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Geometry Optimization of a Gas Preheater Inlet Region – A Case Study

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Measures for the improvement of process waste gas (PWG) distribution into U-tubes of a tube bank heat exchanger, which is a part of a liquid and gaseous wastes incineration unit, are discussed. Since PWG is being preheated by high-temperature flue gas, increasing the distribution uniformity is crucial.
A computational fluid dynamics (CFD) software is used to analyse the existing PWG flow in the entire tube-side subsystem of the preheater and also to optimize the geometry by means of comparing results obtained for several different inlet region designs. Due to the size of the preheater, however, simplified 2D geometries are usually evaluated with detailed 3D evaluations being done only in case of a few key configurations. Such an approach greatly speeds up the optimization process. In addition to PWG distribution, vorticity is taken into account as well in order to reduce fouling.

1. Introduction

Currently, the preheater inlet region (see Figure 1) is very short which, in combination with a large PWG inlet velocity, presence of two stiffening transverse partition plates above the tube sheet, and a residual amount of sticky liquid droplets in the PWG stream, causes PWG to be distributed poorly into U-tubes. Apart from decreasing preheater efficiency, poor PWG distribution also leads to non-uniform thermal expansion of individual tubes in the tube bank. Since there are U-tube support plates in the tube bank with very small diametral clearances, rigid connections are formed between tubes and plates thus causing the displacements to be carried across from excessively heated tubes to lower-temperature ones. These U-tubes then crack, as has already happened in many cases.

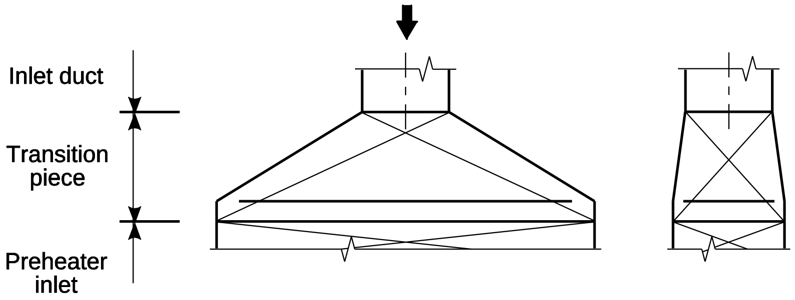

Figure 1: Inlet region of the preheater

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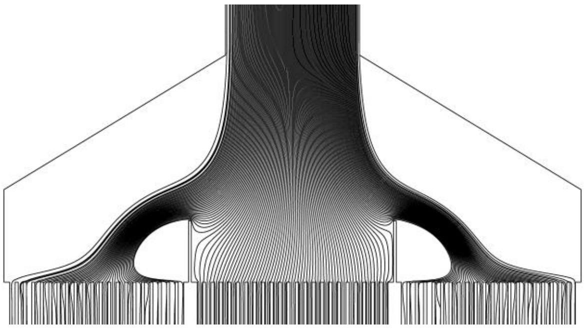

Figure 2: Pathlines in a simplified 2D model of the existing inlet region; empty areas are stagnation zones

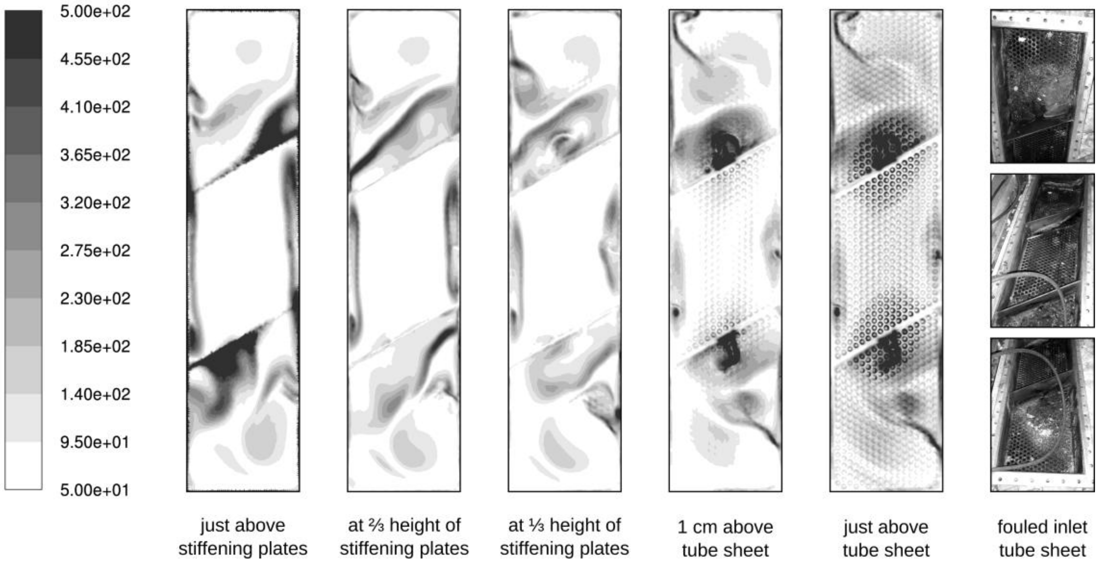

Figure 3: Vorticity magnitude (1/s) in cuts above the inlet tube sheet (3D model); the pattern above closely resembles deposition of particles in the existing preheater depicted right

Moreover, jelly-like deposits form on the tube sheet and in inlet regions of individual tubes due to vortical type of flow in these areas (Blevins, 2003) – see Figures 2 and 3, which aggravates the issue even further. Reduction in quantity and sizes of stagnation zones is therefore desirable as well.

1.1 Methodology

The entire tube-side subsystem (inlet duct – inlet transition piece – U-tubes – outlet transition piece) was evaluated using ANSYS FLUENT (Ansys Inc., 2009) for every considered geometry. In most cases, however, simplified 2D models were employed to speed up the optimization process and only a few key geometries were then verified using detailed 3D models. PWG distribution was rated with relative standard deviation from a uniform distribution,

$$\delta = \frac{100}{\dot{m}_{\mathrm{id}}} \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(\dot{m}_i - \dot{m}_{\mathrm{id}}\right)^2} \quad [\%], \tag{1}$$

where $\dot{m}_{id}$ denotes ideal mass flow rate through one U-tube, n total number of U-tubes, and $\dot{m}_i$ flow

rate through i-th U-tube. Vorticity of flow in the critical areas (near inlet tube sheet and in inlet regions of U-tubes) was evaluated directly in FLUENT using volume integrals of vorticity magnitude to ensure that significant stagnation zones are not present there. A sum of these integrals was then used to compare individual geometries.
All models were transient with simulated time periods being at least 500 s (usually more than 1000 s). These periods were chosen ad hoc according to 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). Simulated time period was at least 3000 s when flow rates oscillated to be sure that these will not reach a steady state after an initial oscillation and that the respective geometry should therefore not be used.
Please note that "spatial" quantities (mass flow rate etc.) are used also in 2D models since these are, in fact, pseudo-3D models created internally by the CFD software. Such quantities cannot be directly compared to their true-3D counterparts, however, 2D results can be normalized to the actual total mass flow rate and a transformation can be applied to them (cf. Section 2) for a rough comparison of 2D and 3D data (constant velocity boundary condition was set on the entrance to the inlet duct and thus the total mass flow rates in 2D and 3D models are different).

2. Current inlet transition piece

Relative standard deviation from a uniform distribution is δ = 6.62 % according to a detailed 3D model of the current transition piece with no fouling layer on the tube sheet or inside inlet regions of U-tubes. Simplified 2D model yields δ = 29.14 %, but the character of flow rate curves obtained with this model and in the middle row of U-tubes of the 3D model is very similar (see Figure 4). Large local differences in flow rates notable in both curves are due to the presence of stagnation zones (and also subsequent fouling).
Considering vorticity, sum of volume integrals of vorticity magnitude over the critical areas obtained using the simplified 2D model is $\Sigma\omega$ = 201.1 m^3/s (please note that the non-standard unit is due to the nature of the model).

2.1 Effect of guiding vanes in the existing transition piece

Guiding vanes placed at the top of the inlet transition piece are necessary to distribute PWG stream to the entire width of the inlet tube sheet because of a large PWG inlet velocity. A second set of vanes placed near the tube sheet must also be provided to direct PWG straight into U-tubes which prevents formation of stagnation zones in tube inlets and thus prevents clogging. However, current inlet

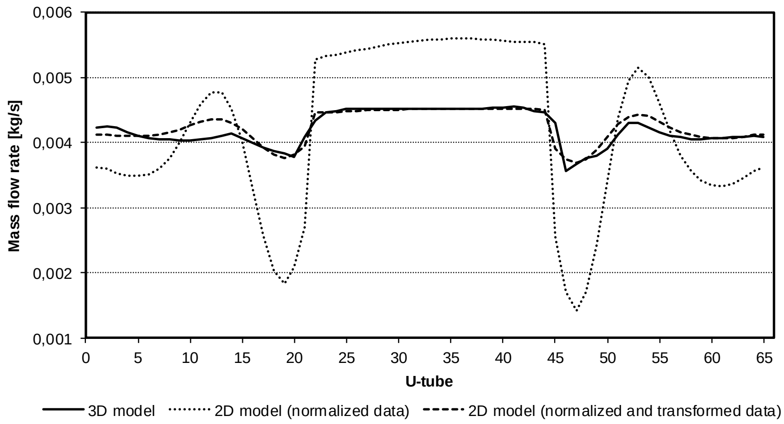

Figure 4: Comparison of flow rates through the middle row of U-tubes (3D model) and through tubes in the simplified 2D model. The transformation used here is 0.2 · X + 0.0034 with X denoting a normalized 2D flow rate.

transition piece is very short and therefore the required number of guiding vanes is prohibitively large – inter-vane spaces would be too small and would clog. Similar problem would arise if a flow conditioner was used instead of vanes. Hence, a longer inlet transition piece with a lower number of guiding vanes must be designed.

3. Optimum inlet transition piece

Very good result in terms of both 2D flow distribution uniformity (δ = 7.34 %) and vorticity ($\Sigma\omega$ = 119.7 m^3/s) can be obtained using 80° transition piece, but only with at least 7 top and 14 bottom guiding vanes. Geometry with this many vanes, again, brings about the risk of clogged inter-vane spaces and as such cannot be accepted.

Pathlines in the optimum (60°) transition piece are shown in Figure 5. In this case inter-vane spaces are acceptable, since 5 top and 10 bottom guiding vanes are necessary to obtain very good 2D flow distribution uniformity (δ = 7.64 %) and low vorticity ($\Sigma\omega$ = 118.5 m^3/s). Comparison of 2D flow rates and volume integrals of vorticity magnitude over individual U-tube inlet parts is in Figures 6 and 7.

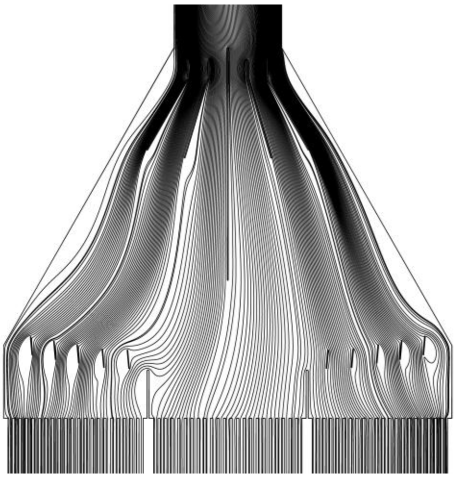

Figure 5: Pathlines in a simplified 2D model of the optimum inlet region

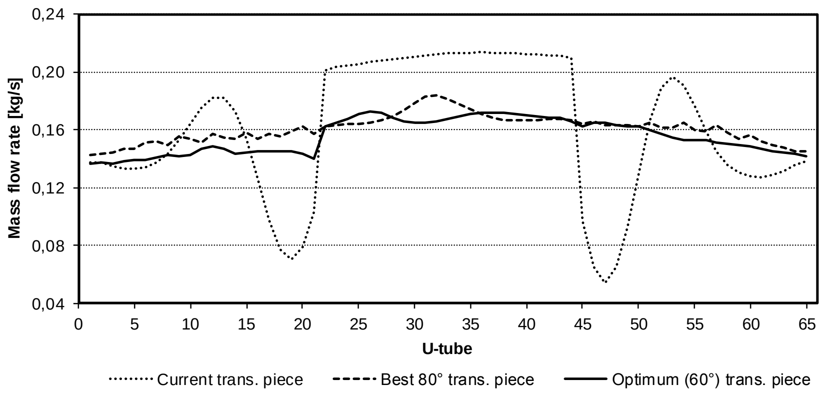

Figure 6: Comparison of flow rates obtained with simplified 2D models

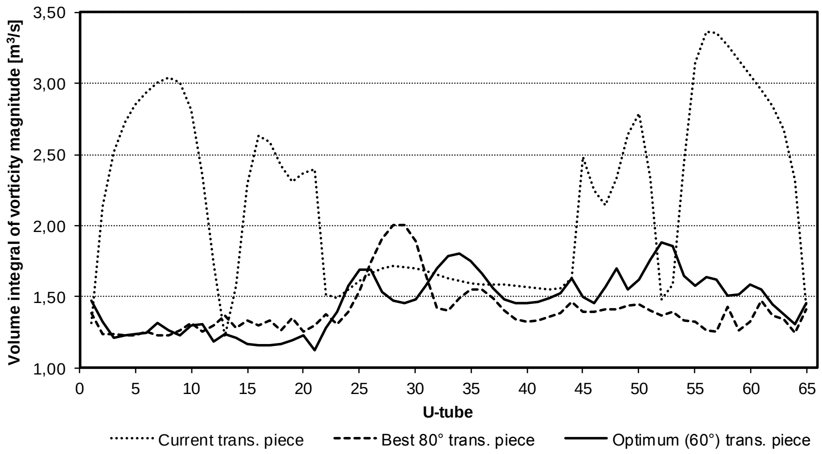

Figure 7: Comparison of volume integrals of vorticity magnitude over inlet parts of individual U-tubes (2D models)

Detailed 3D model of the optimum geometry yielded relative standard deviation from a uniform distribution δ = 4.08 % which is less than 2/3 of the original value. Figure 8 compares 2D flow rates with those obtained using the 3D model. Although 3D and normalized and transformed 2D data are not as close as in Figure 4, they are still very similar. Vorticity magnitude near the inlet tube sheet is significantly lower than originally as can expected with respect to 2D results (see Figure 9). 3D sketch of the optimum transition piece is shown in Figure 10 – top guiding vanes are perpendicular to the longer tube sheet edge while bottom vanes are mounted parallel to the two stiffening transverse partition plates.

4. Conclusion

Geometry optimization of the inlet transition piece was employed to both lower PWG distribution non-uniformity to less than 2/3 of the original value and significantly reduce vorticity of flow near inlet tube sheet and in inlet parts of U-tubes causing secondary distribution problems. This should not only prevent cracking of U-tubes but also lead to improved preheater performance and fewer service shutdowns.

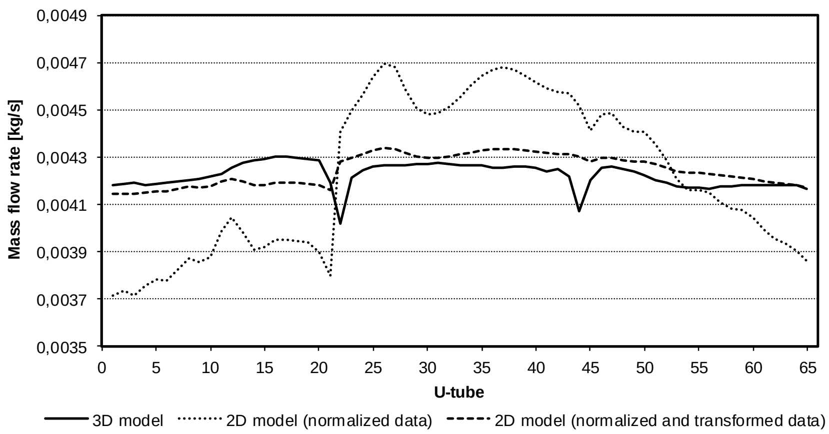

Figure 8: Comparison flow rates obtained using 2D and 3D models; the transformation used here is the same as the one employed in Figure 4

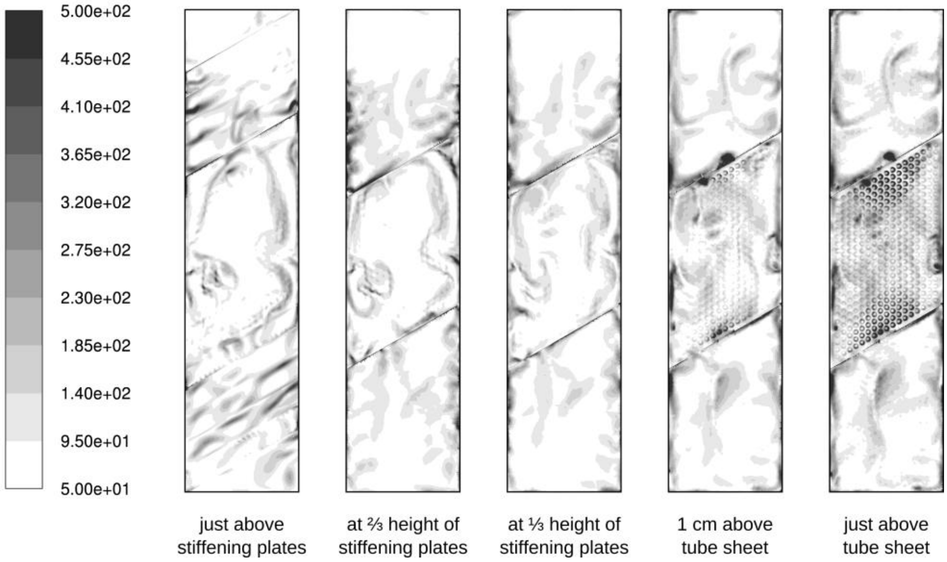

Figure 9: Vorticity magnitude (1/s) above inlet tube sheet in the optimum inlet region geometry

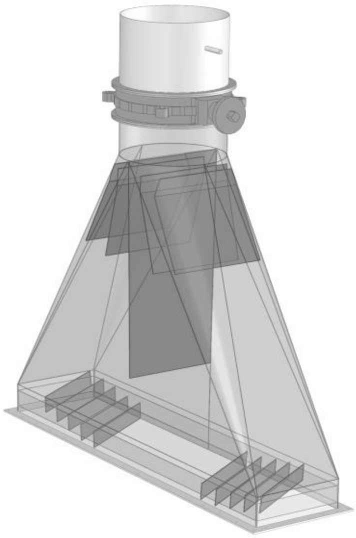

Figure 10: 3D sketch of the optimum inlet transition piece with darkened key parts: throttle valve (top) and guiding vanes (middle and bottom)

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