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COMPUTER-AIDED ANALYSIS OF INNOVATIVE THERMAL ENHANCEMENT ELEMENTS FOR INDUSTRIAL BOILERS

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Abstract: *The Czech Republic is transitioning to low-emission energy sources, planning to decommission coal-fired power plants by 2033. Combined cycle power plants (CCGT) are key to this transition, achieving around 60% efficiency by utilizing natural gas combustion and waste heat recovery in heat recovery steam generator (HRSG) boilers. This paper focuses on enhancing heat transfer in HRSG boilers using finned tubes, which increase the heat exchange surface area on the flue gas side. Three types of finned tubes are analyzed: Spiral Solid Fin, Serrated Fin SF, and Serrated Fin HF. The study uses the BoilerDesigner calculation program to compare their performance. Results show that Serrated Fin HF provides the highest heat output, making it optimal for HRSG design. The paper details the technical properties and performance metrics of each tube type, including heat output, pressure drop, overall heat transfer coefficient, and heat exchange area. Design considerations are discussed, with a focus on optimizing geometric design for desired performance. The study identifies optimal fin density for different configurations and recommends specific designs for superheaters in HRSGs. The paper concludes that further modifications could enhance performance, with Serrated Fin SF as a promising alternative for future research. The findings support the sustainable development of CCGTs and the transition to low-emission energy sources.*

Keywords: Combined cycle power plant (CCGT), Heat recovery steam generator (HRSG), Heat exchangers, Serrated Finned tubes, BoilerDesigner

1. Introduction

The drive to use low-emission energy sources contributes to the development of combined cycle power plants (CCGT) in the Czech Republic, which has committed to decommissioning its remaining coal-fired power plants by 2033 ("Beyond Fossil Fuels", 2024). To meet the ever-increasing electricity demand, eight CCGT plants with a total nominal capacity of 2 050 MW are planned to be commissioned by this milestone ("Beyond Fossil Fuels", 2024). Today, CCGTs typically achieve an efficiency of 60% relative to the lower heating value (LHV) of the fuel, with natural gas combustion in the turbine accounting for about 40% of LHV utilization (Ganapathy, 2003). The remaining 20% is obtained from the waste heat of the flue gas in the heat recovery steam generator (HRSG) boiler. Flue gases with a temperature of about 600°C enter the HRSG boiler behind the gas turbine and give up heat to the water/steam flowing in the heat exchanger tubes. The heat exchange takes place in a system of precisely arranged heating surfaces, thus generating steam at a certain pressure. The steam then expands on the turbine and drives the electric generator. In the design of HRSGs, practically verified empirical relationships have been used since the middle of the last century, which describe reality at a sufficient level. Knowledge of the principal context, as this paper seeks to present, contributes to the sustainable development of CCGTs. The emphasis is on enhanced heat transfer for HRSG boilers through finned tubes, which significantly affect the cost of the boiler.

2. Finned tubes

In the HRSG, the heat transfer coefficient (α) on the flue gas side is significantly smaller than on the water side. Here is space for intensification of the heat transfer, by increasing the heat exchange surface (A) on the flue gas side. The low particulate matter content of the flue gas is crucial when using finned tubes. This

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would threaten to foul the heat exchange surface, and significantly reduce the overall heat transfer coefficient (U). Ganapathy (2003) states that when the thermal resistance (R) on the flue gas side is increased by one order of magnitude, there is a disproportionate decrease in heat output (Q) for finned tubes as compared to bare tubes. Tube bundles with bare tubes are preferred wherever there is a risk of fouling the heat exchange surface and online cleaning is required (e.g., soot blower). In the past they were coal-fired boilers, today they are waste-to-energy plants that use state-of-the-art methods to clean the heating surfaces. In addition to the geometry of the heat exchange surface, the heat transfer is also influenced by the arrangement of the tubes in the bundle. The arrangement of tubes can be twofold, either inline or staggered. If it is necessary to clean the heating surfaces additionally, it is preferable to use an inline arrangement. From the point of view of increasing turbulence and hence heat transfer, the staggered arrangement of the tubes is preferred. The finned tube bundles found in the HRSG contribute to the reduction of noise behind the gas turbine. The following Figure 1 shows standard and innovative heat exchanger fins for industrial boilers.

a) Spiral Solid Fin b) Serrated Fin SF c) Serrated Fin HF

Fig. 1: Types of finned tubes as part of HRSG heat exchangers.

The geometry of the bare tube is defined by the outer diameter of d = 33.7 mm and the wall thickness of e = 2.9 mm. The Spiral Solid Fin (Fig. 1a) has a defined fin height of h = 12 mm, a fin thickness of t = 1 mm, and a number of fins per unit length of n = 258 1/m. In addition, the serrated finned tube, designated SF (Fig. 1b), has a specified fin width of w = 4 mm. The serrated finned tube, designated HF (Fig. 1c), has a defined base height of b = 5 mm. The tubes are arranged in a staggered pattern in two rows in the bundle. There are 62 tubes in a row with a length of l = 11.5 m. For completeness, it is necessary to determine the material of the tubes (X10CrMoVNb9-1) and fins (1.4512). To compare fin types, the heat exchange between steam and flue gas is solved in the BoilerDesigner calculation program, which is part of the PPSD (Power Plant Simulator & Designer) software supplied by KED GmbH. The results from the verification calculation for the bare tube and the three finned tube types from Fig. 1 are given in Table 1.

Tab. 1: Analyzed technical properties of four tube bundle types from the BoilerDesigner program.

Tube Bundle	Bare Tube	Spiral Solid Fin	Serrated Fin SF	Serrated Fin HF
Q [kW]	970	3,248	3,626	3,709
ΔP [Pa]	14.5	42.2	42.5	42.5
U [W/m^2·K]	66.9	30.9	40.3	39.9
A [m^2]	151	1,447	1,320	1,387
W [kg]	3,772.9	8,652.5	7, 371.0	7,793.7

The achieved heat output Q obtained from the bundle design is illustrated in the bar graph shown in Fig. 2 and it can be seen that the Serrated Fin HF achieved the highest heat output for similar geometry. The calculated pressure drop ΔP is approximately at the same level for all three fin types. Table 1 also shows the overall heat transfer coefficient U, the heat exchange area A, and the weight of the exchanger W. Also, the comparison shows in Fig. 2, that if bare tubes were to transfer equivalent heat output to Serrated Fin

HF, 8 rows in a bundle would be required. The pressure drop on the flue gas side would then be similar, namely 43 Pa, but the exchanger itself would weigh 15,087.57 kg, which is twice as much.

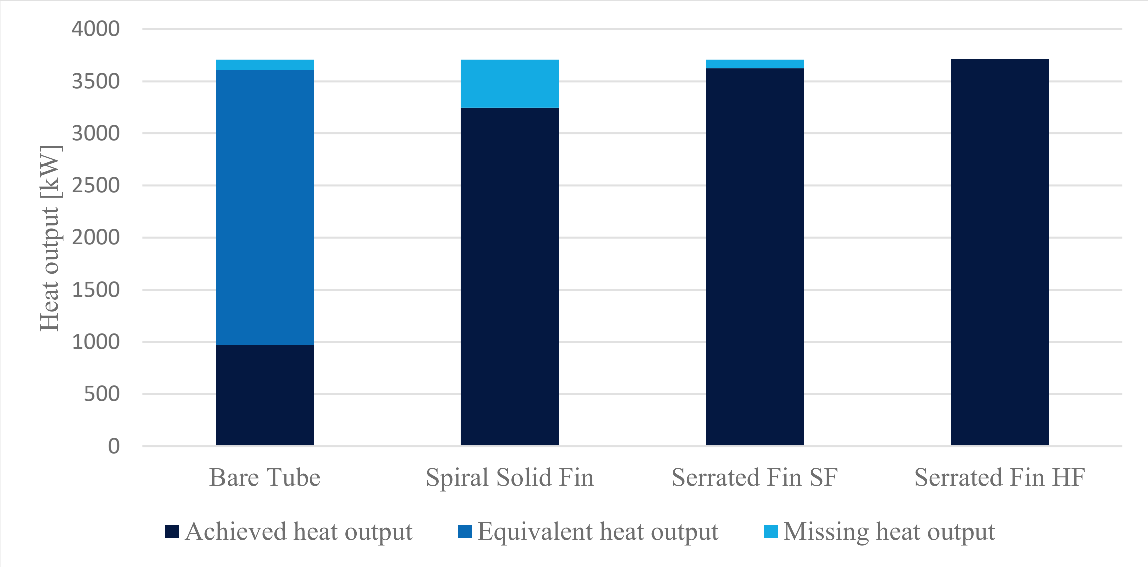

Fig. 2: Visualization of the results from Table 1 in the bar graph.

3. Design of a steam-flue gas heat exchanger with finned tubes

Usually, the logarithmic mean temperature difference (LMTD) method is used to calculate the heat transfer in heat exchangers (Ganapathy, 2003). This is also used in the calculation program BoilerDesigner. The subject of the thermal-hydraulic design of the HRSG boiler is the heating surfaces of individual exchangers (i.e. economizer, evaporator, and superheater), which have their specifics. The superheater is usually the first heating surface in the flue gas direction in the HRSG. In the previous Chapter 2, Serrated Fin HF was identified as the optimal surface intensification.

Now a superheater with a heat output of 3.7 MW determined from the calorimetric equation is to be designed with this type of fins. This heat output corresponds to the product of the heat exchange area and the overall heat transfer coefficient AU of 55,119 W/K at the same temperatures of the mediums. The geometry of the finned tube of the superheater is also based on Chapter 2. The available finning heights are h_1= 12 mm, h_2= 17 mm, and h_3= 20 mm with different fin densities (i.e., by the number of fins per unit length). It is essential to determine the optimal geometric design of the Serrated Fin HF from the available geometric configurations. The calculation of the overall heat transfer coefficient in the BoilerDesigner is based on the empirical ESCOA relationships available in [2]. To analyze the influence of the height and density of the fins on the size of the heat exchange surface, equation (1) can be used, which has the form:

$$\Delta A_i = \frac{Q}{LMTD \cdot U_i} - A_i \tag{1}$$

The deviations from the required heat transfer surface (ΔA) of Serrated Fin HF from equation (1) for each geometric design are plotted on a graph and points are fitted with the linear curve (see Fig. 3). After plugging ΔA = 0 into the three linear trend equations, the optimal fin density comes out. The optimal density of the lowest fin height h_1 came out as n_1 = 258 1/m, followed by n_2 = 205 1/m and n_3 = 191 1/m.

Ganapathy (2003) recommends considering the following criteria when optimizing the exchanger area: bundle weight, maximum tube temperature, and flue gas pressure drop. After additional calculations in BoilerDesigner, configuration 1 with a fin height of 12 mm and a density of 258 fins per meter best meets all three criteria (see Tab. 2). It is important to consider the resistance of the material at elevated temperatures. Higher fins are exposed to higher temperatures of tube wall T_W, and fin temperature T_F, as can be seen from Tab. 2. For the first heating surface in an HRSG, it is particularly desirable to have lower fins. Again, the phenomenon of a decreasing value of the overall heat transfer coefficient with increasing heat exchange area, for example, fin height or number of fins per unit length, can be observed in Table 2.

Tab. 2: Calculated values of the three superheater configurations in BoilerDesigner.

Serrated Fin HF	Configuration 1	Configuration 2	Configuration 3
A [m^2]	1,386.8	1,577.2	1,728.2
ΔP [Pa]	42.5	49.0	54.8
W [kg]	7,793.7	8,335.9	8,789.1
U [$W/m^2 \cdot K$]	39.9	34.7	31.6
T_W	524 °C	527 °C	529 °C
T_F	546 °C	558 °C	563 °C

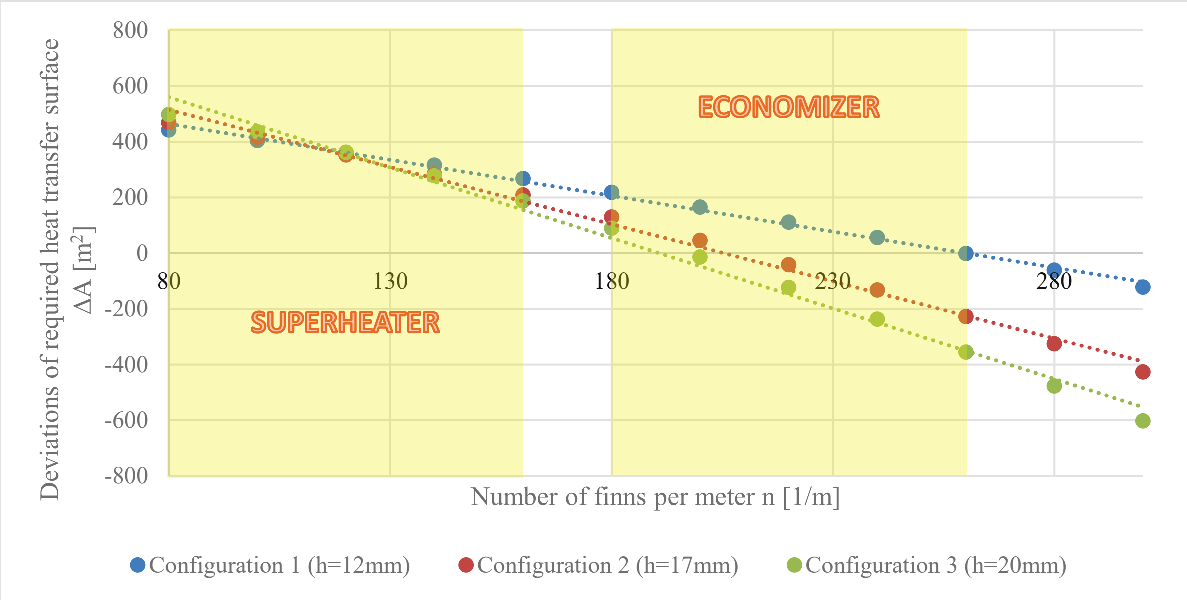

Fig. 3: Dependence of the heat transfer surface deviation on the fin density of the three Serrated Fin HF designs.

4. Evaluation and conclusions

From the harvested results, it can be assumed that if the superheater area were increased by less than 400 m^2 by further modification, all three fin height configurations would achieve the required performance with an approximate fin density of n = 120 1/m (see Fig. 3). For the configuration with a fin height h = 12 mm, this would mean adding one row of tubes to the bundle. The exact calculation by the BoilerDesigner then shows that 100 fins per meter will be sufficient. This fin density would meet the recommendation of Ganapathy (2003) for the superheater (and economizer) as shown in Fig. 3. Such a design would also have a lower pressure drop on the flue side of ΔP = 32.1 Pa and only a slightly higher weight of W = 7,996.1 kg. This represents the pressure drop of 24% and the weight increase of 3%. It should be added, however, that the addition of another row of tubes will increase the steam pressure drop upstream of the turbine.

A very interesting type of finning is the Serrated Fin SF, which in the initial selection phase of the finning type in Chapter 2 competed significantly with the selected Serrated Fin HF, only 83 W of heat output was missing (see Fig. 2). Serrated fin SF with modification of the angle of rotation of the fin teeth is not yet conventionally used in HRSG heat exchangers. However, it represents a progressive alternative to the innovative type of fins and will be the subject of further investigation by the authors of the paper.

References

Beyond Fossil Fuels: European Gas Plant Database, (2024, November 18) https://beyondfossilfuels.org/gas/.

Ganapathy V. (2003) *Industrial Boilers and Heat Recovery Steam Generators*, Marcel Dekker, Inc., New York.