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CONSTRUCTION OF A MODULAR DEVICE FOR TESTING HIGH-TEMPERATURE FLUE-GAS FOULING IN WASTE-HEAT SOURCES

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Abstract: *The article discusses the construction aspects of a developed modular device for testing the influence of high-temperature flue-gas fouling on chosen heat exchanger tube-bundle geometries and the effectiveness of various methods of online tube-bundle cleaning, which is currently being developed by the Institute of Process Engineering (IPE) at Brno University of Technology (BUT), in cooperation with the company Eveco Brno. The device will ease designing new heat exchangers, withstanding longer operation in severe fouling conditions.*

Keywords: Fouling, flue gas, testing device, high-temperature application.

1. Introduction

Combustion of various liquid and, in particular, solid fuels entails the problems of entrainment of inert ash, which is introduced into the combustion process as an integral part of the fuel. Part of the fine fraction of this ash, often enriched with solid products of incomplete combustion, is carried off by the flue-gas stream from the combustion space of the boiler onto the convective heat-exchange surfaces. Here, depending on the flow conditions, temperature, chemical composition of the ash, and other factors, a coating can form on the heat-exchange surfaces (Kakac, 1991).

The effect of the flow is mainly manifested by ash setting in areas with a sharply reduced flue-gas flow rate, especially in the areas of inlets and sudden expansions in the casing of tube boilers and on the downstream side of the tube bundles in water-tube boilers.

The effect of temperature is closely related to chemical composition. Different combinations of inert salts and minerals, which are contained in the burned fuel, lead to the somewhat different behaviour of the ash entrained by the flue gas (Niessen, 2010). Each mineral component exhibits a different melting temperature. Therefore, the empirically determined (average) softening and melting temperatures of the ash, or other recognizable intermediate temperatures according to a relevant local standard, depend on the proportional amounts of these individual components in the ash. If the so-called ash-softening temperature is reached, the cohesion of the ash mass increases considerably. At the melting temperature, fly ash passes into a glassy viscous phase. After resolidification, the heat-exchange surface of the exchanger remains covered with a solid crust, increasing the thermal resistance and significantly reducing the device's efficiency (Spalding and Taborek 1983). The ashes of certain fuels exhibit a softening temperature so low that considerable fouling must be expected even at temperatures necessary for the economical operation of the boiler. In particular, during combustion or co-combustion of grass biomass, ash with an ash-softening temperature lower than 700 °C is often found (Niessen, 2010).

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However, fouling layers can also be created by other processes. In the case of flue-gas heat exchangers, it is possible to encounter ash fractions that tend to form deposits by mainly mechanical binding. Therefore, the variable nature of fouling requires a device that allows engineers to determine the fouling properties of a given flue-gas stream in advance and as precisely as possible so that suitable heat-exchange surfaces can be designed in order to utilize the heat produced. Universal testing devices enabling the determination of the necessary parameters of real flue-gas fouling effects before the final design of an industrial heat exchanger are not currently available. An essential step in designing the heat exchanger is the correct choice of its basic geometric parameters. In the case of applications operated in fouling conditions, however, it is usually unknown which specific geometry will be resistant to fouling and which will perform rather badly. And eventually, what choice of online cleaning technology would offer sufficiently prolonged operation time without necessitating downtime.

The developed modular mobile device (see Fig. 1) aims to prevent operational problems of the newly designed heat exchangers through a better design with higher resistance to fouling and, hence, higher reliability. Thanks to its mobility and modularity, laboratory and industrial experiments can be performed. Consequently, its high potential also lies in the ongoing research at BUT in the field of industrial fouling.

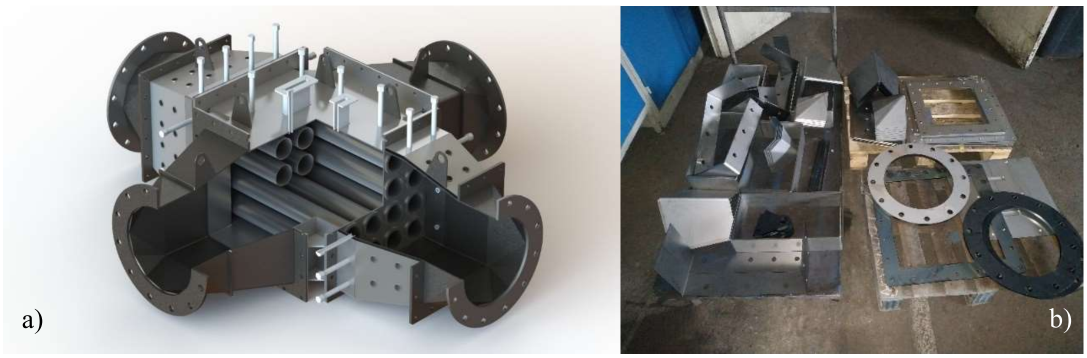

Fig. 1: a) Partial section of the final design of the developed device, b) cut and folded metal sheets of the device prepared for welding.

2. Construction of the high-temperature modular device

The developed construction of the mobile testing system, presented in Fig. 1, is conceptually designed as a modular crossflow flue-gas/air tube exchanger. During its design, the following was emphasized:

1. The closest possible approximation of the geometry parameters of the device's tube bundle to a typical geometry of an industrial flue-gas heat exchanger.
2. Capacity enabling both laboratory tests and tests under industrial conditions.
3. Temperature resistance to withstand high temperatures on the flue gas side up to 800 °C.
4. Modular variability of the tube-bundle geometry and the ability to operate with flue gas both on the tube and shell sides.
5. The device is equipped with welded sockets enabling tests of different tube-bundle cleaning methods, endoscope access for deposit analyses and measurement devices' access for data acquisition.
6. Possibility of easy transport of equipment between laboratory and industrial plants and easy assembly/disassembly

Fulfilment of the above requirements is ensured in the following way:

The device's basic, primarily tested tube bundle contains 16 smooth pipes DN65 (ø 76.1 mm) in a 4 × 4 inline configuration set within a tube sheet with an axial spacing of 98 mm. The tubes' nominal size and spacing correspond to the design of an industrial device rather than a laboratory model. This leads to better approximation of real conditions and eliminates errors introduced by simplifying assumptions (e.g., using characteristic numbers when extrapolating the obtained data to real operation). At the same time, it is thus possible to insert the apparatus into a flue-gas bypass of a real industrial application (for measurements 'in the field') in addition to the laboratory testing.

The 4×4 configuration also determines the size of the device, which can still be supplied with flue gases during laboratory tests, using burners already available in the IPE burner testing facility, but also by sampling from any existing industrial flue pipe with the help of a specially designed ejector (jet pump). Such configuration grants 4 tubes in the bundle that are ‘central’, i.e., the flow around their perimeter is affected only by the surrounding tubes, not the edge effects of the heat-exchanger shell. It will be possible to observe the formation of the deposit layers and the influence of their removal methods with the greatest possible informative value.

The device is designed as modular; therefore, it can be equipped with staggered configurations, smaller nominal diameters, and other tube-bundle modifications, which expands the usability and applicability in various testing scenarios. Although most industrial applications operate at flue-gas temperatures lower than 800 °C, such a high temperature is considered mainly due to the possibility of using equipment for fouling testing even under such extreme conditions. Operability at high temperatures is mainly ensured by the combination of factors listed in Tab. 1.

Concept as a heat exchanger	The fouling tester itself is designed as a flue-gas/air heat exchanger, which enables the cooling of the device by the airflow. An air fan increases the volumetric flow rate and sufficient turbulence of air for intensive heat transfer. The fan can be removed during tests on low-potential flue gases or tests on 'polluted air' (ash carried by the air current), and the device thus can be operated as a non-cooled static obstacle to the flow. In the case of air cooling, the air-stream temperature will be measured at the inlet and outlet.
Materials	All parts of the device, which can be exposed to high temperatures on the flue-gas side, are made of heat-resistant steels of grades 1.4841 and 1.4845. This solution aims to prevent the formation of scalings and other oxidative damage at elevated temperatures. The selection of materials is based on the criteria of a design temperature of 800 °C.
Additional water-cooling	Flue-gas inlet modules are designed as an analogue to a water-cooled jacketed vessel. In the case of operation at temperatures close to the maximum design temperature, cooling water will be introduced into the empty volume between the inner and outer shell. This water will then be diverted into a cooler or a waste sump.
Thermal insulation	This measure is not intended to protect the device but the operators. When operating at high temperatures, the device is coated with an insulating layer designed to maintain the external temperature at the maximum admitted by EN ISO 13732-1 for touchable surfaces.

Tab. 1: High-temperature heat protection concept.

As for the additional water cooling, the flow will be distributed into several inlet sockets on the lower side of each jacketed flue-gas intake/outlet and collected again by hoses connected to several ports on the opposite side. This technical solution leads to a better fluid-flow distribution within the inter-shell space. Each of the distribution sockets in the jacketed inlets is equipped with a ball valve for rough flow regulation, and each module is equipped with a safety valve, preventing an increase of pressure in the inter-shell space in the event of local overheating and boiling of the cooling water. Cooling water temperature and pressure will be monitored. Both the inter-shell space clearance and the dimensions of welded sockets enabling cooling water feed are designed to accommodate the heat output without raising the cooling water temperature by more than 20 K.

The device consists of 6 main modules that might be removed and reattached at any convenience:

- 1× central cross module – the tube-bundle casing and the device's main part;
- 1× tube bundle with two tube sheets – may be replaced with a bundle of any required geometry;
- 2× cooled inlet with double shell (jacketed) – for the hot side of the heat exchanger;
- 2× non-cooled inlet – for the cold side of the heat exchanger.

The central cross module and individual inlets are equipped with identical square flanges with M12 bolt connections. The flange joints are additionally secured with a sealing cord that is resistant to high temperatures.

The tube sheets carrying the tube bundle are designed as intermediate flanges. They can be placed between the central cross module and the cooled jacketed inlet, as well as between the central cross module and the air-cooling inlet. This solution makes it possible to achieve flue-gas flow inside the tubes and on the shell side simply by changing the assembly configuration.

The connection of the device with an existing flue-gas pipe and additional cooling and driving streams is depicted in Fig. 2 below. In the case of laboratory experiments, the assembly may be equipped with a particulate source (as a substitute for fouling flue gas) and a fabric filter.

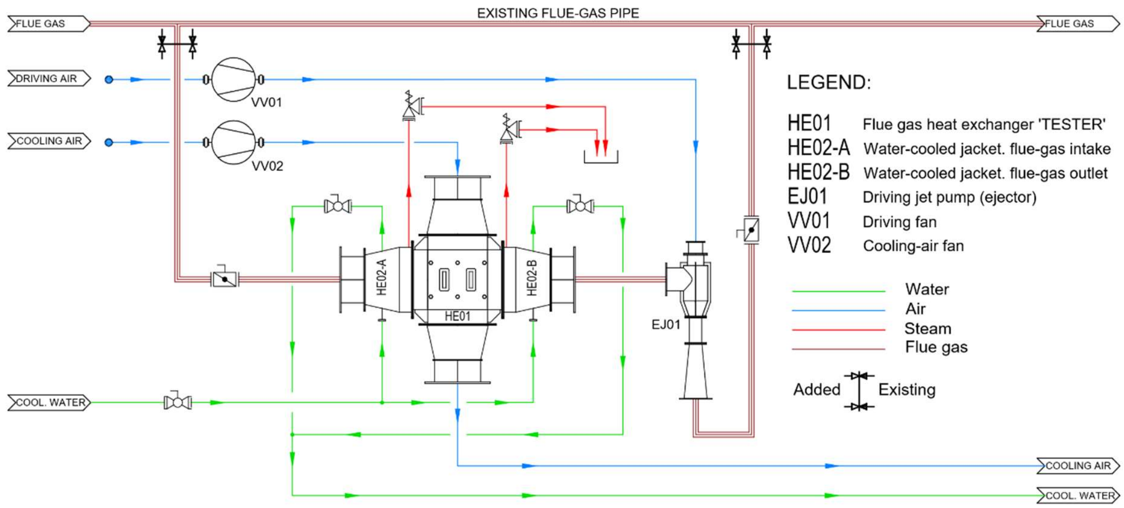

Fig. 2: Simplified operational diagram of the device when connected to an existing flue-gas pipe.

The device has a sufficient number of welded sockets with a plug, distributed on the device in such a way that it is possible to place nozzles for spraying the inner space of the tubes, as well as the space between the tubes, with a stream of compressed air, steam, or water – simulating common on-line fouling-deposit removal methods.

The modules need to be easily transported between the place of industrial application, laboratory, and storage room in the time between individual tests. The size of the assembled device is thus, to some extent, derived from the need for repeated assembly and transport. The body of the apparatus will be placed on a folding frame, which can be secured onto the bed of a truck. The individual modules of the device are equipped with load-bearing eyes, so in addition to manual assembly, it is possible to use a lifting device that will be placed upon the structure of the load-bearing frame.

3. Conclusion

The currently developed construction of the high-temperature flue-gas testing device discussed in this article is supposed to allow the BUT researchers and the private-sector engineers of the company Eveco Brno to determine the real fouling effects of a given flue-gas stream on a chosen heat-exchanger geometry, without the necessity of building a whole new heat exchanger for the initial test or depending overly on the tabular values of the fouling factors with limited accuracy. Compared with commonly used methods, it should offer a wider and more reliable data set to design more economical solutions, withstanding longer maintenance-free operation periods in severe fouling conditions. No comparable testing device is currently available, nor the authors are aware of any other such device being developed.

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