Design Optimization of a Helical Coil Gas Cooler Based on the Results of CFD Modeling of Erosion Wear

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Abstract. Simulation of erosion wear and design optimization have been performed for a convective gas cooler with a helical coil. Based on the results of simulation of the standard gas cooler design with a flat baffle used in Shell gasification-based combined cycle unit, it is concluded that the particle impact angle is the main factor determining the erosion maximum. To reduce erosion, it is necessary to install a structural element instead of the flat baffle to align the flow path of ash particles at the inlet to the gas cooler. The results of simulation for various baffle shapes show that a hemispherical baffle is optimal. The use of a hemispherical baffle plate made it possible to align the ash particle flow path at the inlet to the gas cooler channels and reduce the maximum level of erosion by a factor of almost 4 compared to the standard geometry of the baffle plate.

The erosion wear of the surfaces of heat exchangers in two-phase flow is a fairly common problem for the power industry, in particular, the nuclear power industry.

The erosion (wear) rate is affected by a large number of parameters: the mechanical properties of the two-phase flow particles (material properties, particle size and shape); the properties of the wall material subjected to wear; gas properties; two-phase (gas-particles) flow velocity; particle concentration in the flow; the angle of particle impact on the wall surface; flow channel geometry. For the spiral convective gas cooler (GC) used in a Shell gasification-based combined cycle unit [1], three parameters from the above list are variables: flow velocity, particle concentration, and particle impact angle. According to literature data, the dependence of erosion on the flow velocity ($u$) is a power function with an exponent of 2-4 [2], the dependence of erosion on the particle concentration ($\gamma$) is linear, and its dependence on the particle incidence angle ($\alpha$) has a maximum at $\alpha = 25–45^\circ$ [3, 4].

The GC tubes are made of Inconel nickel alloy, and its erosion resistance is 10–12% higher than that of stainless steel [5]. Therefore, for conservative results in our case, we chose the original empirical constants according to [6]; for the steel surface, they are $K_1 = 1.51 \cdot 10^{-6}$, $K_{12} = 0.296077$, and $K_3 = 5.0 \cdot 10^{-12}$; $\alpha_0 = 25^\circ$.

The simulation of erosion wear and design optimization of the spiral convective gas cooler (GC) was performed using CFD software; turbulence was taken into account by means of a realizable $k-\varepsilon$ model. The computational domain was a sector equal to 1/8 of the total cross section of the GC. The outer diameter of the tubes is 44 mm; the relative pitch between the coils of the tube spiral in the horizontal...
and vertical directions is 88 mm; the distance from the axis of the outer spiral tubes to the body is 44 mm. The computational grid was hexahedral. The parameters of the syngas are presented in Table 1 [1]. The particle diameter is varied from 2 to 100 µm, and the density is 2800 kg/m$^3$. It is assumed that the particles entering the computational domain have a uniform distribution over the cross section.

Table 1. Initial parameters

| Flow Parameters       | Unit of measurement | Value   |
|-----------------------|---------------------|---------|
| Syngas mass flow rate | kg/s                | 113.1   |
| temperature           | °C                  | 750     |
| pressure (abs.)       | bar                 | 42      |
| CO, CO$_2$, H$_2$, N$_2$ | % (vol.)        | 59.2; 5.1; 28.5; 7.2 |
| Ash mass flow rate    | kg/s                | 1.83    |
| density               | kg/m$^3$            | 2800    |
| number of particles   | pcs                 | 112414  |

Erosion was calculated using the Tabakoff-Grant model developed to calculate erosion of steel surfaces by ash particles [6]:

$$E = K_1 f(\alpha_1)V_1^2 \cos^2 \alpha_1 [1 - R_f^2] + f(V_{in})$$  \hspace{1cm} (1) \\
$$R_f = 1 - 0.005249 V_1 \sin \alpha_1$$  \hspace{1cm} (2) \\
$$f(\alpha_1) = \left[ 1 + C_K K_{12} \sin \left( \frac{90}{\alpha_0} \alpha_1 \right) \right]^2$$  \hspace{1cm} (3) \\
$$f(V_{in}) = K_3 (V_1 \sin \alpha_1)^4$$  \hspace{1cm} (4)

where $E$ is the erosion defined as the ratio of the mass loss of the obstacle to the mass of the impinging particles, mg/g; $V_1$ is the particle velocity, m/s; $\alpha_1$ is the angle of particle incidence in degrees; $\alpha_0$ is the angle of particle incidence at which the maximum erosion rate is achieved; $C_k$ is the recovery factor for impact in the tangential direction, $C_K = 1$ at $\alpha_1 \leq 3\alpha_0$ and $C_K = 0$ at $\alpha_1 > 3\alpha_0$; $K_1$, $K_{12}$, and $K_3$ are empirical constants.

In the simulation of the standard GC design with a flat baffle, a high level of erosion of the metal surface of the S2.2 tube element (the second tube spiral - the second turn) was obtained. The erosion on it was 3·10$^8$ kg/(m$^2$·s) (Figure 1), and on the S2.1 and S2.3 tube elements, the maximum erosion reached 0.2·10$^8$ and 0.6·10$^8$ kg/(m$^2$·s), respectively (Figure 2). On the rest (most) of the heat-exchange surface of the GC, the erosion does not exceed 0.2·10$^8$ kg/(m$^2$·s), i.e., an order of magnitude lower.
This is due to the fact that the ash particles directed to the flat baffle are mainly displaced into the nearest annular channel S1-S2 (between the 1st and 2nd tube spirals). As a result, the trajectories of particles at the inlet of the channel deviate noticeably from the vertical and the main flow of these particles collides with the membrane surface and the S2.2 tube element (Figure 3). Let us examine how this affects the change in the three variable parameters $u$, $\gamma$, and $\alpha$.

As can be seen from Figure 4, the maximum particle concentration ($\gamma$) is observed at the junction of the membrane and the S2.2 tube element and reaches 1.7 kg/m$^3$, while the wear varies from 0 to 3.8·10$^8$ kg/(m$^2$·s). The maximum wear is observed in the other area, on the surface of the S2.2 tube element at $\varphi = 55-60^\circ$ (Figures 2 and 5b) and reaches 3.8·10$^8$ kg/(m$^2$·s).
Figure 4. Concentration of particles on the surfaces of the second tube spiral.

Thus, for the given set of structural characteristics of the GC and its operating parameters, the concentration of particles is not a factor that determines the maximum erosion. Consequently, there is no need to equalize the concentration of particles over the GC cross section using, e.g. additional elements that redirect part of the particle flow.

Figure 5. Intensity of erosion along the profile of the second tube spiral.

As can be seen from Figure 6, in all channels (between the S1-S6 tube spirals), the gas velocity changes along the vertical coordinate; in the narrowest sections (between the tube elements), it reaches ~11 m/s, and in the widest sections (between membranes) ~8 m/s. In contrast to the gas flow, the trajectories of particles in the channels between the S2-S6 tube spirals are practically vertical (Figure 3).
and the particle velocity practically does not change with the vertical coordinate; in this case interaction of particles with the surface of the tube elements occurs only in the narrowest sections and along the tangent to the surface.

Figure 6. Gas velocity.

A different picture of particle motion is observed in the S1-S2 channel, in the initial part of the channel (from the first to the second turn), where, due to collisions with the baffle and then with the membrane and the S2.2 tube element, the particle velocity is lower than in the other channels. However, in the S2-S6 channels (with higher particle velocity), the wear is minimal — less than $0.2 \cdot 10^8$ kg/(m$^2$·s), and it can therefore be concluded that for a given set of structural characteristics of the GC and its operating parameters, the particle velocity is not a factor that determined the maximum erosion.

The third parameter highlighted in the analysis of the effect on the erosion rate is the angle of impact of particles on the surface $\alpha$. If we assume that particles collide with the S2.2 tube element moving vertically, then for the cylindrical surface, $\alpha = 90 - \varphi$. According to the simulation results, the maximum wear is obtained at $\varphi = 55^\circ$ (Figure 5), i.e., $\alpha = 35^\circ$, which agrees with the data of [3, 4], where at flow velocities of up to 30 m/s, the experimental dependences of erosion on the particle impact angle have an extreme character with a maximum at angles 25–45°.

Thus, based on the results of simulation of a standard GC design with a flat baffle used for a Shell gasification-based combined cycle unit, it can be concluded that the particle impact angle $\alpha$ is the main factor determining the erosion maximum.

Consequently, to reduce erosion, it is necessary to install a structural element instead of the flat baffle, which allows aligning the trajectory of the ash particle flow at the inlet to the S1-S2 channel. Modeling was conducted for three shapes of the baffle — cylindrical, conical, and hemispherical. A hemispherical baffle was found to be optimal (Figure 7).
Figure 7. Particle trajectories and erosion with the installed hemispherical baffle.

As can be seen from Figure 7, the use of a hemispherical baffle makes it possible align the trajectory of the ash particle flow at the inlet to the channels and reduce the maximum erosion to $10^8$ kg/(m$^2$·s), i.e., by a factor of almost 4 times compared to the standard geometry of the baffle.

References

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