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INDUSTRIAL VALIDATION OF DEVELOPED EQUIPMENT FOR IDENTIFYING THE FOULING CAPABILITIES OF GASEOUS WASTE HEAT-USABLE PROCESS STREAMS

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Abstract: *Particulate fouling in gaseous waste heat-recovery processes reduces heat transfer efficiency and increases operational costs. This paper presents the industrial validation of developed equipment, building on earlier laboratory studies, to identify and characterize fouling capabilities in diverse applications. The device enables to work with a wide range of particulate deposition rates for different types of fouling particles and operating conditions such as temperatures, flow rates, and different heat transfer surface geometries. Industrial tests on operating process streams allow real-time assessment of fouling behavior. The results confirm the equipment's capability to capture key fouling parameters, aiding process optimization reliably. Insights from the collected data support recommendations on heat exchanger geometry and operating conditions to mitigate fouling, helping extend equipment lifespan and reduce maintenance. Results of industrial validation confirm that the device can be used as a reliable and versatile tool to help the industry make better use of waste heat, save energy, and reduce problems associated with particulate deposition.*

Keywords: Flue gas, Heat exchanger, Particulate fouling, Fouling rate, Pressure drop

1. Introduction

Heat exchangers are essential in many industrial sectors, from energy production to chemical processing, where they facilitate heat transfer between flue gases (often from combustion) and the process fluid (e.g. water or steam) (Jouhara et al., 2019). Over time, however, solid particle buildup—known as fouling—can severely degrade their performance by introducing an additional fouling thermal resistance (Rf). This reduces heat transfer efficiency and drives up fuel consumption, maintenance efforts, and overall operating costs. In flue gas heat recovery systems, mechanical (particulate) fouling commonly arises from fine particles deposited by inertial, gravitational, electrostatic, and intermolecular forces, while chemical fouling involves reactions with corrosive components or organic residues, forming robust deposits that are difficult to remove (Bott, 1995). Even a 1 mm deposit layer can cut heat flux by 10%, boosting fuel use by 2.5% (COST ANALYSIS, n.d.).

Fig. 1 shows four principal patterns of deposit growth. In the simplest and least common scenario (curve a), fouling proceeds linearly, reflecting a constant deposition rate unaffected by accumulating layers or shifts in operating conditions. More frequently, however, the growing deposit alters flow distribution—particularly by narrowing passages and increasing local velocity—leading to partial erosion of the fouling layer (curve b). This interplay of deposition and erosion can slow further buildup or even create a dynamic equilibrium where deposits do not thicken uniformly. Under specific conditions, fouling may halt altogether (curve c), typically when factors such as increasing shear forces or local temperature gradients balance out further particle adhesion. A fourth pattern (curve d) features periodic shedding of deposit chunks caused by the fragility or incoherence of the fouling layer and external forces acting upon

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it. These flakes break away at irregular intervals, revealing heat transfer surfaces. Predicting which pattern dominates requires knowledge of the operating conditions, particulate characteristics, and flow conditions.

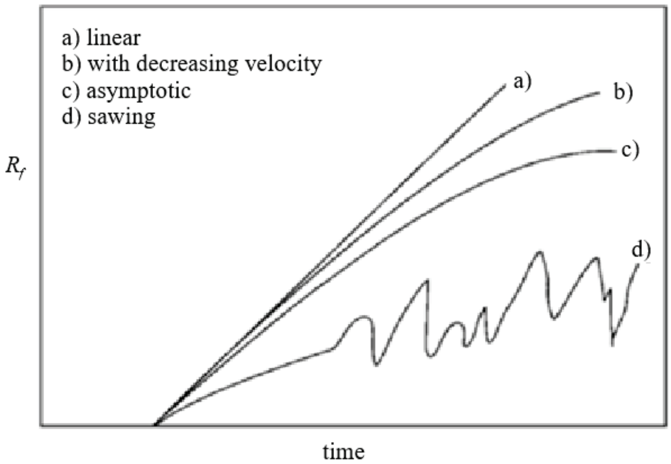

Fig. 1: Possibilities of the development of deposit growth (Müller-Steinhagen, 2010)

Fouling significantly impacts costs and equipment lifespan, driving research into optimized designs and monitoring. Industrial testing is key in evaluating fouling behavior and guiding effective control strategies to reduce energy losses and maintenance needs.

1.2. Description of a developed testing equipment

The testing equipment is configured as a modular cross-flow air-air tube heat exchanger (fouling flue gas-air), equipped with all necessary accessories for monitoring and evaluation. Fig. 2 shows the final version of the device, emphasizing the cross-flow arrangement, which reflects commonly used solutions.

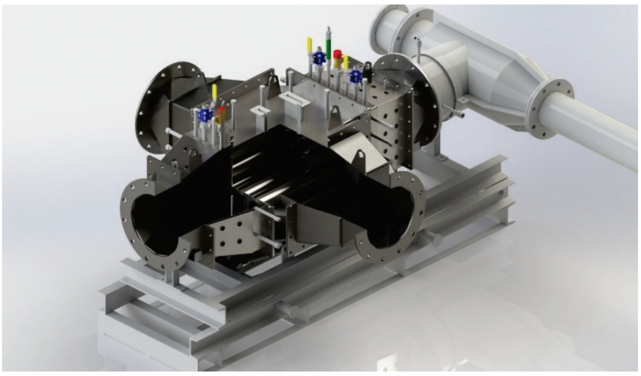

Fig. 2: Equipment assembly (in partial section) with drive ejector on support frame

This design was continuously refined in the first development phase based on thermal deformation analysis, thermal-hydraulic calculations, and operational feedback from specific heat exchangers. The aim was to develop a system meeting both technological and structural requirements—ensuring adequate flue gas velocities, enabling tests of varied cleaning methods, and providing high durability at elevated temperatures. Proper material selection and design modifications were crucial to avoid structural damage—such as crack formation—that could compromise long-term reliability (Daxner et al., 2024).

2. Industrial testing

After completing laboratory tests at the Institute of Process Engineering at the Brno University of Technology, industrial testing was initiated to validate the developed equipment under real operating conditions. These conditions included high concentrations of fouling components, exposure to elevated temperatures, and dynamic flue gas flow. The tests aimed to verify the proposed technology for systematic fouling analysis in gaseous process streams and to ensure the safe and reliable utilization of flue gas waste heat. The experiments were conducted at the Mokrá cement plant of Heidelberg Materials CZ, a.s. The equipment was integrated into the operational system at a point downstream of the filtration unit, where cooled process gas flows (see Fig. 3).

Fig. 3: Installed equipment in a cement plant

The testing was divided into two phases. Fouling in the shell-side of equipment was examined in the first phase. This began with a series of short-term tests, followed by long-term tests, which could not be simulated under laboratory conditions. The second phase focused on fouling in the equipment tube-side space, following the same testing regime as the inter-tube section. A key advantage of the long-term tests was the ability to evaluate fouling progression until a critical failure state was reached, simulating a fully blocked heat exchanger. This provided valuable insights into the severity of fouling under extreme conditions and its impact on heat exchanger operation, which would not be feasible to replicate in a controlled laboratory setting.

2.2. Evaluation of industrial tests

The tests were conducted under extreme fouling conditions, with particle concentrations significantly exceeding typical industrial levels. For reference, fouling component concentrations in HRSG (Heat Recovery Steam Generator) boilers vary based on fuel type: 100–10,000 mg/m³ for coal, 50–1,000 mg/m³ for biomass, and 500–5,000 mg/m³ for municipal waste combustion (Li et al., 2016). In contrast, the process stream used in this study had up to 40,000 mg/m³, based on plant operator data. To characterize the fouling components, laser diffraction analysis was performed, revealing particle size distributions with percentiles of 10% at 0.907 µm, 50% at 2.215 µm, and 90% at 5.543 µm. These fine particles are highly susceptible to electrostatic forces, which play a significant role in deposition mechanisms, as discussed in Chapter 1.

Fig. 4 shows the pressure drop in the shell-side and tube-side during the long-term tests. The accumulation of deposits reduced the effective flow cross-section, leading to a sharp increase in pressure loss. This rise in resistance would require higher energy input to maintain operational flow rates, increasing power consumption and reducing overall efficiency.

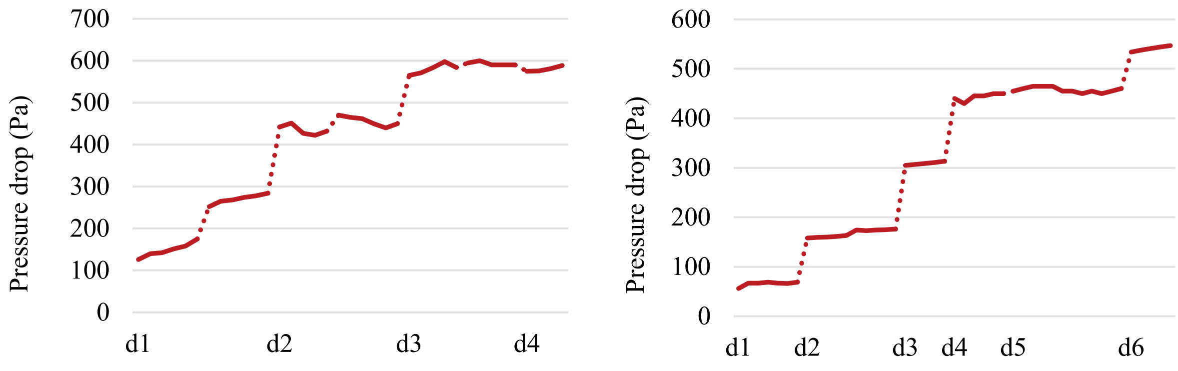

Fig. 4: Development of pressure drop during the long-term fouling test in the shell-side (left) and the tube-side (right) of equipment.

In addition to the pressure drop effects, the deposit accumulation also impacts heat flux performance. Based on the measurements, recommendations were made for the use of a heat exchanger with similar geometry for highly contaminated process streams. The graphs in Fig. 5 show specific performance limits for shell-side and tube-side deposits at minimum (yellow) and maximum (blue) values of the thermal conductivity of the deposits. From the results, the deposits on the outside of the pipes (i.e. shell-side fouling) affect the overall thermal performance much more than the deposits inside the pipes (i.e. tube-side fouling).

The standard recommendation for the use of heat exchangers in air-polluted environments is to shut them down and clean them when there is a 10% drop in performance (green line). If the heat output of a given heat exchanger drops by 20 % or more (red line), shutdown and cleaning are urgent, as the operation of such a polluted heat exchanger is very uneconomical.

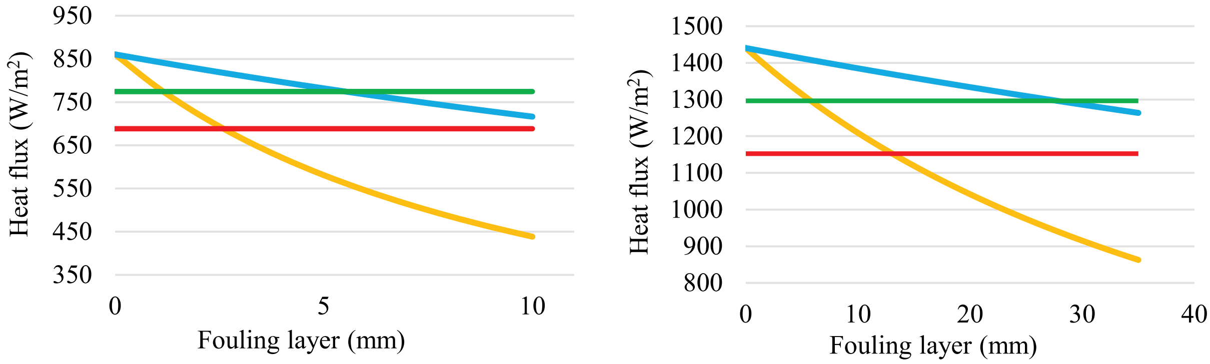

Fig. 5: Heat flux degradation based on deposit accumulation in the shell-side (left) and tube-side (right)

3. Conclusions

This industrial validation confirms that the developed testing system reliably evaluates fouling in challenging operating conditions, exceeding typical industry levels. Monitoring parameters such as particle concentration, mass flow, pressure drop, and heat transfer performance in both shell- and tube-side revealed that the external (i.e. shell side) deposits significantly impact the efficiency of heat transfer more than internal ones in tested gaseous waste heat usable fouled stream in cement plant.

Industry tests have also identified limiting heat flux values for equipment of the same geometry, at which consideration must be given to the possible cleaning of heat transfer surfaces. The system offers precise design and operational guidelines through targeted data collection and analysis, enabling safer, more reliable, and more efficient waste heat recovery in demanding industrial environments.

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