Numerical Investigation on Effect of Thermal Expansion Joint in a Tube Holder Insulating Section in Shell and Tube Heat Exchanger

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Abstract

As shell and tube heat exchangers become more widely used, their challenges are becoming more and more important. In some of these heat exchangers, an insulating section is used to reduce thermal stresses on the tube holder section. In this study, the effect of the presence and absence of expansion joints in this insulating section has been investigated. For this purpose, the desired section with and without expansion joint has been analyzed using the finite element method (FEM) in ANSYS software. Based on the results, it was found that the thermal expansion joint reduces thermal deformation and significantly reduces the rate of stresses in the mentioned section, which increases the life of the tube holder section. Also, the presence of expansion joints reduces the applied pressure to the insulation tape around the tube holder section, which increases the life of the insulation tape around the insulation section.

1. Introduction

Today, shell and tube heat exchangers are widely used in the oil, chemical, and pharmaceutical industries [1]. Therefore, the study and optimization of this widely used industrial equipment have a special place in engineering. One of the effective factors in reducing the life of these heat exchangers is thermal stress. It is very difficult to study the interactions between the tubes and the tube holder section, due to the high working temperature, high-temperature gradient, and complexity of geometry [2]. In this regard, many studies have been performed to predict and estimate the performance of the tube and the tube holder section, which have examined the effects of different parameters on them [3-8].

The strength and durability of a tube holder is a function of the resultant of thermal and mechanical stress, welding and external actions which are key problems in the industry [1]. In order to have a strong and reliable connection between the tube and the tube holder, the standards determined by table RCB.7.41, the tubes should be updated with the standards which set up by TEMA [9, 10]. If the tube expansion in the tube holes is not more than the allowable limit, it causes an acceptable strain in the tube or at its contact surface with the tube holder [9], based on the obtained results by yokell [11], roller joints cannot be used in general for the case that the tube wall is changed more than 12% because they lose their efficiency under working conditions and pressures. Aufaure and co-workers [12] studied the displacement in radial direction and focused on the inner surface of the tube in the investigation of the thermal stresses, which adopted the pseudostatic axis method. Updike and co-workers [5] also demonstrated that the effect of expansion of the contraction gap of the circular model can be modelled as two - dimensional axisymmetric. With the increasing progress of computer technology, the finite element method with acceptable accuracy and application has made its contribution to industry and practical problems and the issue of thermal stresses and residual stresses are not exceptions [13-15]. By improving the numerical method accuracy and finite element method, researchers tend to look similar to the more accurate and more exact ones [16]. For example, Cizelj and Mavko [17] investigated the effect of residual stress on crack growth in the expansion region of the tube by using the axisymmetric method in Abaqus software. Allam and co-workers [8] using the finite element method to investigate the gap between tube and holder and concluded that the gap size has a negligible
effect on contact stress in strain hardening materials. Williams and co-workers [18, 19] used the finite element method and a symmetric two-dimensional finite element analysis of residual stresses in tube connection to the tube supporter section (tube holder).

As well as in the review of the literature, researchers usually study inner tube holder section. In some cases, a tube holder section is placed before the heat exchanger inlet section which is used as a thermal insulation in order to protect the tube holder plate against heat exchangers as well as tube suppression. Although this plate is effective in reducing thermal stresses, it plays an important role in reducing thermal stresses, but the plate itself is exposed to a lot of heat stress and pressure due to expansion of the tubes and expansion tube holder material. In this numerical study, in order to increase the lifetime of the insulating section, the effect of thermal expansion on the dielectric constant is investigated. To best of authors’ knowledge for the first time, the effect of thermal expansion joint on the properties and performance of insulating section was investigated, this problem became more important than past because of insulting material price growth. This study suggests thermal expansion joints to improve insulting material and tube holder section lifetime to save maintenance costs and decrease over hall duration.

2. Problem statement

2.1. Geometry

In this section, the studied geometry and the physical conditions of the problem are discussed. In this study, a step prior to the holding of the input tube is considered and is used to protect the heat exchanger against thermal stresses and also to help keep the tubes. In this project, we used a specific composite in simulation. In addition to the insulation tapes at this section are located outside the outer surface between the section and the inner surface of the heat exchanger fill insulation gap. The front view of the insulation section geometry is shown in Figure 1.

![Figure 1. Front view of the insulation section in the absence of the thermal expansion joint](image)

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![Figure 2. Front view of the insulation section in the presence of the thermal expansion joint](image)

Figure 2. Front view of the insulation section in the presence of the thermal expansion joint
Table 1. Thermophysical properties of applied materials

| section                     | applied material                | Thermal expansion coefficient | Density $\text{kg/m}^3$ | Poisson’s ratio |
|-----------------------------|---------------------------------|------------------------------|--------------------------|-----------------|
| Central section             | Laboratory composite            | 0.75                         | 3.05                     | 0.18            |
| First tape insulating       | Legritte                        | 1.2                          | 1.47                     | 1.4             |
| Second tape insulating      | pirost                          | 0.42                         | 3.8                      | 2.5             |
| third tape insulating       | Compressed glass wool           | 0.23                         | 35                       | 0.82            |

The inner diameter of the studied section is 310 mm, its outer diameter is 2388 mm, and the radial distance of the insulation section to the heat exchanger shell is 262 mm. As shown in Figure 2, by inserting expansion joints, the tube holder section is divided into 7 other sections, in the center of which is a regular hexagon and at the edge, 6 sections are homogeneous and symmetrical. The thickness of the created gap is 4 mm.

Tubes are made of steel and there is a radial distance of 1.6 mm between the pipes and the central insulation section. The wall thickness of small pipes is 1.5 mm and large pipes are 2 mm. The applied insulation section is made of the mentioned laboratory composite. The thermophysical properties of the materials used in the analysis are given in Table 1. In this case, the tubes contain hot gases, which enter the tubes with a temperature of 1020 °C and a pressure of 2.76 MPa.

2.2. Governing equations

Due to the existence of thermal stresses in the problem under study, the stress-strain relationship can be expressed using the following equation.

$$\{\varepsilon\} = [D]^{-1}\{\sigma\} + \{\alpha\} \Delta T$$

In this equation, $\{\varepsilon\} = [\varepsilon_x \varepsilon_y \varepsilon_z \varepsilon_{xy} \varepsilon_{yz} \varepsilon_{xz}]^T$ shows total strain vector. Stress vector calculate via $\{\sigma(Pa)\} = [\sigma_x \sigma_y \sigma_z \sigma_{xy} \sigma_{yz} \sigma_{xz}]^T$. Elastic stiffness matrix showed with [D] and thermal expansion joint vector written as $\{\alpha(1\degree C)\} = [\alpha_x \alpha_y \alpha_z 0 0 0]^T$. Linear thermal expansion ($\alpha$), used to calculate thermal expansion in desired directions. Linear thermal expansion equation described as it written below (equation 2).

$$\alpha = \frac{1}{L} \left( \frac{\partial L}{\partial T} \right)$$

If the material is studied in an isotropic and isotropic material:

$$\beta = 3\alpha$$

$\beta$ is volumetric thermal expansion coefficient. The temperature difference mentioned in Equation (1) is calculated as:

$$\Delta T = T - T_{ref}$$

Where the $T$ (°C) temperature is the moment temperature and the $T_{ref}$ (°C) reference temperature is shown.

2.3. Boundary conditions

As mentioned above, the fluid flows into the tubes at a temperature of 1020 °C and pressure of 2.76 MPa, so the boundary conditions of temperature and pressure within the tubes are known. Also, another boundary condition that has been applied, the lack of shape change and the size of the external diameter of the insulated section is due to the outer surface of the insulating section with the inner wall of the heat exchanger. As a primary condition, the initial temperature is considered to be equal to the standard temperature of the environment.

2.4. Numerical simulation

The development of numerical methods and computer technology has revolutionized the industry by reducing design and manufacturing costs. In these methods, the governing nonlinear differential equations can be solved according to the boundary conditions and the initial conditions of the problem and the solution of the problem is presented numerically. Numerical methods, in addition to greatly reducing design and construction costs, sometimes provide the
researcher with information that cannot be extracted using experimental methods. Among the known methods in stress-strain analysis, we can mention the finite element method. Due to the increasing development of finite element method, software has been presented, each of which has its own capabilities and can be used in design and numerical design. ANSYS is one of the well-known software that is used in many industrial designs around the world and today it is used as a standard tool in engineering design. Due to the ability of ANSYS software to analyze thermal stresses in this issue, this software has been used.

2.5. Meshing

In general, the studied geometry includes three meshing areas (tubes, three layers of insulation and the retaining surface of the pipe). Meshing in this paper has been done with the help of Ansys software meshing module. The method and type of meshing implemented in this geometry is implemented in regular quadrilateral shapes in tubes (Figure 3) and in other surfaces by triangular method (Figure 4). The mesh settings are on the automatic, and due to the holes in the tube on their holding surface, the mesh has become smaller, the purpose is to study these sensitive areas more accurate. Figures 4 and 5 show an example of the meshing done in the presence and absence of expansion joint. Table 2 also shows the number of cells in each analysis.

| Table 2. Number of cells in simulations |
|----------------------------------------|
| Type of simulation                  | Number of cells |
|--------------------------------------|-----------------|
| Without thermal expansion joint      | 597870          |
| With thermal expansion joint         | 1665247         |
3. Results

In order to investigate the effect of expansion joints, both geometries without joints and with joints were simulated and analyzed. The results obtained from the simulation of two geometries are presented in this section, which we will examine in the following:

3.1. The effect of the presence of expansion joint on the amount of geometry deformation

Figure 6 shows the contour deformation of the geometry in the radial direction in two states without expansion seam and with expansion seam. As can be seen from the comparison of the two shapes, with the installation of expansion joints, the amount of deformation in the side walls that are tangential to the strip insulation is greatly reduced, which indicates a reduction in pressure on the insulation and thus increase their lifespan. In general, it can be said that the increase in length in the radial direction at the point of contact of the desired section and the insulation tape around it, has decreased from 12.8 mm to 5 mm. As it can be seen in Fig.6, the highest amount of total deformation occurred in the contact surface between central insulting section and insulting tapes. The amount of total deformation in central section (around central tube) decreases 204% by adding thermal expansion joints.

![Figure 6. Total deformation in radial direction (a) with and (b) without thermal expansion joint](image)

3.2. The effect of expansion joint on the stress on the geometry

Figure 7 shows the normal stress contour which applied in the radial direction in the presence and absence of thermal expansion joint. By comparing the two cases, it is clear that by adding thermal expansion joints, the stress applied to the whole geometry has been significantly reduced. In order to compare numerically with the definition of ten points at the point of contact of the desired section and the insulation tape around it and extract the amount of normal stresses applied to them, the effect of thermal expansion joints on vertical stress can be shown. In Table 4, the relative status of the stresses in these two cases can be compared.

![Figure 7. Normal stress contour in radial direction (a) with and (b) without thermal expansion joint](image)
Table 3. Amount of normal stress in ten selected point

| Point coordinates \((r, \theta)\) | Normal stress (pa) |
|---------------------------------|--------------------|
|                                | With expansion joint | Without expansion joint |
| (2388, 0)                      | 2.12E+09            | 2.76E+09               |
| (2388, 40)                     | 2.20E+09            | 2.76E+09               |
| (2388, 80)                     | 2.18E+09            | 2.66E+09               |
| (2388, 120)                    | 2.31E+09            | 2.68E+09               |
| (2388, 160)                    | 2.18E+09            | 2.59E+09               |
| (2388, 200)                    | 2.20E+09            | 2.69E+09               |
| (2388, 240)                    | 2.22E+09            | 2.73E+09               |
| (2388, 280)                    | 2.22E+09            | 2.75E+09               |
| (2388, 320)                    | 2.23E+09            | 2.78E+09               |

4. Conclusions

In this study, the effect of the presence of expansion joints in the insulation section was investigated numerically. According to the simulations performed and comparing the behavior of the insulation section in two cases without the expansion joint and despite the expansion joint, the following results can be mentioned:

- Adding thermal expansion joint can improve the deformation rate in the insulation section. This effect is especially visible at the contact surface of the desired section and the insulation tape around it and deformation factor improved about 204%.
- By installing the expansion joint, the amount of stresses which applied to the section is reduced more than 20% in the measured points.
- Due to the effect of adding expansion joint in reducing radial deformation and also reducing stress in the insulation section, it can be said that the presence of expansion joint in the insulation section in addition to increasing the working life and efficiency of the insulation section, by reducing the pressure on the surrounding insulation tape Insulation cross section increases the life of insulation tape.
- By adding thermal expansion joints, insulation section efficiency and working life will increase as a result, thermal expansion joints play an important role in economic aspect of maintenance and prevent huge costs which caused by repair, replacing and insulation material charging.
- The highest amount of normal stress when the expansion joint is added, occurs in the edges of the central hexagonal and will be the critical zone which tolerate high stresses.

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