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APPLICATION OF COMPLEX APPROACH TO TROUBLESHOOTING RELATED TO WASTE GAS PREHEATER FOULING

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ABSTRACT

Application of a complex approach to solution of elimination of fouling and operating troubles of a waste gas preheater is presented in the paper. The waste gas preheater is a part of a gaseous wastes incineration plant serving for incineration of wastes from acrylic monomer production plant. The preheater is configured as a specific U-tube bank heat exchanger and is used for preheating of a process waste gas (PWG), flowing inside tubes, before its incineration. Flue gas a product of incineration of PWG serves as hot fluid in the shell-side of the preheater. Thermal duty of the preheater (given by outlet PWG temperature) substantially influences quality of incineration and emissions in the exiting flue gas. Operating difficulties of preheater consist of plucking of U-tubes from tube sheet at the cold end of the preheater and of decreasing the duty due to intensive fouling (by both process fluids). Moreover, fouling present on the PWG side causes clogging of some tubes due to drifted sticky droplets contained in the PWG stream. Due to operating troubles of this preheater requiring frequent cleaning and maintenance, currently the incineration plant requires frequent shutdowns. This fact negatively influences not only lifetime of individual parts of the incineration plant but also (even more) production of the monomer plant which cannot be operated without a running incineration plant. Complex approach applied to solving of the preheater problems includes analysis and troubleshooting procedures which are described in detail in the paper. A comprehensive set of non-costly measures is proposed and successfully realized for the elimination of preheater operating troubles.

INTRODUCTION

Fouling is generally an important problem which significantly influences function of heat exchangers. It usually brings about a decrease in heat duty of the equipment and can also be the cause of various types of mechanical failures.

One such case is presented in this paper. It concerns a gaseous wastes incineration plant that is a part of an acrylic monomer production plant. Simplified flow sheet of the incineration unit is shown in Fig. 1. The problem occurred in preheater HE3 (see also Fig. 2) which is used to preheat process waste gas (PWG) by flue gas produced in furnace FU. Although PWG passes through the demister D before entering the preheater, there still remains a large amount of sticky droplets which then form a jelly-like layer on the inlet tube sheet and, consequently, clog inlets of some of the tubes of the preheater. This results in a significant decrease in preheater HE3 heat duty.

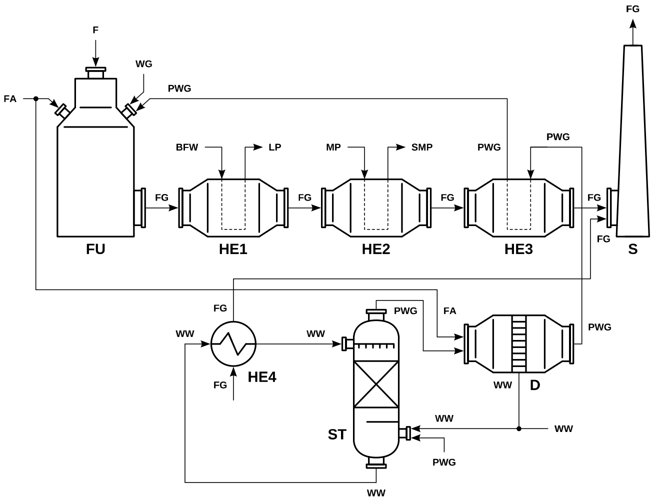

Fig. 1 Simplified flow sheet of the gaseous waste incineration unit
Legend: Streams: BFW-boiler feed water, F-fuel, FA-air, FG-flue gas, LP-low pressure steam, MP-medium pressure steam, PWG-process waste gas, SMP-superheated medium pressure steam, WG-waste gas, WW-waste water. Equipment: FU-furnace, HE-heat exchanger, ST-stripper, D-demister, S-stack)

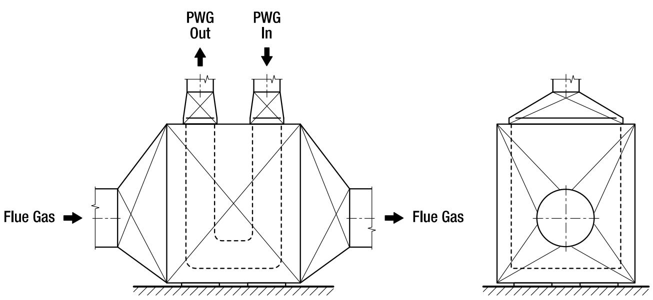

Fig. 2 Scheme of the preheater HE3

As will be clear from the following text, the primary causes were presence of sticky droplets in the PWG stream and an unsuitable geometry of the inlet transition piece between the circular inlet duct and the rectangular inlet tube sheet. Such a geometry promoted formation of stagnation zones in the tube side inlet region which, in combination with presence of droplets in the PWG stream, resulted in extensive fouling and consequently also clogging of inlet parts of some of the U-tubes in the bundle (see Fig. 3). Increased thermal loading due to insufficient cooling of the clogged tubes then caused cracking of some of the unobstructed tubes in the bundle (see Fig. 4) and thus also a leakage of PWG into the shell side of the preheater (see Fig. 5), where flue gas temperature is about 250°C.

Fig. 3 Fouled inlet tube sheet

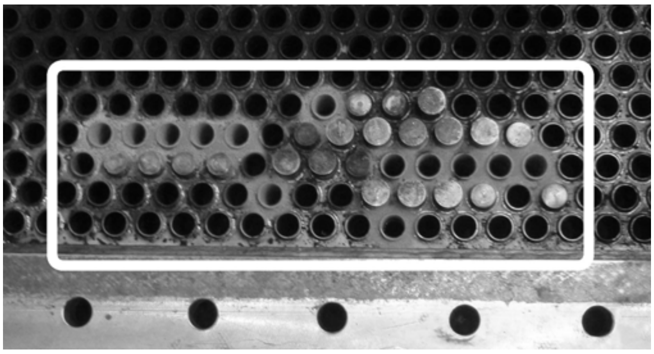

Fig. 4 Cracked U-tubes; some of them have already been blanked during the last service shutdown, the other marked tubes have cracked since then.

Obviously, lower heat duty of the preheater led to substantially worse incineration and therefore impermissible amount of emissions in the flue gas. Additionally, PWG that leaked into tube side inevitably left the unit through the stack which introduced a further increase in the amount of emissions let out into the atmosphere.

In accordance with the complex approach proposed by Stehlík et al. (2011) (see Fig. 6) a thorough analysis was carried out to determine causes of the problems and propose suitable countermeasures. The complex approach can, however, be applied to virtually any industrial case that involves fouling.

Fig. 5 Fouled shell side of the preheater; the black matter is, in fact, solidified PWG leaking into the shell-side through cracked U-tubes.

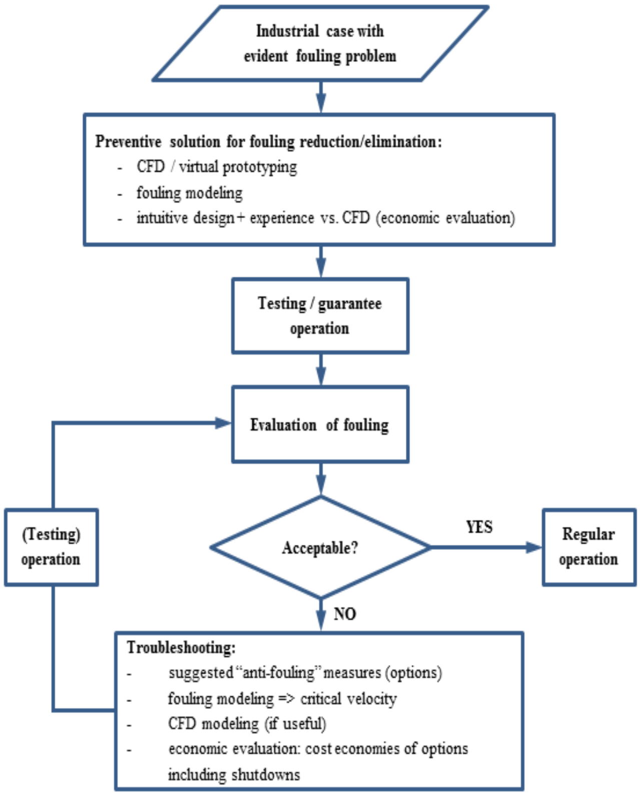

Fig. 6 Complex approach to industrial problems involving fouling (Stehlík et al., 2011)

STRESS ANALYSIS

One of the severe problems encountered in the course of operation of the preheater is cracking of the U-tubes just below the inlet tube sheet. Since under the current fouling conditions some of the U-tubes become clogged, they are not cooled properly by the PWG. Therefore, it was necessary to first establish whether the temperature differences can be the cause of cracking, i.e., whether the U-tube bundle is able to compensate the resulting non-uniform thermal loading.

Methodology

Thermal and structural computational models of the preheater were built to identify and evaluate causes of U-tube cracking. Several modes of operation were investigated – (i) clean preheater, (ii) middle part of the inlet tube sheet being clogged with the rest of the tube sheet being clean, (iii) middle part of the inlet tube sheet being clean with the rest of the tube sheet being clogged, and (iv) inlet tube sheet being fouled according to the provided photographs (as shown in part in Fig. 3). Results obtained via thermal models were then used as initial data for static structural analyses.

As for the actual structural models, these were built in Ansys Mechanical (Ansys Inc., 2012) and contained several simplifications incorporated according to the results of preliminary analyses of individual elements of the geometry in order to ensure reasonable computational cost. These simplifications are described in detail in Lošák et al. (2012). The provided results were then qualitative rather than quantitative and provided insight as to where in the structure potential problems might arise.

U-tube Bundle Layout

Layout of the U-tube bundle is shown in Fig. 7. PWG enters the bundle through the inlet chamber split into three parts by two stiffening transverse partition plates above the tube sheet. Then it divides into individual U-tubes and after flowing through these, it merges into a single stream in the outlet chamber. This chamber is, again, split by two stiffening transverse partition plates. In addition, there are two baffles that prevent vibration and deformation of U-tubes in the bundle.

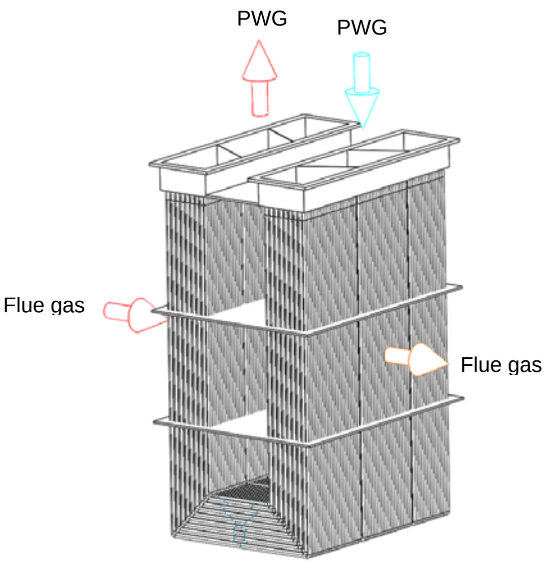

Fig. 7 U-tube bundle (Lošák et al., 2012)

Results

Analysis of the preheater when no fouling layer was present yielded an even stress distribution over the entire tube bundle. There were no places with the allowed stress being exceeded.

In all the other three cases, on the other hand, clogged tubes were not cooled properly. Since the baffles featured holes with very small diametral clearances, rigid connections were formed between the tubes and the baffles thus causing displacements to be carried across from excessively heated tubes to lower-temperature ones. The cooler U-tubes then cracked (as shown in Fig. 4). In fact, when fouling was modeled according to the provided photographs of the actual inlet tube sheet, the model accurately predicted the critical areas where cracking would occur.

In reality, stress redistribution caused by movement of tubes in the baffles can be expected. When an analysis was carried out without any baffles being present, U-tubes could dilate freely and no problems occurred. However, possible vibrations of the tube bundle due to Kármán vortices might introduce the risk of fatigue and removing the baffles is therefore not advisable. Consequently, the most effective solutions seem to be either removing droplets from the PWG stream (rather problematic – see the next section) or changing shape of the inlet transition piece so that there are as little stagnation zones, which promote fouling, as possible.

REMOVAL OF LIQUID CONTENT

The main goal here was to ensure that as low an amount of droplets as possible would enter the preheater. Stripper ST is operated at its maximum capacity. Analysis of the data provided by the plant operator (PWG composition at the outlet of the stripping equipment ST, PWG parameters at the inlet of the preheater, and data related to several operating regimes) was therefore performed as the first step.

The data are presented in Table 1 alongside data obtained via simulations. According to the operator, there were no droplets in the PWG stream (degree of evaporation equal to unity), however, this could not have been the case, because the existing demister D removed 20 – 30 L of liquid every hour.

Table 1 Operating conditions of the preheater HE3 according to the plant operator versus the results of simulations (Pačíska et al., 2012)

Parameter	Plant operator	Simulation
Degree of evaporation, –	1	0,9968
PWG inlet temperature, °C	70	70
Absolute pressure, kPa	110	112
Total amount of the liquid (before demister), L/h	0	57

Simulations confirmed that full evaporation is, indeed, theoretically feasible. Nonetheless, considering the respective dew point curve (see Fig. 8), the actual (nominal) operating conditions (70 °C, 110 kPa), and the inevitable fluctuations of temperature and pressure,

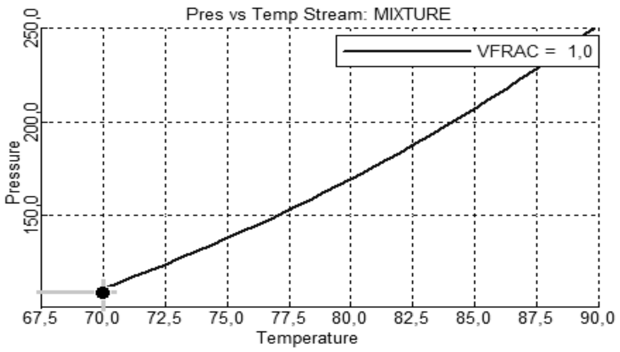

Fig. 8 Dew point curve of the PWG stream (Pačíska et al., 2012) (Pressure units: kPa, Temperature units: °C.)

some liquid had to be present in the PWG stream. The data obtained via simulation (see in Table 1) match the actual conditions quite well and thus they were used during the subsequent design of additional droplet-removing equipment. This, obviously, is because the current demister is not able to remove sufficient amount of the droplets which then leads to the fouling mentioned earlier.

A cyclone in combination with flue gas injection into the PWG stream (to evaporate/solidify as much droplets as possible) would be an ideal solution. The necessary calculations were therefore carried out according to Green and Perry (2008) and Stephan et al. (2010), but the resulting equipment was always prohibitively large considering the existing spatial limitations.

Hence, a different solution was presented to the plant operator, namely integration of another demister identical to the existing one. Its efficiency would clearly be lower compared to the cyclone, but overall the separation rate would be greatly improved. Considering the results of the simulations, it can be stated that efficiency of the current demister D is roughly 50%. By adding another demister, a sufficient total efficiency can be reached with minimum investment and operating costs. Moreover, should a suitable adjustment of the PWG inlet region geometry be performed, an additional decrease in fouling rate could be expected.

IMPROVEMENT OF FLOW DISTRIBUTION

As mentioned in the previous sections, no stress-related damage occurs when inlets of individual tubes and the inlet tube sheet are clean. Since one cannot guarantee droplet-free PWG stream, any stagnant zone presents a risk of locally increased fouling rate and subsequent clogging of the respective tube inlets. This is why a detailed flow analysis of the entire tube-side of the preheater was performed in the course of which particular attention was paid to flow vorticity.

The analysis was carried out using the computational fluid dynamics (CFD) software Ansys Fluent (Ansys Inc., 2011). Obtained results were then utilized during shape optimization of the inlet transition piece in order to ensure as high a flow distribution uniformity as possible. Vortical character of flow is minimized by minimization of volume integrals of vorticity magnitude over the entire PWG inlet region of the preheater (see Fig. 9).

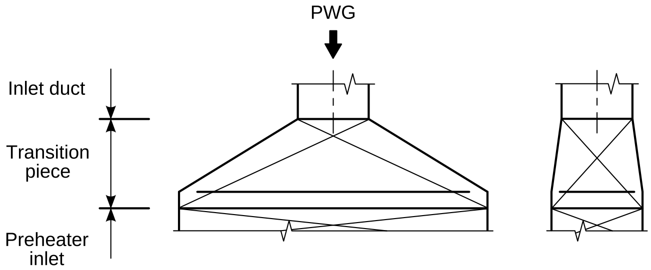

Fig. 9 Inlet region of the preheater (Turek et al., 2012)

Methodology

Each considered tube-side geometry was evaluated in its entirety, that is, each model contained the inlet duct, inlet transition piece, U-tubes, and outlet transition piece. Due to the size of the preheater, however, evaluation of full 3D models was rather time-intensive and so in most cases only simplified 2D geometries were analyzed.

Several baseline geometries were evaluated first using both 2D and detailed 3D models in order to get estimates of performances of 3D geometries. Comparison of the results then yielded a transformation between the respective data. In other words, by evaluating a simplified 2D geometry, which took only a few hours, and applying the transformation to the resulting data, one could easily approximate data that would have been obtained via a full 3D evaluation in several days' time. Obviously, such an approach speeds optimization a lot while still yielding reasonably accurate data (Turek et al., 2012).

Comparison of geometries in terms of performance was then done using two indicators – relative standard deviation from uniform flow distribution and volume integral of vorticity magnitude over the entire PWG inlet region. The former one was a measure of uniformity of distribution of the PWG stream into individual tubes of the U-tube bundle. The latter indicator was used to ensure that no significant stagnation zones were present in the inlet region, i.e., that there were no areas with fouling layers building up quickly.

Considering the actual CFD models, all of them were unsteady with simulated time periods being chosen ad hoc based on the behaviour of flow rates (steady state must be reached otherwise U-tubes would be subjected to variable/cyclic loading due to changes in their temperature).

Baseline Situation

Although relative standard deviation from uniform flow distribution was not too high (6.62 %), relatively large stagnation zones enabling formation of fouling layers existed in the inlet transition piece and also in inlets of the U-tubes (see Fig. 10). Here, value of the volume integral of vorticity magnitude was 141.3 m^3/s.

It was obvious that with the current flow velocity and width-to-height ratio of the inlet transition piece the stream could not possible be widened accordingly. What was more,

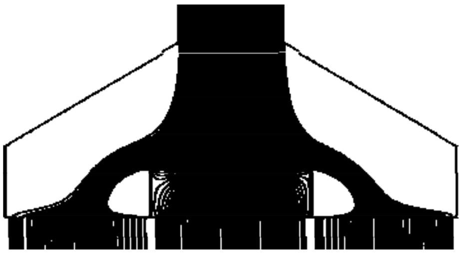

Fig. 10 Pathlines in a simplified 2D model of the baseline inlet region; empty areas are stagnation zones (Turek et al., 2012)

presence of the two stiffening transverse partition plates above the tube sheet made the situation even worse.

Optimum Inlet Transition Piece Geometry

In the course of evaluating various geometries it became clear that not only one but two sets of guiding vanes would be necessary to make the stream enter the tubes across the entire tube sheet at an angle as close to 90° as possible (that is, at the angle of the tubes). Also, a much higher transition piece was required.

Pathlines related to the optimum geometry are shown in Fig. 11. This geometry features large-enough inter-vane spaces so that they will not get clogged. As for values of the performance indicators, detailed 3D model yielded relative standard deviation from uniform distribution 4.08 % (less than 2/3 of the original value) and volume integral of vorticity magnitude 94.8 m^3/s (again roughly 2/3 of the original value).

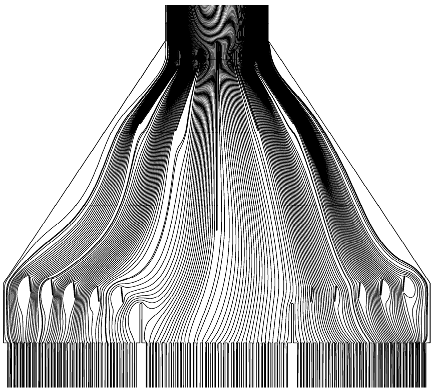

Fig. 11 Pathlines in a simplified 2D model of the optimum inlet region (Turek et al., 2012)

As can be seen in the Fig. 11, there are no large stagnation zones in the transition piece and pathlines indicate inflow almost directly into the U-tubes, hence significant stagnation zones should not be present in the U-tube inlets either. Since now the PWG stream contains lower amount of droplets due to the newly installed second demister, the inlets should not become clogged thus allowing the tube bundle to be cooled uniformly.

CONCLUSIONS

The presented industrial problem involving heavy fouling was investigated thoroughly so that efficient but low-cost countermeasures could be suggested to the plant operator. Stress analysis revealed that the cause of tube cracking is that when some of the U-tube inlets get clogged by jelly-like fouling layers consisting of droplets from the PWG stream, these U-tubes are not properly cooled and dilate extensively. The displacements are then carried over to the cooler tubes via the baffle system which, ultimately, leads to mechanical failures of these tubes.

Theoretically speaking, the PWG stream should not contain any droplets, since the inlet operating conditions correspond to a stream with the entire liquid content being evaporated. Nonetheless, due to pressure and temperature fluctuations about the nominal operating conditions there is a significant amount of droplets present. Ideally, one would install a cyclone coupled with flue gas injection into the PWG stream, however, due to spatial limitations this was not possible. Installation of an additional demister identical to the one already present is therefore suggested to improve the liquid separation rate.

Finally, geometry optimization of the inlet transition piece was employed to further lower the risk of fouling and attain as uniform a flow distribution into the individual U-tubes of the bundle as possible. Particular attention was paid to vorticity to make sure there are no significant stagnation zones in the inlet region.

These low-cost measures (addition of a demister and change of the inlet transition piece of the preheater) not only prevent cracking of the U-tubes but also lead to improved preheater performance and elimination of undesirable service shutdowns.

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