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ASPECTS OF FOULING IN CASE OF HEAT EXCHANGERS WITH POLLUTED GAS

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ABSTRACT

This paper presents and discusses various aspects of fouling in case of heavily polluted flue gas (and/or off-gas) coming especially from incinerators/waste-to-energy systems.

A long-term experience and know-how from this area as well as continuing research and development brings new insights into manufacturing of equipment and their operating. Polluted off-gas causes high propensity to fouling and necessity of consequent cleaning. In some cases, it is not possible to utilize a conventional approach.

Introductory part of the paper provides a description of various types of units for thermal processing of wastes (including sludge and contaminated biomass). Fouling is classified according to various cases of industrial applications connected with easy/difficult cleaning. It is shown how fouling can influence geometry of heat exchangers and their selection.

In the following part, several industrial cases are shown taking into account aspects like:

- solid particles (ash and flying ash) in the gas, and adapting design according to their concentration;
- species contained in flue gas which can chemically react and create fouling deposits on heat transfer surfaces;
- potential corrosion between the fouling layer and heat transfer surface caused by local temperature decrease.

The above aspects are clearly illustrated through industrial applications as follows:

- heat recovery system of unit for the thermal treatment of sludge coming from pulp and paper production;
- boiler systems in incineration plants and chemical industry plants.

There are various methods to reduce fouling. We have utilized very efficient approach combining intuitive design and sophisticated tools based on CFD (Computational Fluid Dynamics). However, fouling cannot be eliminated completely therefore various efficient methods (mostly tailor-made ones) are utilized (like common mechanical cleaning, air guns, controlled local explosion) for cleaning of surfaces.

There is also an effort to develop a mathematical model for fouling prediction, and selection of the most economically acceptable systems connected with current research and development in the field. However, it is difficult to validate the models.

Fouling in the field described in the paper is in fact a “never ending story”.

INTRODUCTION

Once we are familiar with various aspects of fouling in case of heavily polluted flue gas (and/or off-gas) coming from incinerators/waste-to-energy systems, it is easier to solve other industrial problems connected with fouling in case of similar applications.

A long-term experience and know-how from this area as well as continuing research and development [1, 2] bring new insights into manufacturing of equipment and their operating. Polluted off-gas causes high propensity to fouling and necessity of consequent cleaning. In some cases, it is not possible to utilize a conventional approach.

It is useful to illustrate and explain experience with fouling problems through various types of units for the thermal processing of wastes (including sludge and contaminated biomass). It can be shown how fouling can influence geometry of heat exchangers and their selection.

Let us describe the “polluted flue gas applications” first in other words units for the thermal processing of waste.

Flue gas from waste incineration plants as the most difficult case

Ever rising production of municipal and hazardous waste inevitably leads to the issue of its suitable treatment. Waste to energy operation in waste incinerators seems to be the best solution. Heat contained in flue gas may be used for other purposes, such as heating of combustion air, water heating, etc. However, produced flue gas and/or off-gas also contains pollutants which have a negative impact upon other equipment such as heat exchangers since the pollutants decrease their efficiency and increase pressure drop. Therefore, special attention has to be paid when choosing a suitable heat exchanger.

Technologies with heavily polluted gas

The suppliers of 21st century's incinerators have to meet more and more strict environmental regulations and at the same time achieve maximized utilization of energy from the waste incineration. To compare the effectiveness of energy production in different incineration plants a simple method has been developed by The Confederation of European Waste-to-Energy Plants [3], which associates 200 operators of waste-to-energy plants in Europe. This approach is based on evaluating two criteria, *Plant Efficiency factor* and *Energy Utilization Rate* [3]. The first criterion defines the ratio between energy produced by incinerating the waste and energy consumed by the process itself and the second one shows what part of the total energy released is utilized. Currently, increasing importance of the design of heat recovery system as a whole as well as individual equipment for heat recovery is obvious from references concerning Best Available Techniques (BAT), see e.g. [4, 5]. Various types of heat exchangers serve this purpose and, on the other hand, the same or similar heat exchangers are used in different types of incinerators. Waste processing is described in many references and monographs, e.g. [6-8]. Let us only briefly mention typical waste processing technologies related to the waste type and origin.

Waste incineration is performed in a combustion chamber equipped with a moving grate and followed by a secondary combustion chamber under temperatures ranging between 850 °C and 1,000 °C. The heat released in this process is utilized in a heat recovery steam generator, most often for the production of superheated steam. Flue gas is cooled down to approximately 250 °C to 280 °C in the boiler and at the same time major part of fine fly ash particles (entrained by flue gas from the combustion chamber) is separated. Mechanical cleaning of flue gas with the aim to collect the remaining particulates is performed in electrostatic precipitator. A part of flue gas (and/or off-gas in terms of incineration terminology) leaving this equipment is recycled back to the combustion chamber and the remaining part enters the block of off-gas cleaning, comprising a wet scrubber and a system for removal of nitrogen oxides (DeNOx). The overall technology can also involve a unit for destruction of dioxins and furans (e.g. very efficient dioxin filter). This is a feature of up to date incinerators since recycling contributes to decreasing exhaust emissions amount. Thus based on the lower off-gas flow rate, size of equipment constituting the final part of the off-gas cleaning system is decreased as well.

In order to achieve a perfect combustion, two-stage incineration is the most common unit in case of the thermal treatment of industrial and hazardous waste. Rotary kiln is usually used as key equipment in the first stage of incineration. Combustible portion of the waste burns under the condition of oxygen excess and therefore the heat releasing process is actually completed in the kiln. Thermal decomposition and oxidation continue in the secondary combustion (after-burner) chamber, where temperature of flue gas is increased to the required level by means of burners firing an auxiliary (gaseous) fuel.

Cooling of flue gases is partially carried out in the air preheater, and particularly in the waste heat boiler and/or heat recovery steam generator. 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, sulfur oxides, emissions of heavy metals, etc.) would be removed down to the level required by emission regulations.

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 preheating) to solve heat transfer problems. In this case the heat exchanger for air preheating represents the main concern because its design has to enable cleaning during operation due to excessive fouling by tarry products on the flue gas side [9].

Off gas as process fluid

Both gas products and solid residues are produced from combustion of waste, i.e. incineration. 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 elements and compounds. It contains harmless components like nitrogen, carbon dioxide and water vapor, but also included in flue gas are harmful components like nitrogen oxides and sulfur oxides, carbon monoxide, hydrogen chloride and fluoride, dust, heavy metals and their chemical compounds, phosphorus compounds and organic compounds like hydrocarbons. It is necessary to take into consideration that harmful compounds of acid character are transferred into gas phase. Hydrogen chloride produced by thermal decomposition of chlorinated plastics is considered as a predominant one. Sulfur dioxide, heavy metals (Cd, Hg, Cr, Zn, Cu, Pb) and dust also belong among the main harmful pollutants. Further to that, chlorinated hydrocarbons like 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_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 from conventional combustion chambers, furnaces, boilers etc. Fouling obviously represents a serious problem.

Fouling in incinerators vs. selection of heat exchangers

Fouling represents a very important and complex problem in waste incineration plants. Fouling of a surface takes place as a result of the complex 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 [10].

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.

Dominant mechanism of fouling in waste incinerators is particulate fouling. Particulate fouling is defined as deposition of unwanted material (i.e., particles) on a heat transfer surface. Products of fouling (i.e., sticking deposits) cause heat transfer resistance and lead to increased capital and maintenance costs and major production and energy losses in many especially energy-intensive industries [11]. This is the dominant fouling mechanism of heat transfer equipment installed at waste incineration plants and other related applications.

Fouling of heat exchangers cannot be completely avoided. However, it may be significantly influenced by choosing a proper type of heat exchanger. A typical problem concerning design of heat exchangers in this field is given by fact that most of applications are different and therefore we face demand on specific types of equipment. For heat transfer surfaces of heat exchangers are preferred smooth tubes or tube banks and/or exchangers with plain plates where possible. Such configurations allow easy cleaning on both outer and inner heat transfer areas.

If we use finned tubes for heat exchanger where flue gas contains a lot of ash, heat transfer surface fouls quickly and heat transfer decreases while pressure drop increases. This type of heat exchanger has to be cleaned, which leads to frequent shut downs of operation.

IMPORTANCE OF MODELING AND OPTIMIZATION IN CASES OF HIGHLY FOULING FLUIDS

This chapter deals with operation problems of heat transfer in processes with great amount of fouling and with potential of implementation of CFD for modeling and optimization for prediction and reduction of fouling. As mentioned before, heat exchangers with plain tubes or plate types should be used for heat transfer processes in waste incinerators whenever possible. These configurations allow easy cleaning on both outer and inner heat transfer areas.

Industrial examples

Any alteration to the above mentioned fact may lead to important cost losses or to other problems. Figure 1 shows an example of unsuitable (upward) flue gas flow direction in a heat exchanger module with plain tube coils (before and after cleaning). The problem was solved by using tube bank inserts for an increased auto-cleaning capability (cf. further; Figures 12, 13 and 14).

a) Module with tube coils

b) Fouled and cleaned tube bank

Figure 1 Heat exchanger from thermal oil circuit

If in the incinerator the air preheater 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 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 [1] 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 preheating.

In the case of low fouling applications the common method is to use a conventional plate type heat exchanger with a modular arrangement (see Figure 2), which can be classified as a low-compact solution - area density typically ranges from 100 to 200 m^2/m^3. However, such an application must be designed very carefully.

Authors of this article have had an experience with such an application where a conventional plate type heat exchanger (shown in Figure 2) 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 3).

For this application a new type of the air preheater (see Figure 4) was designed, manufactured and successfully put into operation and has operated without any problem since then.

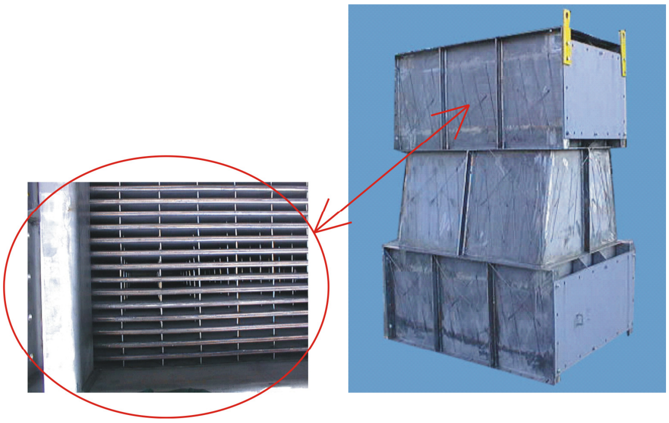

Figure 2 Plate type heat exchanger for air preheating (left – arrangement of plates; right – whole module) (Courtesy of EVECO Brno Ltd)

Figure 3 Heat exchanger after operation (Courtesy of EVECO Brno Ltd)

Figure 4 New design of "double-U-tube" air preheater (Courtesy of EVECO Brno Ltd)

This non-conventional design is based on using "double-U-tube" banks (Figure 5) in a modular arrangement. Inlet and outlet air collectors can be optimized for uniform air distribution [12]. The overall design enables a potential replacement of tube bank even during operation.

Figure 5 U-tube bank (Courtesy of EVECO Brno Ltd)

There are also other ways of reducing fouling during operation. For example if flue gas contains solid particles (fly-ash) that tend to deposit in certain areas of the equipment. These areas (sometimes called stagnation zones) can be characterized by a relatively low flow velocity or presence of eddies [13]. Usually, they exist near obstructions in flow channels or near places where flow direction changes considerably (wyes, sudden channel expansions or contractions, etc.) [14]. It is therefore beneficial to analyze the system using a CFD tool (e.g. FLUENT) in order to identify possible critical areas. Once such areas are identified, geometry of relevant parts can adequately be modified. However, the analysis has always to be performed with regard to the actual operating conditions (total flow rate, heat transfer, velocity field at inlet, etc.), since these largely influence velocity fields along the unit's channels.

Considering the discussed air preheater in which U-tube ends protrude into splitting and collecting manifolds, critical areas can be expected to exist around these ends. Figure 6 shows an expected flow pattern based on available literature and author's experience while pathlines in an actual splitting manifold obtained by CFD simulation using FLUENT are depicted in Figure 7. Ideally, smooth wyes (Figure 8) could be used to rectify the situation around the U-tube ends, however, fabrication of such wyes and their connection to the manifolds would be very problematic. Therefore, wyes with vanes and exserted cut U-tube ends (Figure 9) could be used to both decrease the fouling rate and improve fluid distribution.

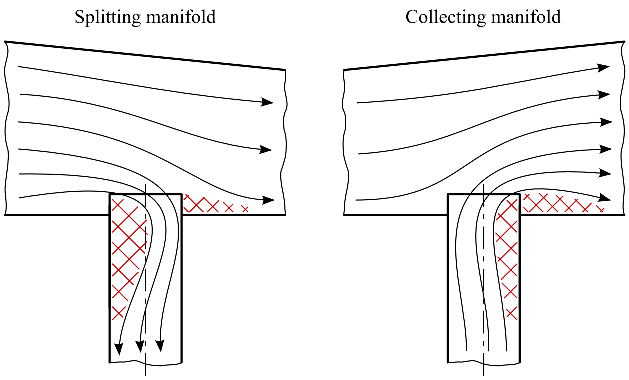

Figure 6 Flow pattern near U-tube ends – hatching denotes areas with high propensity to particle deposition (based on available literature and authors' experience)

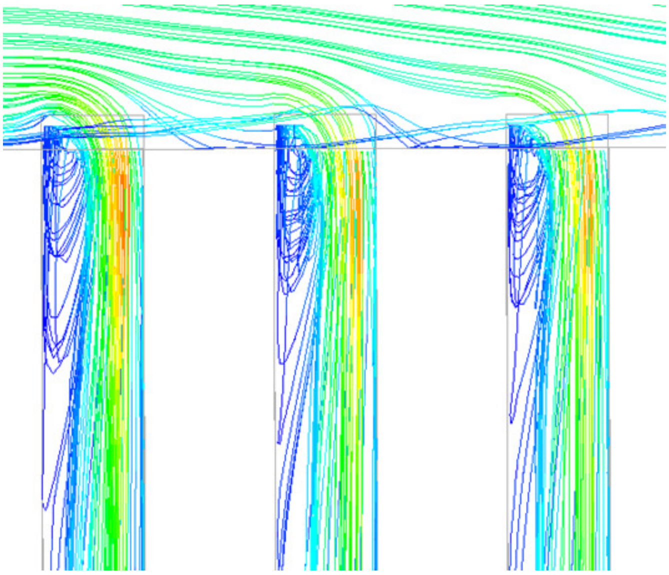

Figure 7 Pathlines in an actual splitting manifold obtained by CFD simulation using FLUENT

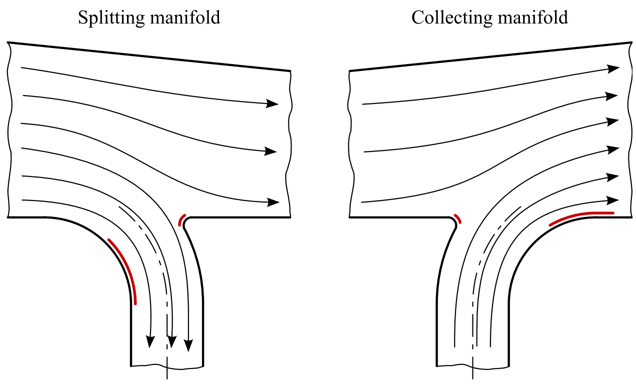

Figure 8 Smooth wyes (theoretical solution) – thick red lines denote areas with high propensity to particle deposition

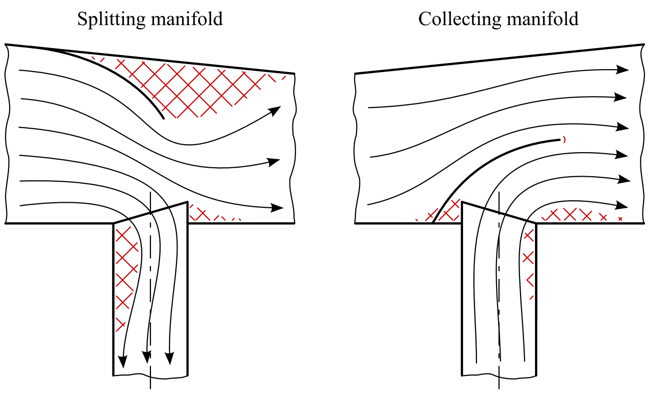

Figure 9 Wyes with vanes and protruding cut U-tube ends (potential practical solution) – hatching denotes areas with high propensity to particle deposition

It is obvious that when a fouling fluid is used the resulting flow distribution can influence formation of deposits as well. Flow distribution uniformity should therefore be as high as possible. Since the amounts of fluid that discharge from (or flow into) a manifold through U-tubes are governed by pressure conditions in the distribution system, changing those conditions will also change the distribution. This can be achieved using three different approaches [14]:

1. U-tubes of different diameters or other modifications of geometry of tube inlets (nozzles etc.) based on known pressure profiles in manifolds ensuring uniform or nearly-uniform distribution;
2. manifolds with large cross-sectional areas so that pressure changes therein are sufficiently small compared to pressure changes in U-tubes (in this case manifolds can be considered as constant pressure reservoirs);
3. variable cross-sections of the splitting and collecting manifolds ensuring uniform static pressure along their lengths.

Option 1 includes e.g. variable exsertion of U-tube ends along manifolds' lengths, however, based on performed simulations such a measure only causes insignificant changes of flow distribution uniformity (order of tenths of a percent). Other modifications falling into this category are usually not feasible due to the fact that additional nozzles or other barriers in the tubes can cause an unacceptable increase of the total pressure drop or fouling rate.

Option 2, on the other hand, is very good considering cost and ease of manufacturing, but there is rarely enough space for manifolds large enough to achieve the desired effect. Thus we are left with option 3, i.e., construction of manifolds such that the cross-sections vary along their lengths. As for the discussed air preheater, a distributor and collector shape optimization package has been developed using data obtained from the CFD flow modeling tool FLUENT [12]. Using this package, one can analyze an existing flow distribution system similar to the one in Figure 5 or find the best possible shapes of both manifolds in such a system in terms of flow distribution uniformity or total pressure drop.

Regarding general fluid distribution systems, an optimization tool developed in Maple [15] is available. As of now, this tool supports constant cross-section manifolds only, but the tube bundle connecting the splitting and collecting manifolds is user-definable and can be completely arbitrary.

Use of CFD simulations

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 Figure 10. Let us indicate which units/equipment of the system are the main candidates for modeling using CFD and potential achievements: secondary combustion chamber, flue gas ducts,

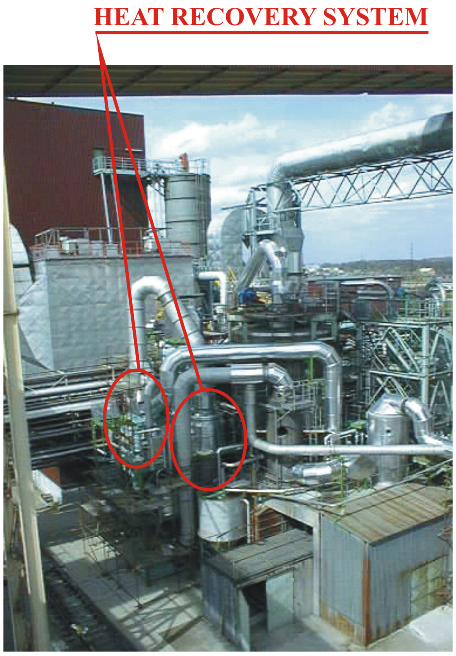

Figure 10 View of unit for the thermal treatment of sludge with heat recovery system [17]

low-NO_x burners, filters, heat exchangers. Let us focus on examples related to heat recovery system [16].

Example 1: 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 utilized for studying the flow inside exhaust duct of an incineration plant. Flow pattern in this flue gas duct (see Figures 10 and 11) 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. 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

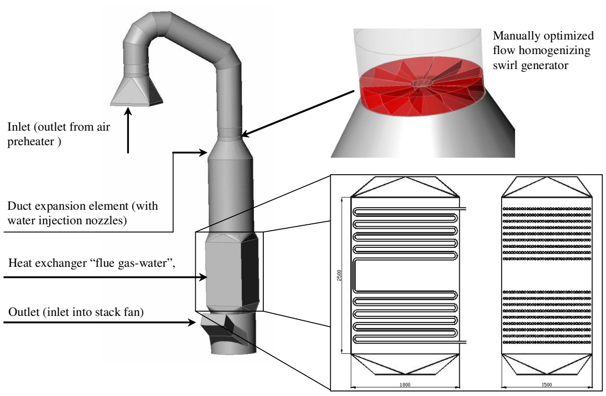

Figure 11 Geometry of flue gas duct with heat exchanger

work has focused on several flow homogenizing measures in the form of vanes and swirl generators [16].

An improvement of about 10% in terms of maximum velocity magnitude has been obtained with the so called "manual optimization" approach [16]. First results from the computational optimization show that further improvement by 8% is still possible [18].

Example 2: tube bank inserts.

The problems with heavy particulate fouling of heat recovery tube bank of an incineration plant were solved using the developed model for prediction of critical velocity [19] (will be discussed in the following chapter) 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 modeling 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 Figures 12 and 13).

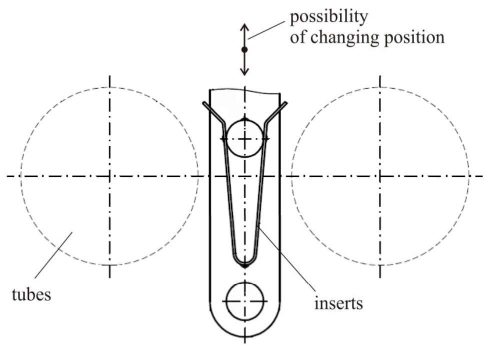

Figure 12 Example of passive enhancement approach for improved auto-cleaning capability in applications with highly fouling flue gas containing high amounts of ash particles (Courtesy of EVECO Brno Ltd)

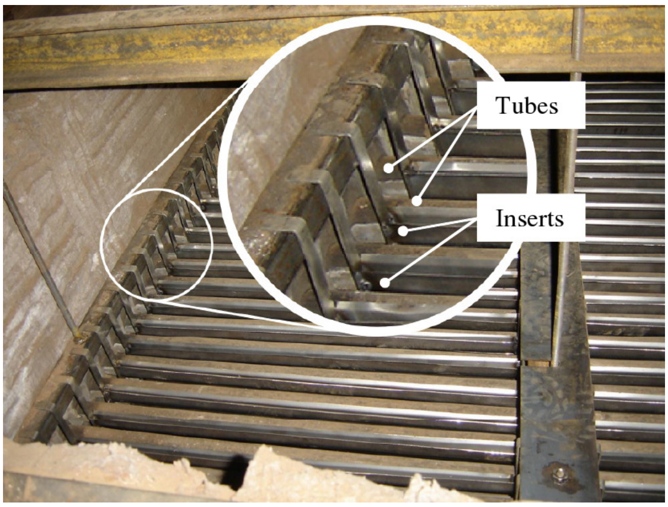

Figure 13 Installed tube bank inserts (Courtesy of EVECO Brno Ltd)

Illustration of CFD results is obvious from Figure 14. 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 flow velocity.

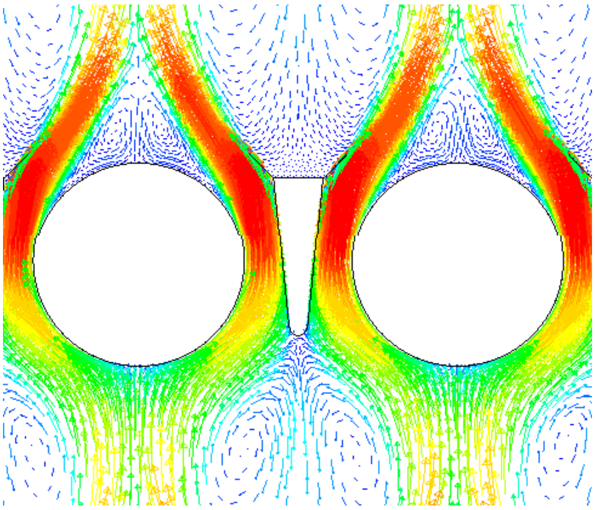

Figure 14 Flue gas velocity distribution around tube bank inserts (from Figure 12) obtained by CFD simulation

ASPECTS OF FOULING MODELING

Heat exchangers in relatively lower temperature applications such as economizers of boilers are subjected to gases that contain particles of a wide range of sizes. To prevent fouling of heat exchangers based on critical fouling velocity, the critical fouling velocity should be selected on the basis of the particle size that is most likely to stick first to the heat exchanger tubes. As reported in [20], fouling layer found on economizer tubes of a boiler contained particles of size ranging from 1 to 10 μm. This range represented only a small portion of the fly ash particle sizes in the flue gases, which contained particles with sizes ranging from 1 to 450 μm [20].

Such a large particle size range is typical for the applications just mentioned, and such a fouling process is accompanied by some important aspects as identified in [20, 21], such as mechanism of sticking, sintering of layer of sticking particles, and thus the change of fouled layer properties during operating time of equipment.

As was observed in [22], the smallest particles contained in the flue gas flow first deposit on tubes of the heat exchanger at the areas of minimum fouling velocities. Then the large particles deposit and the fouling layer starts to build up. The fouling layer thickness and growth over the heat exchanger tube are predominantly influenced by the flow speed. As the flow speed in the heat exchanger increases, the thickness of the fouling layer deposited over the heat exchanger tube is reduced. There is a limiting flow speed above which fouling is avoided. This limiting speed is related to the so-called critical fouling velocity required to roll a particle resting on a flat surface. To prevent fouling, the flue gas speed around heat transfer area should be larger than the critical (limiting) fouling velocity that corresponds to the particle size most likely to stick on the heat exchanger tube.

As identified in [23], electrostatic forces may play a significant role in bringing particles to surfaces for adhesion. The presence of a liquid between the particle and surface, either due to an immersion with a subsequent removal from a liquid or due to high humidity conditions, can add a very large capillary force to the total force of adhesion. This capillary force is known to stay, in some cases, even after baking at above the liquid boiling point for many hours. Although there are certain possibilities for particle removal, it turns out to be extremely difficult in practice due to these large forces.

It is necessary to compose the balance of forces affecting the particle in order to determine the boundary (limit) speed of flue gas flowing. As shown in Figure 15, there are several forces affecting a particle placed on the heat exchanger surface that is exposed to a flue gas flow.

Our analytical model [19] is then characterized by an extended definition of the ratio between the hydrodynamic rolling moment and the adhesion resting moment, denoted as RM_E and equal to

$$RM_E = \frac{\text{Hydrodynamic rolling moment}}{\text{Extended adhesion resting moment}} \quad (1)$$

After evaluation, we obtained

$$RM_E = \frac{F_d(1.399R - \alpha)}{(F_a + F_g + F_{eli} + F_{elU} + F_{cap} - F_b - F_l)\,d/2}, \quad (2)$$

where F_d denotes drag force, R particle radius, α particle radius deformation, F_a adhesion force, F_g gravitational force, F_{eli} electrostatic image force, F_{elU} electrostatic double layer force, F_{cap} capillary force, F_b buoyancy force, F_l lift force, and d contact diameter due to particle deformation.

The critical fouling velocity is then determined from condition that RM_E equals 1 together with expression of individual forces and terms in Equation 2. Using this model we performed calculations in order to determine the value of critical fouling velocity. Calculations were carried out for a typical industrial case (such as an economizer in [20]). The input data used are summarized in Table 1.

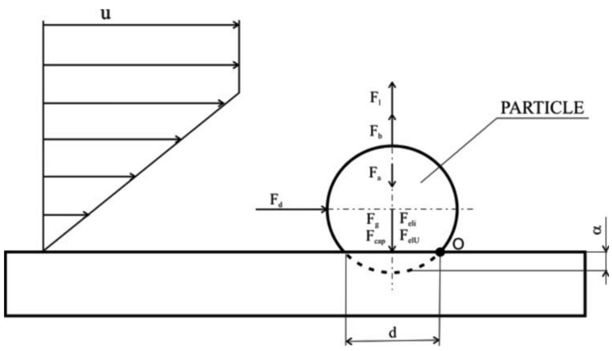

Figure 15 Schematic showing the different forces acting on particle resting over a surface and exposed to fluid flow

Table 1 Input data for typical industrial example solved by our developed analytical model

Temperature [°C]	200 °C	340 °C
Flue gas density [kg·m^{-3}]	0.731	0.564
Flue gas viscosity [Pa·s]	$26.24 \cdot 10^{-6}$	$31.32 \cdot 10^{-6}$
Surface tension of water [N·m^{-1}]	$37.69 \cdot 10^{-3}$	$5.59 \cdot 10^{-3}$
Density of ash particles [kg·m^{-3}]	208	
Flue gas pressure [Pa]	99,325	

Results of calculations of this model are summarized in Table 2.

Table 2 Critical fouling velocity for typical industrial case obtained by our developed model

Particle size [mm]	0.5	0.3	0.1	0.01	0.001
Critical flue gas fouling velocity (200 °C) [m·s^{-1}]	9.59	13.5	29.5	162	513
Critical flue gas fouling velocity (340 °C) [m·s^{-1}]	10.6	14.3	28.2	81.6	251

Evaluation of influence of flue gas temperature (and properties) on obtained results in Table 2 is interesting. It is obvious that change of flue gas viscosity and density is more important in small particles (less than 10 μm). Moreover, the temperature change of water surface tension significantly changes the capillary force acting on these small particles. Influence of temperature is very important in industrial practice, as it strongly influences deposit character (slagging process of fouling layer). It was clearly demonstrated in paper [20] on comparison of structure and composition of flue gas side deposits from a steam superheater (inlet flue gas temperature was 580 °C) and an economizer (inlet flue gas temperature was 340 °C) from a boiler installed at a waste incineration process plant. The deposit analyzed from superheater tubes was hard and thick in comparison with the deposit from economizer tubes, which was thin and powdery.

According to [20] is possible for a typical industrial case (by a suitable arrangement of tubes in tube bank of heat exchanger) to achieve an elimination of fouling from 70 up to 80% of total amount of particles, since flue gas velocity of about 25–30 m/s is accessible and likely but depends on concrete technical application and its limitations.

Complete evaluation of the design of a heat exchanger from the fouling point of view must be supported by technical-economic analysis that takes into account investment, operating, and maintenance costs with respect to character and constitution of deposit.

Our developed model, allows improved prediction of critical (limiting) fouling velocity. Model is suitable for equipment fouling tendency prediction and for prevention in design and operating of tubular heat transfer equipment designed for applications in waste incinerating plants. Derivation and detailed explanation of this model is presented in [19] where practical application with appropriate selection of heat exchanger geometry (based on technical-economic analysis) is presented, too.

IMPORTANT ROLE OF CLEANING SYSTEM

As it has been demonstrated in the previous paragraphs, fouling is a phenomenon that has to be taken into account as early as during the design of process equipment. Fouling itself can be caused by sedimentation of dust particles (sedimentation fouling) or by other mechanisms – e.g. biological fouling. Considering sedimentation, particles in the layer can either be loose or consolidated by physical-chemical mechanisms (inverse solubility fouling and chemical reacting fouling – smelting of particles, thermal degradation of one of the components of the medium, chemical reaction, change of solubility causing crystallization in case of water solutions, etc.). Dust particles containing alkali metals (Na, K), vanadium, sulfur, chlorides, etc. tend to smelt and create corrosive deposits at the combustion chamber outlet.

If fouling cannot be prevented, it is necessary to make certain provisions for periodic removal of deposits. This involves a combination of dissolution, erosion or spalling of the deposited material. There are two types of engineering approaches to the elimination of fouling. The first one lies in designing the equipment in such a way that fouling is minimized whereas in the second case an additional on-line heat transfer area cleaning system is installed. However, on-line removals cannot be too frequent and therefore formation of deposits can only be controlled by maintaining proper operating conditions. In such a case removal of deposits when equipment is shut down periodically 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 when cleaning hard to access areas. Mechanical methods of cleaning are expensive and also tend to erode heat transfer surfaces. It is often noted in boiler-related sources that 2mm deposit will effectively increase fuel consumption by approximately 5% [24]. Thus, because fouling is a very important problem in heat transfer equipment used for thermal treatment of wastes it is necessary to use only smooth heat transfer surfaces without any extensions. This restriction strongly limits possible configurations of heat transfer equipment. Any offence against this fact can lead to important financial losses.

Corrosion of heat transfer surfaces, which occurs especially in case of heat transfer equipment in plants for thermal treatment of waste, is an additional problem related to fouling. If flue gas contains acidic compounds such as SO_2 or HCl and its temperature reaches the condensation temperature of these acids, it becomes very aggressive. Obviously, local decrease in tube surface temperature can be caused by a layer of deposits and then acidic gases can diffuse through this layer to the metal surface of the tube, condense there and cause corrosion. It is therefore advisable to maintain the temperature of the tubes above 150°C or to coat heat transfer surfaces with an anti-corrosive material.

SUGGESTED COMPLEX APPROACH

Considering solving problems related to fouling in heat exchangers based on a complex solution described above, we suggest the approach outlined in Figure 16.

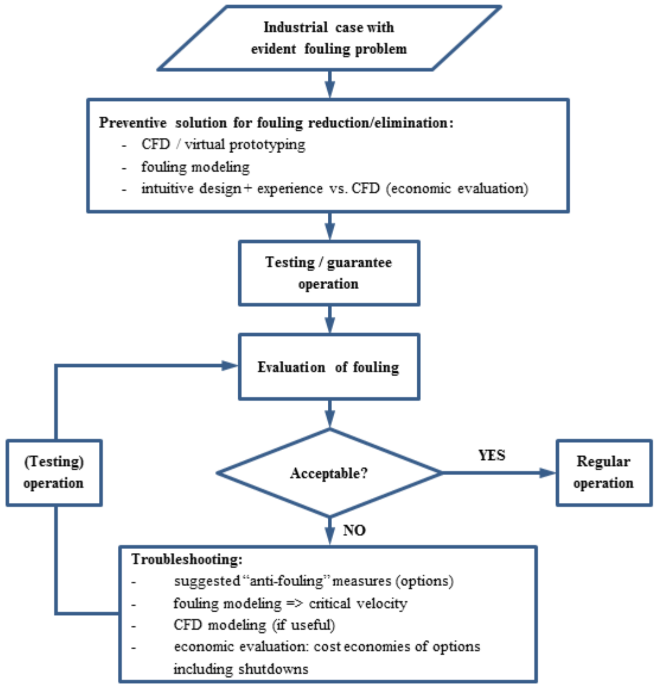

Figure 16 Suggested complex approach illustrated through block diagram

CONCLUSION

Problems related to fouling when a highly fouling fluid is used were discussed, especially the case of heat recovery equipment in waste treatment plants where flue gas tends to contain high amount of pollutants. Fouling is a serious problem there and as such it has to be taken into account as soon as during process equipment design. For instance, upward flow of flue gas through heat exchangers should be avoided to limit particle accumulation on the upper heat transfer surfaces. Moreover, plain heat transfer surfaces have to be used.

Importance of modeling and optimization was demonstrated through several industrial examples and a method for particulate fouling modeling was presented. Also, fluid distribution in tubular heat exchangers was mentioned since it can (together with system geometry) largely influence velocity fields, presence of eddies and stagnant zones, etc., which consequently affect fouling rate. Possible design modifications for distribution uniformity increase were proposed as well.

The role of a cleaning system, be it an on-line one or a regular one, was discussed along with the possibility of a secondary corrosion of heat transfer surfaces. Such corrosion can occur when temperature of these surfaces is below condensation temperature of acidic compounds present in the flue gas (for instance when the surfaces are fouled, thus colder, and acidic compounds diffuse through the layer of accumulated solid particles).

Last but not least, a complex approach to problems related to fouling was presented. Even when process equipment has been designed according to the guidelines and with fouling in mind, regular evaluation of formation of deposits is necessary to ensure the required performance.

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