The assessment of stressed-deformed state of tube bundle of the heat-exchange apparatus with the fixed pipe grids

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Abstract. Ensuring reliable operation of heat exchange equipment is the key to continuous and efficient operation of the entire technological unit or assembly as a whole. During installation, repair or operation, various deviations of the construction elements of the heat exchangers from the values specified by the project are possible. One of the possible scenarios of such deviations is the deviation of the transverse baffles of the tube bundle from the vertical design position during installation. Since the transverse baffles in the tube bundle play the role of supporting constructions, when they deviate from the vertical design position and at the same time are exposed to operational loads, it is possible to form zones of concentration of increased stresses in the heat transfer pipes, and then the occurrence of defects in these zones. Currently, the work on modeling heat-exchange equipment using specialized software systems for assessing the stress-deformed state taking into account the influencing factors and identifying the most unfavorable zones with maximum effective stresses is relevant. This paper investigates the interconnection between the magnitude and direction of deviation of the transverse baffles from the vertical design position on the stress-deformed state of the tube bundle of the heat exchanger with fixed tube grids along the rows of heat transfer tubes.

1. Introduction

At oil and gas refining and petrochemical enterprises, heat exchangers occupy one of the main places in terms of metal consumption and are intended for heating, cooling, evaporation or condensation of feedstock, as well as finished products. According to the current regulatory documents in the field of industrial safety, heat exchangers are technical devices operating at hazardous production facilities. Therefore, more strict and restrictive measures should be applied to them in the field of ensuring reliability and workability in the process of work [1-4].

For this purpose, periodic monitoring of the technical condition of the elements of shell-and-tube heat exchangers is carried out. To control their technical condition, methods are applied that are regulated by current regulatory and technical documents in the field of industrial safety [5-6].

According to statistics, the largest number of failures of heat exchangers (about 99%) occurs due to the passage of the tube bundle. Therefore, special attention in diagnosing tube bundles has to be given to heat exchangers with fixed tube grids, since it is not possible to fully and sufficiently qualitatively examine a tube bundle due to limited access to it [7-8].

A significant impact on the operational reliability of the tube bundle, and, accordingly, on the entire heat exchanger, is also exerted by the quality of the installation of elements before commissioning. This may especially apply to transverse baffles, which serve as supports for heat transfer pipes. In case
of insufficient fastening of the baffles in the tube bundle during the installation process, the baffles may deviate from the design vertical position and, as a result, zones of stress concentration in those sections of the pipes, which may subsequently be zones of the onset of defects, can arise.

In this regard, the urgent task is to simulate the stress-deformed state of the tube bundle in order to timely identify potentially dangerous places in heat exchanger tubes based on identifying areas of maximum stress dislocation [9-15].

2. Methodology of the research
For research, a heat exchanger with fixed tube grids of one of the oil refineries with the following technical and operational characteristics was selected:

- type of heat exchanger: with fixed tube grids (TF);
- inner diameter of a shell, mm: 400;
- tube bundle length, mm: 2000;
- number of pipe strokes: 1;
- the location of the pipes in the tube grids: along the vertices of the triangle;
- total number of tubes, pieces: 109;
- pipe surface: smooth;
- outer diameter of pipes, mm: 25;
- tube wall thickness, mm: 2.5;
- tube temperature, °C: 85 °C;
- the temperature between the tubes, °C: 50 °C;
- pressure in the pipe space, MPa: 3.9 MPa;
- the pressure between the tubes, MPa: 0.6 MPa;
- tube material: steel 20;
- baffle material: steel 20;
- tube grid material: steel 20;
- the number of rows of heat exchange pipes, pieces: 11.

A tube bundle with fixed tube grids and transverse baffles of the studied heat exchanger is shown in figure 1.

![Figure 1](image1.png)

Figure 1. A tube bundle with fixed tube grids and transverse baffles of the studied heat exchanger.

Figure 2 shows a drawing of the tube grid with the numbering of the rows of tubes, and figure 3 shows a drawing of the transverse baffle.

To solve the problem of assessing the stress-deformed state (SDS) of a tube bundle, the SolidWorks software package was used. The SolidWorks software package uses the principle of three-dimensional solid-state and surface parametric design, which allows you to create volumetric parts and assemble assemblies in the form of three-dimensional electronic models.
Strength analysis was carried out in the SolidWorks Simulation Standard software package, in which linear static, dynamic and fatigue analysis are carried out. In static problems (the “Static Study” function) it is assumed that materials have elastic and linear properties, and all loads and fastenings are static, that is, they do not change with time. Based on the initial conditions, stresses in the structure, deformations, shears and strength characteristics are calculated.

Figure 2. Drawing of a tube grid with numbering of rows of tubes.

Figure 3. Drawing of the transverse baffle.

Tube bundle SDS was evaluated for the following scenarios:

- when deviating from the vertical design position of the transverse baffles No. 1 and No. 6 by values from 0 to 15° in increments of 3°, both clockwise and counterclockwise for the values of the thickness of the baffles;
- with a mutual deviation from the vertical design position of the neighboring transverse baffles No. 1 and 2 with a thickness of 8 mm clockwise by values from 3 to 15° in increments of 6°;
- with a mutual deviation from the vertical design position of the transverse baffle No. 1 clockwise, and the transverse baffle No. 2 counterclockwise by values from 3 to 15° in increments of 6°;
- with a mutual deviation from the vertical design position of the transverse baffles No. 1 and 3 clockwise by values from 3 to 15° in increments of 6°;
- with a mutual deviation from the vertical design position of the transverse baffle No. 1 clockwise, and the transverse baffle No. 3 counterclockwise by values from 3 to 15° in increments of 6°. The thickness of the baffles when evaluating the SDS of the tube bundle with various values of their deviation from the vertical design position was taken equal to 8 mm.

3. Research results and discussion
Based on the results of estimating the SDS of the tube bundle for the rows of heat-exchanging tubes under the above scenarios, the results of the stress distribution range are obtained, which are presented in tables 1-8.

Table 1. The stress distribution range for each row of tube bundle tubes at different deviations of the baffle No. 1 from the vertical design position clockwise.

| № row of pipes | The range of stress distribution, MPa, when the baffle deviates from the vertical design position, deg. | 15 | 12 | 9 | 6 | 3 | 0 |
|----------------|-------------------------------------------------------------------------------------------------|----|----|---|---|---|---|
| 1 row          |                                                                                                  | 97.45-175.4 | 96.08-172.9 | 95.72-191.4 | 95.46-171.8 | 95.13-171.2 | 94.58-170.2 |
| 2 row          |                                                                                                  | 77.96-175.4 | 76.87-172.9 | 95.72-172.3 | 95.46-152.7 | 95.13-152.2 | 94.58-151.3 |
Table 2. The range of stress distribution for each row of tube bundle tubes at various deviations of baffle No. 1 from the vertical design position counterclockwise.

| № row of tubes | Range of stress distribution, MPa | deviation 15° | deviation 12° | deviation 9° | deviation 6° | deviation 3° |
|----------------|----------------------------------|---------------|---------------|--------------|--------------|--------------|
| 1 row          | 97.46-175.4                      | 96.07-172.9   | 95.71-172.3   | 95.21-171.4  | 95.05-171.1  |
| 2 row          | 97.46-155.9                      | 96.07-153.7   | 95.71-153.1   | 95.21-152.3  | 95.05-171.1  |
| 3 row          | 97.46-194.9                      | 96.07-211.3   | 95.71-191.4   | 95.21-209.5  | 95.05-209.1  |
| 4 row          | 97.46-214.4                      | 96.07-192.1   | 95.71-210.6   | 95.21-190.4  | 95.05-209.1  |
| 5 row          | 97.46-175.4                      | 96.07-192.1   | 95.71-172.3   | 95.21-190.4  | 95.05-209.1  |
| 6 row          | 97.46-175.4                      | 96.07-192.1   | 95.71-191.4   | 95.21-190.4  | 95.05-209.1  |
| 7 row          | 97.46-214.4                      | 96.07-211.3   | 95.71-229.7   | 95.21-209.5  | 95.05-209.1  |
| 8 row          | 97.46-233.9                      | 96.07-230.6   | 95.71-172.3   | 95.21-228.5  | 95.05-190.1  |
| 9 row          | 97.46-175.4                      | 96.07-192.1   | 95.71-172.3   | 95.21-190.4  | 95.05-171.1  |
| 10 row         | 97.46-175.4                      | 96.07-192.1   | 95.71-153.1   | 95.21-152.3  | 95.05-171.1  |
| 11 row         | 97.46-214.4                      | 96.07-172.9   | 95.71-229.7   | 95.21-190.4  | 95.05-228.1  |

Table 3. The range of stress distribution for each row of tube bundle tubes at various deviations of baffle No. 6 from the vertical design position clockwise.

| № row of tubes | The range of stress distribution, MPa, when the baffle deviates from the vertical design position, deg. |
|----------------|---------------------------------------------------------------------------------------------------|
|                | 15                                                  | 12                                                  | 9                                                  | 6                                                  | 3                                                  | 0                                                  |
| 1 row          | 94.94-170.9                                        | 94.94-170.9                                        | 94.94-170.9                                        | 94.9-171.9                                         | 94.58-170.2                                        |
| 2 row          | 94.94-151.9                                        | 94.94-151.9                                        | 94.94-151.9                                        | 94.9-152.9                                         | 94.58-151.3                                        |
| 3 row          | 94.94-208.9                                        | 94.94-189.9                                        | 94.94-208.9                                        | 94.9-207.9                                         | 75.66-189.1                                        |
| 4 row          | 94.94-189.9                                        | 94.94-189.9                                        | 94.94-189.9                                        | 94.9-188.9                                         | 75.66-208.1                                        |
| 5 row          | 94.94-170.9                                        | 94.94-170.9                                        | 94.94-170.9                                        | 94.9-171.9                                         | 94.58-208.1                                        |
| 6 row          | 94.94-208.9                                        | 94.94-208.9                                        | 94.94-208.9                                        | 94.9-207.9                                         | 75.66-227.0                                        |
| 7 row          | 94.94-189.9                                        | 94.94-189.9                                        | 94.94-189.9                                        | 94.9-188.9                                         | 75.66-170.2                                        |
| 8 row          | 94.94-170.9                                        | 94.94-170.9                                        | 94.94-170.9                                        | 94.9-171.9                                         | 75.66-189.1                                        |
| 9 row          | 94.94-170.9                                        | 94.94-170.9                                        | 94.94-170.9                                        | 94.9-152.9                                         | 75.66-170.2                                        |
| 10 row         | 94.94-151.9                                        | 94.94-151.9                                        | 94.94-151.9                                        | 94.9-152.9                                         | 75.66-170.2                                        |
| 11 row         | 94.94-227.8                                        | 94.94-227.8                                        | 94.94-227.8                                        | 94.9-227.6                                         | 75.66-170.2                                        |

Table 4. The range of stress distribution for each row of tube bundle tubes at various deviations of baffle 6 from the vertical design position counterclockwise.

| № row of tubes | The range of stress distribution, MPa, when the baffle deviates from the vertical design position, deg. |
|----------------|---------------------------------------------------------------------------------------------------|
|                | 15                                                  | 12                                                  | 9                                                  | 6                                                  | 3                                                  | 0                                                  |
| 1 row          | 94.88-170.8                                        | 94.88-170.8                                        | 94.88-170.8                                        | 94.9-171.9                                         | 94.58-170.2                                        |
| 2 row          | 94.88-151.8                                        | 94.88-151.8                                        | 94.88-151.8                                        | 94.9-152.9                                         | 94.58-151.3                                        |
### Table 5. The range of stress distribution for each row of tube bundle tubes at different deviations of the baffles No. 1 and No. 2 from the vertical design position clockwise.

| № row of tubes | The range of stress distribution, MPa, when the baffles deviate from the vertical design position, deg. |
|----------------|---------------------------------------------------------------------------------------------|
|                | 15                                           | 12   | 9   | 6   | 3   | 0       |
| 1 row          | 98.59-177.5                                  | 97.46-175.4 | 96.1-192.2 | 94.58-170.2 |
| 2 row          | 98.59-177.5                                  | 97.46-155.9 | 96.1-173.0 | 94.58-151.3 |
| 3 row          | 98.59-216.9                                  | 97.46-194.9 | 96.1-211.4 | 75.66-189.1 |
| 4 row          | 98.59-197.2                                  | 97.46-214.4 | 96.1-192.2 | 75.66-208.1 |
| 5 row          | 98.59-197.2                                  | 97.46-175.4 | 96.1-192.2 | 94.58-208.1 |
| 6 row          | 98.59-197.2                                  | 97.46-175.4 | 96.1-192.2 | 75.66-170.2 |
| 7 row          | 98.59-216.9                                  | 97.46-214.4 | 96.1-192.2 | 75.66-227.0 |
| 8 row          | 98.59-236.6                                  | 97.46-233.0 | 96.1-230.6 | 94.58-208.1 |
| 9 row          | 98.59-197.2                                  | 97.46-175.4 | 96.1-192.2 | 75.66-189.1 |
| 10 row         | 98.59-197.2                                  | 97.46-175.4 | 96.1-192.2 | 75.66-170.2 |
| 11 row         | 98.59-216.9                                  | 97.46-175.4 | 96.1-192.2 | 75.66-170.2 |

### Table 6. Range of stress distribution for each row of tube bundle tubes at different deviations of baffle No. 1 clockwise, No. 2 counterclockwise from the vertical design position.

| № row of tubes | The range of stress distribution, MPa, when the baffles deviate from the vertical design position, deg. |
|----------------|--------------------------------------------------------------------------------------------------------|
|                | 15                                           | 9   | 3   | 0       |
| 1 row          | 98.64-177.5                                  | 97.34-171.5 | 96.08-172.9 | 94.58-170.2 |
| 2 row          | 98.64-177.5                                  | 97.34-171.5 | 96.08-172.9 | 94.58-151.3 |
| 3 row          | 98.64-217.0                                  | 97.34-213.4 | 96.08-211.4 | 75.66-189.1 |
| 4 row          | 98.64-197.3                                  | 97.34-191.4 | 96.08-192.2 | 75.66-208.1 |
| 5 row          | 98.64-177.5                                  | 97.34-171.5 | 96.08-172.9 | 94.58-208.1 |
| 6 row          | 98.64-177.5                                  | 97.34-171.5 | 96.08-172.9 | 75.66-170.2 |
| 7 row          | 98.64-217.0                                  | 97.34-213.4 | 96.08-211.4 | 75.66-227.0 |
| 8 row          | 98.64-236.7                                  | 97.34-232.1 | 96.08-230.6 | 94.58-208.1 |
| 9 row          | 98.64-197.3                                  | 97.34-191.4 | 96.08-192.2 | 75.66-189.1 |
| 10 row         | 98.64-177.5                                  | 97.34-171.5 | 96.08-172.9 | 75.66-170.2 |
| 11 row         | 98.64-177.5                                  | 97.34-171.5 | 96.08-172.9 | 75.66-170.2 |
Table 7. The range of stress distribution for each row of tube bundle tubes at different deviations of the baffles No. 1 and No. 3 from the vertical design position clockwise.

| № row of tubes | The range of stress distribution, MPa, when the baffles deviate from the vertical design position, deg. |
|----------------|---------------------------------------------------------------|
|                | 15                  | 9                  | 3                  | 0                  |
| 1 row          | 98.83-177.9         | 96.07-172.9        | 96.07-172.9        | 94.58-170.2        |
| 2 row          | 98.83-177.9         | 96.07-172.9        | 96.07-172.9        | 94.58-151.3        |
| 3 row          | 98.83-217.4         | 96.07-211.3        | 96.07-211.3        | 75.66-189.1        |
| 4 row          | 98.83-197.7         | 96.07-192.1        | 96.07-192.1        | 75.66-208.1        |
| 5 row          | 98.83-177.9         | 96.07-172.9        | 96.07-172.9        | 94.58-208.1        |
| 6 row          | 98.83-177.9         | 96.07-172.9        | 96.07-172.9        | 75.66-170.2        |
| 7 row          | 98.83-197.7         | 96.07-192.1        | 96.07-192.1        | 75.66-227.0        |
| 8 row          | 98.83-237.2         | 96.07-230.6        | 96.07-230.6        | 94.58-208.1        |
| 9 row          | 98.83-177.9         | 96.07-172.9        | 96.07-172.9        | 75.66-189.1        |
| 10 row         | 98.83-177.9         | 96.07-172.9        | 96.07-172.9        | 75.66-170.2        |
| 11 row         | 98.83-177.9         | 96.07-172.9        | 96.07-172.9        | 75.66-170.2        |

Table 8. Range of stress distribution for each row of tube bundle tubes at different deviations from the vertical design position of baffle No. 1 clockwise, No. 3 counterclockwise.

| № row of tubes | The range of stress distribution, MPa, when the baffles deviate from the vertical design position, deg. |
|----------------|---------------------------------------------------------------|
|                | 15                  | 9                  | 3                  | 0                  |
| 1 row          | 98.8-177.8          | 96.05-172.9        | 96.06-172.9        | 94.58-170.2        |
| 2 row          | 98.8-177.8          | 96.05-172.9        | 96.06-172.9        | 94.58-151.3        |
| 3 row          | 98.8-217.4          | 96.05-211.3        | 96.06-211.3        | 75.66-189.1        |
| 4 row          | 98.8-197.6          | 96.05-192.1        | 96.06-192.1        | 75.66-208.1        |
| 5 row          | 98.8-177.8          | 96.05-172.9        | 96.06-172.9        | 94.58-208.1        |
| 6 row          | 98.8-177.8          | 96.05-172.9        | 96.06-172.9        | 75.66-170.2        |
| 7 row          | 98.8-177.8          | 96.05-172.9        | 96.06-172.9        | 75.66-227.0        |
| 8 row          | 98.8-237.1          | 96.05-230.5        | 96.06-230.5        | 94.58-208.1        |
| 9 row          | 98.8-197.6          | 96.05-192.1        | 96.06-192.1        | 75.66-189.1        |
| 10 row         | 98.8-177.8          | 96.05-172.9        | 96.06-172.9        | 75.66-170.2        |
| 11 row         | 98.8-177.8          | 96.05-172.9        | 96.06-172.9        | 75.66-170.2        |

Analyzing the results, we can conclude that when the deflection of the transverse baffles 8 mm thick from the vertical position by values from 3° to 15° both clockwise and counterclockwise there is a redistribution of SDS pipes and a change in the location of the zone of maximum stress in their rows. Also, the values of the maximum stresses and the location of this zone are affected not only by the magnitude and direction of deviations from the vertical design position clockwise and counterclockwise, but also by the direction of their mutual deviation.

4. Conclusions

Based on the modeling results of the SDS of the tube bundle of a heat exchanger with fixed tube grids with different deviations of the transverse baffles from the design vertical position, the following conclusions can be made:

- the maximum stresses in the rows of tubes of the tube bundle change their value and location depending on the magnitude of the deviation of the baffles from the design vertical position, as well as the direction of deviation and the location of the baffles in the construction.
• the magnitude of the maximum stresses and the place of their concentration along the rows of pipes of the tube bundle depends on the degree of deviation and the direction of deviation of two different baffles located nearby and mutually affect each other.

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