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DESIGN OF A DEVICE FOR MEASURING THE RATE OF PARTICULATE FOULING OF HEAT TRANSFER SURFACES

Daxner J.*, Jegla Z., Zabloudil J.***, Babička Fialová D.†, Reppich M.††**

Abstract: *This paper presents the process of designing an experimental device (TESTER) developed to test and assess the comprehensive rate of particulate fouling in various heat recovery processes. The evaluation can be used not only for direct flue gas heat recovery from combustion processes (e.g., process furnaces, water- or steam-boilers, etc.) but also for flue gas waste heat recovery processes (such as cement production, zinc dioxide production, etc.). The assessment of particulate fouling requires diverse operating conditions, including gas velocity, temperature, particles volume, size, and different types of TESTER geometry, such as tube diameter and arrangement. The main output of the experimental analysis is the identification of the optimal geometry or operating conditions of a heat exchanger and recommendation for the process operator.*

Keywords: Flue gas, waste heat recovery, heat exchanger, particulate fouling, fouling rate.

1. Introduction

Heat exchangers have an important role across the industry. They are used in power generation, chemical industry, waste treatment, etc. All recently stated processes can carry heat in flue gas regardless of whether flue gas are direct combustion products or merely waste heat stream (Jouhara et al., 2019). The primary goal of heat exchanger designers is to achieve maximum heat transfer rate while considering factors such as pressure drops, thermophysical properties of heat carriers, geometry configuration, etc. The main limitation in the design of heat exchangers for flue gas is the presence of particulate pollutants contained in the flue gas (Müller-Steinhagen et al., 2011). Despite research efforts, these add complexity to the heat exchanger design mainly because there is still a lack of information in predicting particulate fouling. The design of heat exchangers for fouling environments is therefore based only on the experience of the designer but lacks the knowledge of the actual fouling rate of the flue gas stream. Examples of processes that produce flue gas containing particulate matter are all processes where solid fuel (e.g. coal, biomass, municipal waste) is incinerated (Bott, 1995). On the other hand, there are processes where flue gas with solid particles are not direct products of combustion such as cement production, wood and pulp drying, or various chemical manufacturing methods (Bianchi et al., 2019).

Particulate fouling is caused by the deposition of colloidal solid particles, either organic or inorganic origin, present in the heat carrier. In gaseous media, the most common pollutants are by-products of combustion. They form deposits with varying mechanical and chemical properties depending on the type of fuel and combustion conditions (Trojan et al., 2019). Fig. 1 shows examples of heat exchangers fouled by ash.

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[*] Ing. Ján Daxner: Institute of Process Engineering, Faculty of Mechanical Engineering, Brno University of Technology; Technická 2; 616 69, Brno; CZ, jan.daxner@vutbr.cz

[**] Assoc. Prof. Ing. Zdeněk Jegla, PhD.: Institute of Process Engineering, Faculty of Mechanical Engineering, Brno University of Technology; Technická 2; 616 69, Brno; CZ, zdenek.jegla@vut.cz

[***] Ing. Jan Zabloudil: Eveco Brno, s.r.o.; Hudcova 321/76d; 612 00, Brno; CZ, zabloudil@evecobrno.cz

[†] Ing. Dominika Babička Fialová, PhD.: Institute of Process Engineering, Faculty of Mechanical Engineering, Brno University of Technology; Technická 2; 616 69, Brno; CZ, dominika.fialova@vutbr.cz

[††] Prof. Dr.-Ing. Marcus Reppich: Faculty of Mechanical and Process Engineering, Augsburg University of Applied Sciences; An der Hochschule 1; 86161 Augsburg; DE, marcus.reppich@hs-augsburg.de

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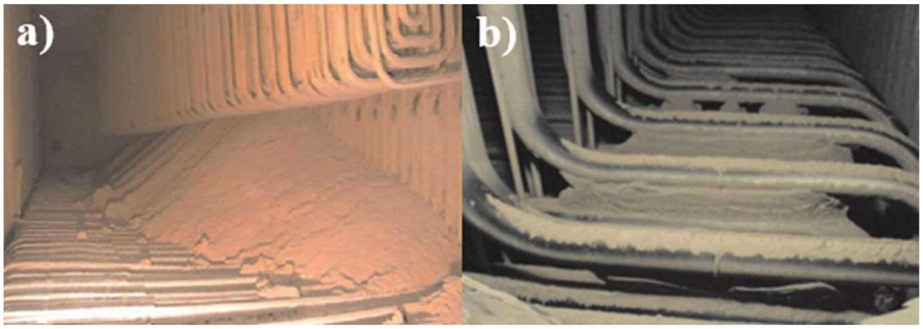

Fig. 1: Heavily fouled tubes of a) superheater and b) re-heater by ash (Trojan et al., 2019).

As mentioned, particulate fouling causes many problems in heat exchanger operation. Predicting fouling is challenging due to the low amount of experimental data which is usually the main reason for poor design of heat exchangers. For this reason, new ways for designing heat exchangers in fouling environments are being sought. This paper presents the design procedure of the experimental device TESTER, which will investigate the nature of fouling for a specific case and determine measures to mitigate fouling.

2. Design of the experimental device

The initial phase of the TESTER's technological design involved defining the experimental concept. The main parameter emphasized was the variability of the TESTER's geometry. Heat exchangers across the industry have various designs because there is no uniform heat exchanger concept for the use of heat from fouling flue gas. Flexibility in TESTER's geometry is crucial for approaching the complexity seen in practical solutions. Thus, it is necessary to be able to vary several most common types of geometries to mimic real industry solutions.

Alongside flexible geometry, mobility became a pivotal parameter in the TESTER's design. As is clear from the text, the main output of the TESTER's application will be a recommendation for operators of processes. For this reason, the tests must be carried out not only in laboratory (relevant) conditions but also in operational environments in already operating plants. Therefore, the device must be mobile, easy to transport, and simple to assemble, aligning with the practical demands of on-site experiments. These requisites were fundamental in our design consideration.

Considering these two parameters, the very first version of a TESTER was designed (see Fig. 2a), based on industry insights and expertise. Fig. 2b shows a cross-section of a TESTER. As shown in Fig. 2b, it is a cross-flow arrangement that corresponds most closely to industrially used heat exchanger designs, where one stream carries a heated medium and the second consists of flue gas with particulate matter. This initial version underwent subsequent modifications based on thermal-stress analysis and thermal-hydraulic calculations.

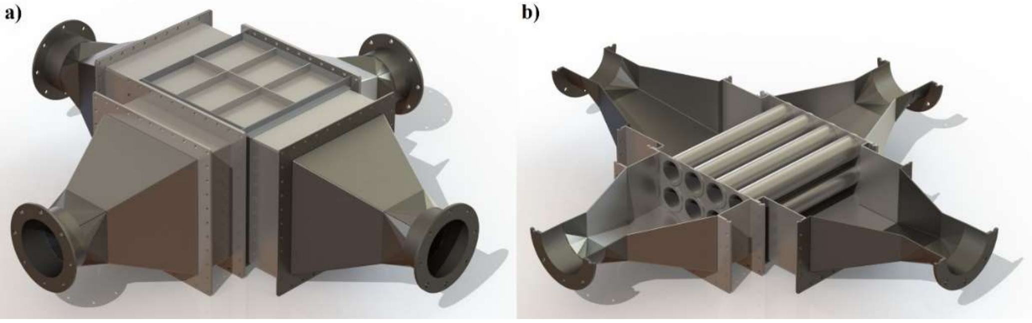

Fig. 2: a) First version of TESTER and b) first version of TESTER in cross-section.

The main purpose of the thermal-stress analysis was identifying and rectifying critical points within the TESTER's construction. This analysis used ANSYS Mechanical software (ANSYS Inc., 2023) to eliminate vulnerabilities and enhance TESTER's structure integrity. Consequently, for thermo-hydraulic calculations, the Heat Exchanger Design Handbook (Kuppan, 2013) was employed to optimize the fluid dynamics aspects of the TESTER.

2.1. Thermal Analysis

The first step of a thermal analysis was determining the maximum operating temperature at which the TESTER will be operated. Based on research and communication with industrial partners was this temperature determined to be 800 °C. Such a high temperature precludes the use of conventional structural steels due to the degradation of their material properties. For this reason, the individual components of the TESTER were made of durable materials, namely refractory steels 1.4841 and 1.4845. The inputs and assumptions for the thermal analysis are stated in Tab. 1. Fouling resistances were not considered.

Temperature TS (tube side)/SS (shell side) (°C)	800/15
Heat transfer coefficient TS/SS (W/(m^2·K))	80/35
Meshing size of the element through-thickness (mm)	1.5
Meshing size of the element on the surfaces (mm)	5
Thermal conductivity of refractory steel (W/(m.·K))	15

Tab. 1: Input parameters of a thermal analysis.

The thermal analysis results provided information about the temperature of individual parts of the TESTER and was used as the input parameter for stress analysis.

2.2. Stress Analysis

The thermal analysis was followed by a stress analysis performed in the same software ANSYS Mechanical (ANSYS Inc., 2023). Input parameters for stress analysis were results acquired in thermal analysis. All other input parameters were the same as stated in Sect. 2.1. As is shown in Fig. 3a, TESTER is symmetrical through all planes passing its center. This fact made it possible to perform cuts with all planes, resulting in 8 symmetrical parts of the TESTER (see Fig 3b) and only 1/8th of a TESTER was used for calculations. Subsequently, symmetry conditions were applied to the cutting surfaces. This modification ensured lower time requirement calculation and significantly reduced the required computing power.

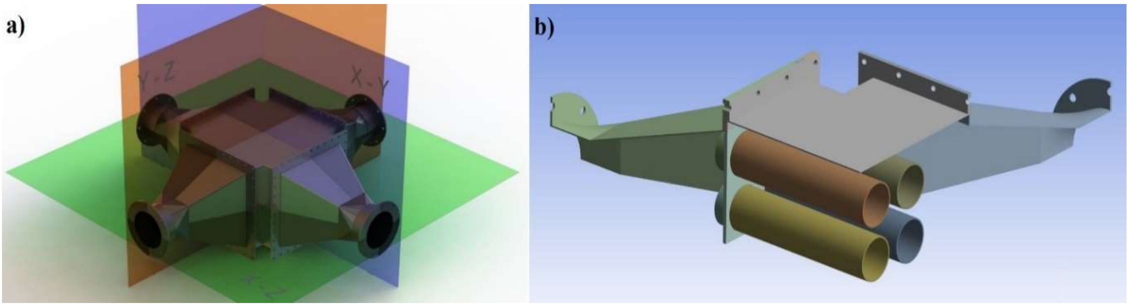

Fig. 3: a) TESTER's planes of symmetry, b) 1/8th of a TESTER created with cuts by planes.

Boundary conditions for all contact surfaces of individual parts have been set to bonded. When considering frictional connections, whose properties are closer to reality, computation difficulty increased extensively but differences between bonded and frictional connections were for subject analysis negligible. Fig. 4 shows critical areas of the structure revealed by thermal-stress analysis in terms of stress peaks.

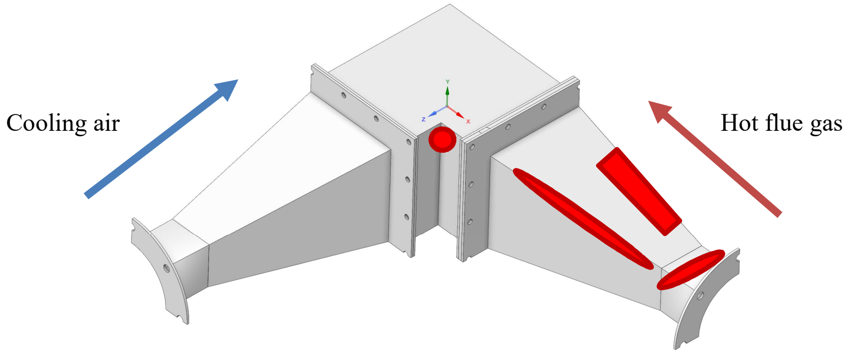

Fig. 4: Thermal-stress analysis of the very first version of a TESTER.

2.3. Thermal-hydraulic calculation

In contrast to the thermal stress analysis, a wider range of flue-gas flow conditions (an inlet temperature varying from 250 °C to 800 °C, the hot fluid located in the TS or SS) were analyzed using Heat Exchanger Design Handbook (Kuppan, 2013). Simultaneously, the most common tube bundle arrangements (in-line and staggered) were investigated. In addition to the geometrical parameters and inlet temperatures, the basic assumptions comprised the inlet pressure and the mean velocity of both fluids, flue gas, and air. The objective of the thermal-hydraulic calculations was to determine the flue gas and air flow rates, the heat duty of the clean TESTER (i.e., no fouling resistances were considered), and the pressure drops of both working fluids. Tab. 2 shows the results of a thermal-hydraulic analysis.

Temperature (°C)	**250**	**400**	**600**	**800**
Flow rate SS/TS (kg/s)	0.736/0.428	0.733/0.338	0.729/0.265	0.725/0.218
Pressure drop SS/TS (kPa)	0.079/0.088	0.083/0.070	0.086/0.055	0.090/0.045
Mean velocity SS/TS (m/s)	9.56/10.24	9.57/10.32	9.57/10.42	9.57/10.48

Tab. 2: Main output parameters of a thermal-hydraulic calculations with flue gas in tubes.

3. Conclusions

In this paper, the design procedure of the test heat exchanger (TESTER) for the investigation of the fouling rate of flue gas containing particulate matter has been presented. A key part of the overall design was performing thermal-stress analysis and thermal-hydraulic calculations. Those provided valuable results on which further modifications to the design of individual parts of the TESTER were based.

The TESTER is currently being assembled and commissioned in laboratory conditions. The results obtained by computational modeling and calculations will be experimentally verified in this step. At the same time, pilot fouling tests of the designed TESTER's geometry will be performed. Tests with industrial partners will start in the second half of 2024.

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