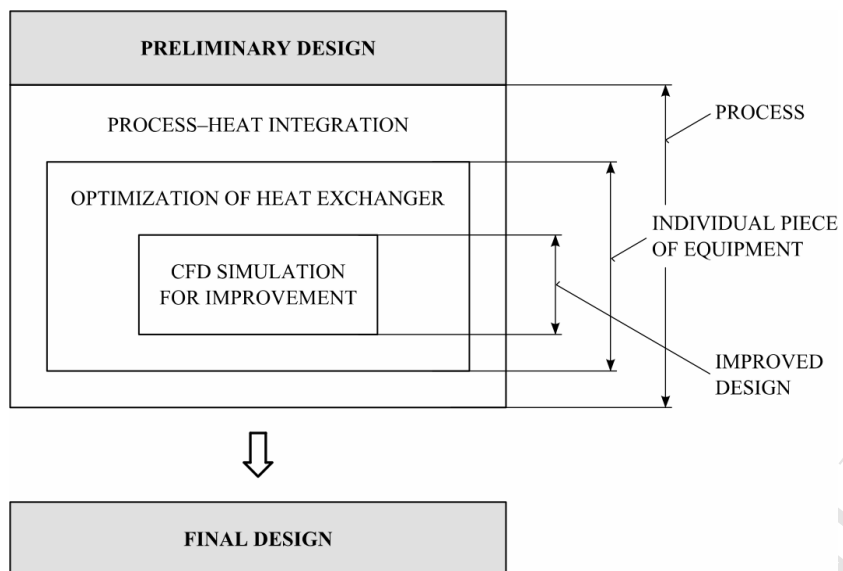


Fig. 17 Composite curves for incineration plant [23]

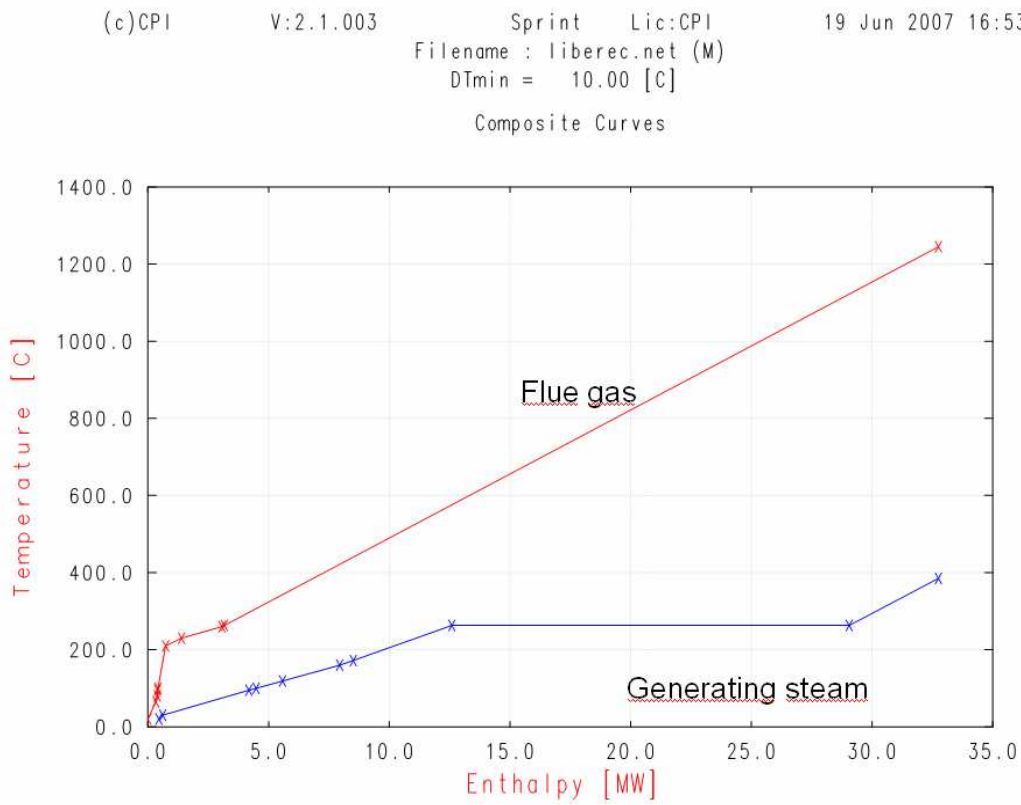




Fig. 18 A zoomed part of composite curves from Fig. 17 for lower temperatures [23]

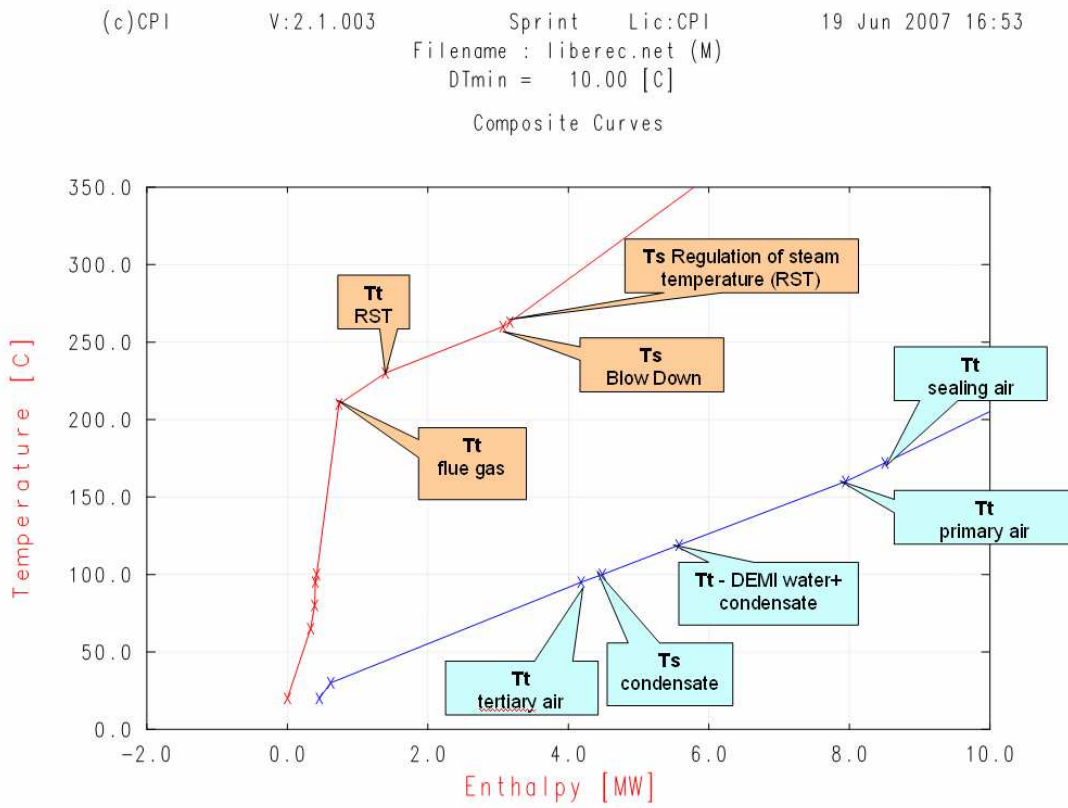


Fig. 19 Heat exchanger system for „flue gas/air“ application

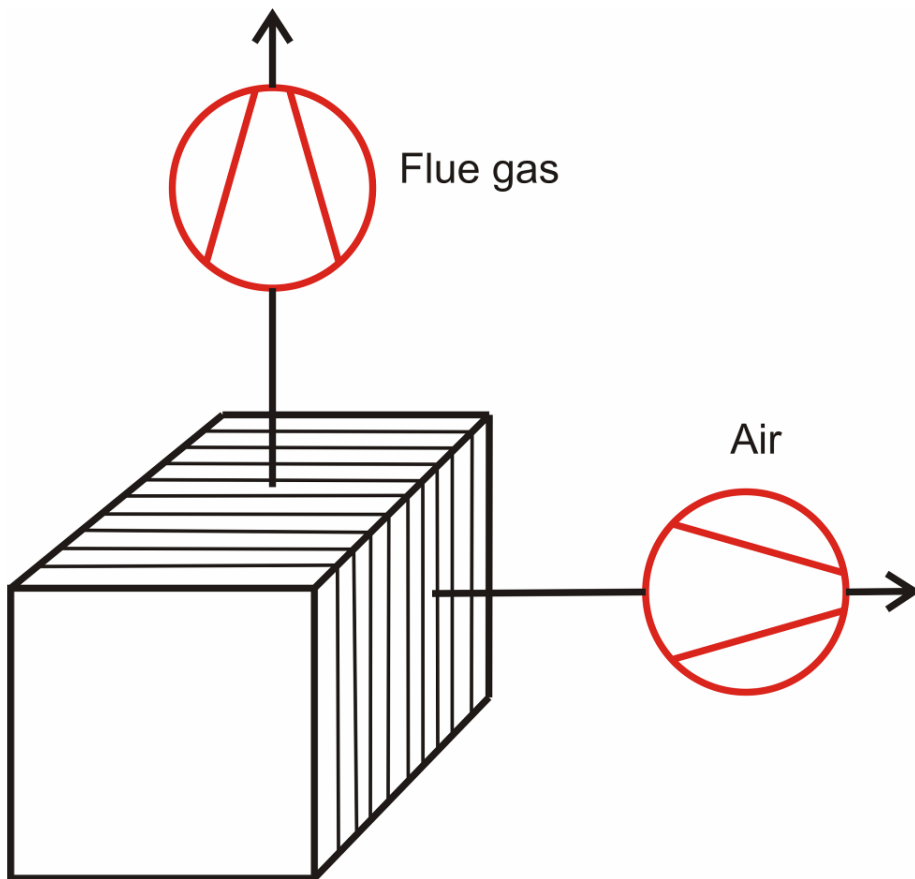


Fig. 20 Geometry of flue gas duct with heat exchanger [33]

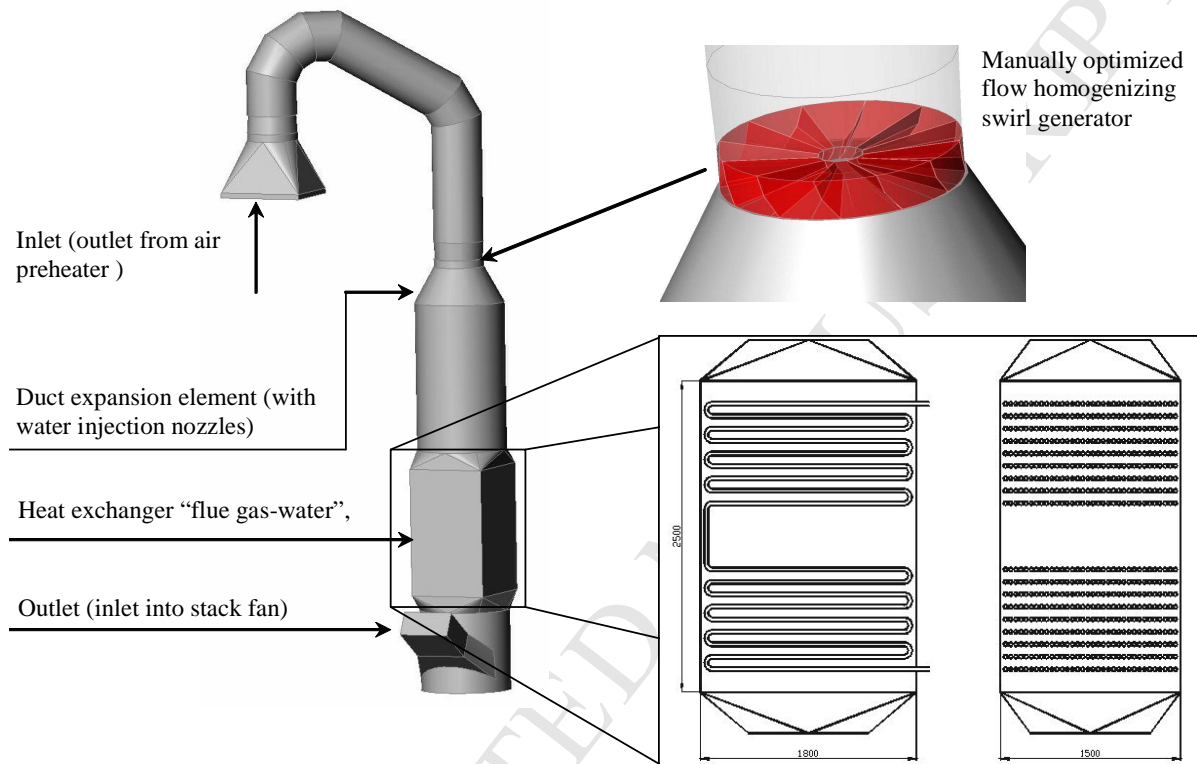


Fig. 21 Flue gas velocity distribution around tube bank inserts (from Fig. 4) obtained by CFD simulation

