Similarity criteria for modeling the process of pipes pulse pressing into the tube sheet

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Abstract. In the presented article, the phenomena that characterize the essence of the process of fastening pipes to the tube sheet by the method of electropulse pressing are described. The article presents the results relating to methods and means of measurement, testing and operation of products in engineering, including theoretical studies of methods for fastening heat-exchange tubes into a tube sheet. The disadvantages of traditional methods of fastening pipes to the tube sheet are revealed. The analysis of the prospects of pipes electropulse pressing into the tube sheet is conducted. Using the dimensional analysis method, similarity criteria were obtained for the process of electropulse press-fitting of pipes into a tube sheet, which allow extending the results obtained on a reduced-scale model to products of natural dimensions.

1. Introduction

Heat exchangers, as devices for transferring heat from one medium to another, are widespread in many industries and are used as elements of various heat power plants. In the chemical, petrochemical and oil refining industries, the single unit capacity increases and will increase by about 4 times every ten years [1].

Nowadays, there are a large number of heat exchangers types that differ in design, type of coolant, performance, heat transfer surface, working conditions, repair regulations, etc.

With this variety of heat exchangers designs, the types of pipe connections with tube sheets can be classified according to the technology of their implementation into press, combined and welded [2, 3].

The operational characteristics of the heat exchange equipment largely depend on the quality of fastening of the heat exchange pipes in the tube sheet. Surveys in the oil refining and petrochemical industries showed that the losses associated with the downtime of technological lines, as a result of the poor quality of pipe fasteners in tube sheets, are 10-15 times higher than the cost of the heat exchangers themselves [4 - 6]. It is also worth noting that the operations associated with the fastening of heat-exchange pipes into tube sheets are one of the most labor-intensive and make up about 40% of the laboriousness of the apparatus assembly work [7, 8].

Caustic and poisonous coolants are often used in heat exchangers; therefore, depressurization of pipes can lead to a serious accident, both from the side of the environment and industrial safety of the enterprise.

Therefore, the problem of the quality and reliability of pipe fastening in the tube sheets of heat exchangers becomes especially urgent and the pipe connections created in them are technological only in conditions of using new technological methods developing in parallel.

The most common is the use of traditional mechanical methods of fastening pipes, usually with a rolling tool. But despite its prevalence, this method is not deprived of many significant drawbacks. There are difficulties when expanding pipes in tube sheets with a thickness of more than 100 mm, in double intermediate tube sheets, as well as pipes with an inner diameter of less than 10 mm and pipes made of steels with increased strength properties [9, 10].

Due to the low level of mechanization and automation of the process, low labor productivity is inherent - the fastening time of one end of the pipe varies from 1.5 to 12 minutes [11].

It is not possible to fasten pipes in tube sheets with preliminary welding (according to GOST R 55601-2013) due to the occurring axial deformations of the pipes, which lead to the destruction of the weld. Due to local deformation and hardening on the inner surface of the pipe and tube sheet, the corrosion resistance of the joints decreases [12]. Everything else, the tool wears out quickly.

Therefore, further in the article, as a method of fastening pipes with tube sheets, we will consider the electric pulse method as the most technologically advanced and promising.

The purpose of this work is to obtain criteria for the similarity of the process of electropulse press fitting of pipes into a tube sheet, which allow reducing the results obtained on a reduced-scale model to nature. Often, heat exchangers have large overall dimensions and, accordingly, have a large number of pressed pipes into the tube sheet, which primarily affects the modeling and processing of the information under study, therefore, when researching and studying this process, the application of similarity criteria will reduce information processing time and optimize the process building models.

2. Prospects of pipes pulsed pressing methods into the tube sheet

One of the promising methods of fastening pipes in tube sheets is electric pulse pressing. The use of an electric pulse makes it possible to automatically control energy parameters, control the process of energy release, create an optimized process and mechanized high-performance equipment [13].

By changing the pressure pulse in the pipe by controlling the energy parameters of the discharge, it is possible to control the quality of the connection, taking into account the properties of its materials and sizes. With an increase in the discharge voltage, the pressure amplitude and the radius of propagation of the plastic strain zone in the compound increase.

By eliminating the possible sharp increase in the rate of pipe deformation, its hardening during deformation and rebound from the grating, it is possible to increase the tightness of the joints. Reducing the gap between the pipe and the hole of the tube sheet due to the use of high precision pipes and reducing the size of the hole increased the tightness by more than 1.5 times. It is possible to increase the efficiency of pressing in by increasing the load resistance, the relative length of the pressing in, and a higher discharge voltage.

The statistical estimate of the mean time between failure of joints obtained by electropulse pressing exceeds the corresponding index of joints obtained by mechanical expansion, sometimes by more than 25 times. This is also confirmed by the experience of operating heat exchangers at the corresponding facilities [14].

It is also worth noting that the industrial sites and workshops for the pulsed processing of high-strength metals based on explosive technology created in the former USSR made it possible to obtain an economic effect of about 1 billion rubles at defense enterprises of the Soviet country [14].

The first research results and their analysis confirmed the prospects of work on pulse pressing of pipes, predetermined the relevance of further developments in this direction [15].

3. Parameters characterizing the process of electropulse press fitting of pipes into the tube sheet

When modeling the process of electropulse press-fitting of pipes into a tube sheet, it is necessary to describe the following phenomena: generating an electric-discharge disturbance in the circuit of an electric pulse installation and transferring the corresponding charge to a working member (cartridge) of press-fitting tubes into a tube sheet; the interaction of the perturbed working body of the press fitting with the pressed pipe and the plastic deformation of the latter.

The generation and transmission of a certain electrical discharge disturbance to the working body of the press-fit is characterized by the possible operating modes of the corresponding installation. In turn, the operation modes of the installation are determined by parametric values, the main of which are: inductance of the excitation coil, installation frequency, charging voltage of the capacitor bank and current in the working circuit.

In turn, the interaction of a perturbed working body with an extruded pipe and its plastic deformation depends on the mode of the electropulse installation, as well as the following values, such as the length of the insert, the mass of the working body (cartridge), the specific work of deformation, the elastic modulus of the pipe.

Taken together, the phenomena described above allow characterizing the process of electropulse pressing of pipes into the tube sheet in sufficient volume to obtain the corresponding similarity criteria, so that in the subsequent simulation of the process of electropulse pressing, you have the necessary amount of information for analyzing the results.

4. Similarity criteria of electropulse press fitting of pipes into the tube sheet

Based on the previous section, we identify the necessary parameters characterizing the process of electropulse pressing of pipes into the tube sheet for further transformations in order to obtain the corresponding similarity criteria by the dimensional analysis method.

The parameters characterizing the process: M_{EBC} – weight of electric blasting cartridge [kg]; A_{SW} – specific work required for deformation of a pipe's unit length [J]; ν – frequency of the electric pulse installation [Hz]; L_C – coil inductance [GN]; U – voltage applied to the discharge circuit [V]; l – fitting length [m]; I – loop current [A]; E – pipe modulus [Pa].

Thus, the total number of participating quantities: m=8.

Let the existing relations between the parameters of the process of electropulse press fitting and the parameters of the elements of the system in which the process of electropulse press fitting takes place, can be represented as follows:

$$F(P_1, P_2, P_3, P_4, P_5, P_6, P_7, P_8) = 0, \tag{1}$$

$$F(\mathrm{M}_{EBC}, \mathrm{A}_{SW}, \nu, L_C, U, l\ , I, E) = 0. \tag{2}$$

We choose four (k = 4) independent variables that are applicable to the LMTI measurement system (length, mass, time, current):

$$P_1 = \mathrm{M}_{EBC}\ (kg), \tag{3}$$

$$P_2 = A_{SW}\ \left({kg \cdot m^2}/{s^2} \right), \tag{4}$$

$$P_3 = \nu\ (s^{-1}), \tag{5}$$

$$P_4 = L_C\ \left({kg \cdot m^2}/{s^2 \cdot A^2} \right). \tag{6}$$

Next, we determine the dimension of each basic basis parameter:

$$X = L^{\alpha} M^{\beta} T^{\gamma} I^{\epsilon}. \tag{7}$$

$P_1 = [\mathrm{M}_{EBC}] = [L]^0 [M]^1 [T]^0 [I]^0;$

$P_2 = [A_{SW}] = [L]^2[M]^1[T]^{-2}[I]^0;$
$P_3 = [\nu] = [L]^0[M]^0[T]^{-1}[I]^0;$
$P_4 = [L_C] = [L]^2[M]^1[T]^{-2}[I]^{-2}.$

We define the dimensions for the remaining related parameters.

$P_5 = [U] = [L]^2[M]^1[T]^{-3}[I]^{-1};$
$P_6 = [l] = [L]^1[M]^0[T]^0[I]^0;$
$P_7 = [I] = [L]^0[M]^0[T]^0[I]^1;$
$P_8 = [E] = [L]^{-1}[M]^1[T]^{-1}[I]^0.$

We compose a matrix of the basic basis parameters and find the determinant of this matrix.

$$D_{1-4} = \begin{array}{c} P_1 \\ P_2 \\ P_3 \\ P_4 \end{array} \begin{vmatrix} 0 & 1 & 0 & 0 \\ 2 & 1 & -2 & 0 \\ 0 & 0 & -1 & 0 \\ 2 & 1 & -2 & -2 \end{vmatrix} = -4 \neq 0.$$

As $D_{1-4} = -4 \neq 0$, then the parameters are independent of each other.
We compose expressions for the remaining $n = m - k$ similarity criteria:

$$P_5 = \frac{[U]}{[\mathrm{M}_{EBC}]^{\alpha s}[A_{SW}]^{\beta s}[\nu]^{\gamma s}[L_C]^{\varepsilon s}};$$

$$P_6 = \frac{[l]}{[\mathrm{M}_{EBC}]^{\alpha k}[A_{SW}]^{\beta k}[\nu]^{\gamma k}[L_C]^{\varepsilon k}};$$

$$P_7 = \frac{[I]}{[\mathrm{M}_{EBC}]^{\alpha c}[A_{SW}]^{\beta c}[\nu]^{\gamma c}[L_C]^{\varepsilon c}};$$

$$P_8 = \frac{[E]}{[\mathrm{M}_{EBC}]^{\alpha t}[A_{SW}]^{\beta t}[\nu]^{\gamma t}[L_C]^{\varepsilon t}}.$$

We make the corresponding matrix calculations and find similarity criteria:

$$D_{5\alpha} = \begin{array}{c} P_5 \\ P_2 \\ P_3 \\ P_4 \end{array} \begin{vmatrix} 2 & 1 & -3 & -1 \\ 2 & 1 & -2 & 0 \\ 0 & 0 & -1 & 0 \\ 2 & 1 & -2 & -2 \end{vmatrix} = 0, \quad D_{5\beta} = \begin{array}{c} P_1 \\ P_5 \\ P_3 \\ P_4 \end{array} \begin{vmatrix} 0 & 1 & 0 & 0 \\ 2 & 1 & -3 & -1 \\ 0 & 0 & -1 & 0 \\ 2 & 1 & -2 & -2 \end{vmatrix} = -2,$$

$$D_{5\gamma} = \begin{array}{c} P_1 \\ P_2 \\ P_5 \\ P_4 \end{array} \begin{vmatrix} 0 & 1 & 0 & 0 \\ 2 & 1 & -2 & 0 \\ 2 & 1 & -3 & -1 \\ 2 & 1 & -2 & -2 \end{vmatrix} = -4, \quad D_{5\varepsilon} = \begin{array}{c} P_1 \\ P_2 \\ P_3 \\ P_5 \end{array} \begin{vmatrix} 0 & 1 & 0 & 0 \\ 2 & 1 & -2 & 0 \\ 0 & 0 & -1 & 0 \\ 2 & 1 & -3 & -1 \end{vmatrix} = -2.$$

$$\alpha_s = \frac{D_{5\alpha}}{D_{1-4}} = \frac{0}{-4} = 0;$$

$$\beta_s = \frac{D_{5\beta}}{D_{1-4}} = \frac{-2}{-4} = 0.5;$$

$$\gamma_s = \frac{D_{5\gamma}}{D_{1-4}} = \frac{-4}{-4} = 1;$$

$\varepsilon_s = \frac{D_{5\varepsilon}}{D_{1-4}} = \frac{-2}{-4} = 0.5$.

$$P_5 = \frac{[P_5]}{[P_1]^{\alpha s}[P_2]^{\beta s}[P_3]^{\gamma s}[P_4]^{\varepsilon s}} = \frac{[U]}{[\mathrm{M}_{EBC}]^0[A_{SW}]^{0.5}[v]^1[L_C]^{0.5}} = \frac{[L]^2[M]^1[T]^{-3}[I]^{-1}}{[L]^1[M]^{0.5}[T]^{-1}[T]^{-1}[L]^1[M]^{0.5}[T]^{-1}[I]^{-1}} = 1$$

The obtained criterion P_5 is dimensionless ($P_5 = 1$), verification passed.
Further similarly we find the following criteria: P_6, P_7, P_8.

$D_{1-4} = -4$;
$D_{6\alpha} = 2$,
$D_{6\beta} = -2$,
$D_{6\gamma} = 4$,
$D_{6\varepsilon} = 0$.
$\alpha_k = \frac{2}{-4} = -0.5$;
$\beta_k = \frac{-2}{-4} = 0.5$;
$\gamma_k = \frac{4}{-4} = -1$;
$\varepsilon_k = \frac{0}{-4} = 0$.

$$P_6 = \frac{[l]}{[\mathrm{M}_{EBC}]^{-0.5}[A_{SW}]^{0.5}[v]^{-1}[L_C]^0} = \frac{[L]^1}{[M]^{-0.5}[L]^1[M]^{0.5}[T]^{-1}[T]^1} = 1$$

The obtained criterion P_6 is dimensionless ($P_6 = 1$), verification passed.

$D_{1-4} = -4$;
$D_{7\alpha} = 0$,
$D_{7\beta} = -2$,
$D_{7\gamma} = 0$,
$D_{7\varepsilon} = 2$.
$\alpha_c = \frac{0}{-4} = 0$;
$\beta_c = \frac{-2}{-4} = 0.5$;
$\gamma_c = \frac{0}{-4} = 0$;
$\varepsilon_c = \frac{2}{-4} = -0.5$.

$$P_7 = \frac{[I]}{[\mathrm{M}_{EBC}]^0[A_{SW}]^{0.5}[v]^0[L_C]^{-0.5}} = \frac{[I]^1}{[L]^1[M]^{0.5}[T]^{-1}[L]^{-1}[M]^{-0.5}[T]^1[I]^1} = 1$$

The obtained criterion P_7 is dimensionless ($P_7 = 1$), verification passed.

$D_{1-4} = -4$;
$D_{8\alpha} = -6$,
$D_{8\beta} = 2$,
$D_{8\gamma} = -8$,
$D_{8\varepsilon} = 0$.
$\alpha_t = \frac{-6}{-4} = 1.5$;
$\beta_t = \frac{2}{-4} = -0.5$;

$\gamma_t = \frac{-8}{-4} = 2;$
$\varepsilon_t = \frac{0}{-4} = 0$.

$$P_8 = \frac{[E]}{[\mathrm{M}_{EBC}]^{1.5}[A_{SW}]^{-0.5}[v]^2[L_C]^0} = \frac{[L]^{-1}[M]^1[T]^{-1}}{[M]^{1.5}[L]^{-1}[M]^{-0.5}[T]^1[T]^{-2}} = 1$$

The obtained criterion P_8 is dimensionless ($P_8 = 1$), verification passed.
Next, a general check was made.

$$F(P_5, P_6, P_7, P_8) = 0$$

All criteria passed the test.

5. Conclusion

Obtaining one-piece pipe connections in the tube sheets of heat exchangers by creating a guaranteed interference fit on the surface of their contact due to the interconnected stress state consists of the following steps:

- Pipe deformation by the amount of radial clearance between the pipe and the tube sheet.
- Joint deformation of pipes and tube sheets to the maximum value, due to the dynamics of the process of pressing in.
- Process of elastic unloading of the joint from the maximum deformed equilibrium stress state, leading to the formation of an interference fit and contact pressure on the contact surface of the joint, which determines the residual stresses and operational characteristics of the resulting compound.

In the presented article, the above-mentioned phenomena were described that characterize the essence of the process of fastening pipes to the tube sheet by the method of electropulse pressing. Criteria were obtained for the similarity of the process of electropulse press fitting of pipes into a tube sheet, which allow reducing the results obtained on a scaled-down model to nature. This will facilitate the modeling process for further experiments on objects in natural dimensions.

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