Stress-deformed state of the coil of the pyrolysis furnace at deviation of the shape of pipes

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Abstract. A distinctive feature of the pyrolysis furnaces of hydrocarbon raw materials from other types of furnaces operated at the facilities of oil and gas chemical enterprises is the strict operating conditions necessary for the implementation of this process. At the same time, the temperature of the radiant coil in operating conditions can reach 1050 °C. In this regard, the probability of failure of coils of pyrolysis furnaces due to defects and damages during operation is extremely high. In addition, variations in coil shape and dimensions that occur during manufacturing or operation can negatively affect the overall stress-strain state of the coil during operational loads. In this work, the influence of permissible deviations in the shape and dimensions of pipes used in the welding of the coil on its stress-strain state in working conditions is investigated.

1. Introduction

The process of pyrolysis of hydrocarbon raw materials is becoming more and more popular in conditions of increasing consumption of polymer materials and plastics. Ensuring high efficiency of cracking plants depends largely on the reliability and efficiency of cracking furnaces, which operate under high-temperature heating conditions.

Due to the intense effect of extremely high operating temperatures (up to 1050 °C) and aggressive media, coils of pyrolysis furnaces are susceptible to defects, such as: pipe wear along the inner surface; brittle destruction of pipes; local strains of pipes to form strippers; external combustion of pipes; formation of through fistulas and rains in pipes [1-7].

One of the factors contributing to the occurrence and development of defects is the change in the stress-strain state of the coil as a result of various geometric deviations of pipes and branches formed during the manufacture and operation of the coil [8-10]. However, in the current regulatory documentation for the design and strength calculations of coils of tubular furnaces of pyrolysis, these factors are not taken into account if their value does not exceed the permissible value.

Therefore, the current task is to simulate the stress-strain state (SF) of the coil of the pyrolysis furnace in case of deviations in the shape and size of pipes within the permissible values, to analyze the change in the value of maximum equivalent stresses arising in the coil design.
2. Study procedure

In order to study the effect of deviations in the shape and dimensions of the cross section of pipes on the stress-strain state of the coils of the pyrolysis furnace, a numerical simulation of the radiant coil was carried out in this work with different arrangement of deviations along the length of the pipes, and a static calculation was made for strength in working conditions taking into account the temperature effect.

The model was based on the design of the radiant coil of the pyrolysis furnace, operated at one of the petrochemical production facilities. This coil is made of six pipes 140 × 8 mm long, 10220 mm long. The pipes are connected by taps (taps) 140 × 12 mm with an angle of 180 °. The material design of the coil is austenitic steel AISI 310S. Coil is installed on vertical suspensions.

Coil operating conditions: operating temperature on external surface of coil t = 840 °C, on internal surface of coil - t = 820 °C, maximum operating pressure P = 1.0 MPa.

To build a three-dimensional model of the coil, the licensed software complex "SolidWorks" was used, and to study its stress-strain state, the finite-element analysis system "ANSYS Workbench."

At the first stage, a three-dimensional model of the coils of the pyrolysis furnace was built. The model was then exported to ANSYS Workbench for boundary conditions and further calculation. Initially, the Engineering Data module simulates the coil material - steel AISI 310S. Further, in the Steady-State Thermal module, the operating temperatures of the coil on the outer and inner surface are set. Then, the sections "Engineering Data," "Geometry" from the "Steady-State Thermal" module were transferred to the "Static Structural" module, and the data from the "Solution" section to the "Setup" section.

In the Static Structural solver, the internal surface of the coil has a maximum operating pressure (P), and the racks are rigid. The contact type "No Separation" - friction-free sliding is used as the contact model between pipes and racks, since given the number of contact points, it is not possible to use the «Frictional» and «Frictionless» models.

Next, an "ideal" coil model is calculated without deviating pipes in shape and size. The obtained result showed that equivalent stresses are distributed uniformly along the length of coil pipes, the average value of stresses is in the range from 30 to 35 MPa. The maximum equivalent stresses occur in the area of the branch connection with the pipes and are 62.3 MPa, which is explained by the edge effect in the area of the rigid connection of the branch and pipes.

In order to reduce the calculation time and dimensions of the finite element grid, the simulation model is optimized. To do this, a similar coil was modeled, consisting of two pipes connected by a branch on one side. The free ends of the pipes are fixed: the lower pipe is rigidly fixed, and the movement of the end of the upper pipe is limited along the z axis. The results of the calculation of the simplified model showed that the maximum and average equivalent stresses in the coil design differ from the original result by 1.8%, which is not a significant error. Therefore, for further calculations, it is customary to use a simplified coil model.

![Figure 1. Result of refined calculation of coil model without shape deviations.](image-url)
To obtain the most accurate result, the optimal size of the grid on the branch and pipes in the area of their connection was determined, reducing the size of the final elements to obtain stable readings of maximum equivalent stresses. As a result of the refined calculation (figure 1), the value of the maximum equivalent stresses in the "ideal" coil model is 67.3 MPa and is located in the area of the connection of the upper coil pipe and the tap.

According to the requirements of the standards, coil pipes may have limit deviations in the outer diameter ± 1.5%, and the curvature of the pipe should not exceed 1.5 mm per 1 m of length. In accordance with these data, a 1 m long section of the coil tube was modeled, having a deviation from the rectilinearity of 1.5 mm, as well as an ovality of the cross section of 1.5% (maximum outer diameter - 142.1 mm, minimum - 137.9 mm).

The position of this section was considered at a distance of 200, 5200 and 8200 mm from the tap in the lower and upper pipe of the coil, taking into account the direction of curvature of the section (bend up and bend down).

Results of static calculation of coil model at location of section with shape deviations in lower pipe at distance of 200 mm from tap are shown in figures 2 and 3.

In the case of deflection of the pipe section upwards (figure 2), the maximum equivalent stresses, compared to the "ideal" coil model without deviations, increased by 6 MPa. At the same time, the region of maximum stresses moved to the welded joint of the lower part of the branch, while in the coil model without defects, maximum stresses arose in the main metal of the branch near the welded joint with the upper pipe.

![Figure 2](image2.png)

**Figure 2.** Stress distribution in coil at location of section of lower pipe with shape deviations (pipe deflection upwards) at distance of 200 mm from tap.

When the lower pipe section is deflected downwards, the maximum equivalent stresses reach 101 MPa, and they are localized in the contact zone of the upper pipe with the post closest to the branch (figure 3).

![Figure 3](image3.png)

**Figure 3.** Stress distribution in coil at location of section of lower pipe with shape deviations (pipe deflection down) at distance of 200 mm from tap.
Deflection of a section of the lower pipe as a result of deviation from rectilinear leads to the formation of additional forces and local stresses from the post in the lower pipe, which explains the concentration of maximum stresses in this area. In addition, the deflection of the pipe increases the equivalent stresses in the main withdrawal metal in the vicinity of the welded joint to 78 MPa, both with the upper and lower pipes, which is 1.5 times higher than when the pipe section is deflected upwards.

The location of the section with deviations in the lower pipe of the coil at a distance of 5200 mm from the tap (figure 4) leads to a decrease in maximum equivalent stresses to 79.3 MPa and their localization in the welded connection of the tap and the lower pipe.

When the section with deviations in the lower pipe is located at a distance of 8200 mm from the drain, the distribution and the value of equivalent stresses correspond to the results of the calculation of the coil model without deviations.

Further, the studies were repeated according to the same scheme for the upper pipe, taking into account the direction of curvature of the section (deflection down).

The results of the static calculation of the coil model at the location of the section with shape deviations in the upper pipe at a distance of 200 and 8200 mm from the tap are shown in figures 5 and 6, respectively.

Analysis of the presented stress distribution patterns in the coil in comparison with the results obtained with the location of deviations in the lower pipe shows that deviations in the shape of the upper pipe lead to a similar redistribution of stresses, while local zones of maximum equivalent stresses are formed mirror in the lower pipe. However, the overall stress level in the coil is slightly higher.

So, with the location of the upper pipe section with deviations at a distance of 200 mm from the drain, the maximum stresses are 103.5 MPa (figure 5).
When a portion of the upper pipe with shape deviations is located at a distance of 5200 mm from the tap, the maximum equivalent stresses reach 84 MPa and occur at the point of contact of the underlying pipe with the fifth from the tap of the post. In addition, there is an increase in stresses in the welded joints of coil pipes among themselves, which is associated with deformation due to a change in the shape of the pipe.

The location of the section of the upper pipe with shape deviations at a distance of 8200 mm from the drain does not have a significant effect on the stressed-deformed state of the coil (figure 6).

![Figure 6. Stress distribution in coil at location of section of upper pipe with shape deviations (deflection of pipe downwards) at a distance of 8200 mm from tap.](image)

Analyzing the results given in figure 6, we can conclude that the nature of the distribution of equivalent stresses corresponds to the results of calculating the "ideal" coil without deviations. Therefore, the presence of deviations at a remote distance from the diversion does not affect the stress-strain state of the coil.

### 3. Conclusion

The results of the study show that the presence in the radiant coil of the pyrolysis furnace of pipe sections with deviations from straightness and ovality of the cross section leads to the formation of local zones of increased equivalent stresses, even if these deviations do not exceed the permissible values according to regulatory documentation. At the same time, the location of sections with deviations in relation to the interface of the tap and coil pipes and the direction of curvature of the section (deflection down) have a significant influence on the value of maximum equivalent stresses. Thus, when forming the rectilinear deflection of the upper pipe portion downwards, the maximum equivalent stresses in the local zone reach 103.5 MPa, while the yield strength of steel AISI 310S at the operating temperature is 160 MPa.

Thus, for a better strength analysis of the structures of radiant coils of pyrolysis furnaces at operational loads and the detection of zones of formation of increased stresses, it is necessary to take into account the presence and location of pipe sections with permissible values of geometric deviations of shape and cross section in the process of modeling and calculation of stress-strain state.

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