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EVALUATION OF THE EFFICIENCY OF METHODS FOR EXPANDING THICK-WALLED TUBES INTO TUBE SHEETS OF HEAT EXCHANGERS

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ОЦІНКА ЕФЕКТИВНОСТІ МЕТОДІВ РОЗВАЛЬЦЮВАННЯ ТОВСТОСТІННИХ ТРУБ В ТРУБНІЙ РЕШІТЦІ ТЕПЛООБМІННИКІВ

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The present work is devoted to the experimental study of methods of reaming thick-walled tubes in thick tube grids used in modern heat exchangers. The efficiency of industrial systems largely depends on the reliability of the equipment, the main element of which are heat exchangers. Recently, the use of thick-walled tubes is gaining popularity, which provides higher indicators of strength and tightness of connections. However, the use of such pipes requires the use of methods of pre-deformation of the pipe ends at an angle that corresponds to the conical surface of the holes in the pipe grid. This provides a tighter joint prior to subsequent welding and reaming over the full thickness of the lattice.

The main objective of the work was to comparatively analyze stepwise and continuous reaming methods, which are widely used in industry. These methods differ significantly in their productivity, quality and time consumption. The evaluation of these parameters allowed to identify advantages and disadvantages of each of them, which became the basis for the subsequent selection of the optimal method depending on the operating conditions. During the study, special attention was paid to key indicators such as joint strength and tightness, as well as the condition of the surfaces of the flared pipe sections. The research was conducted on the basis of the production unit of Yuzhenergo LLC, Dnipro city.

Experimental data were obtained on the basis of studies of pipe joints made of A335 Grade P12 steel with different parameters of diameters and wall thicknesses. In the process of work also quantitative estimation of time spent on execution of reaming operations by each method was carried out. The results of the research have shown that band-screw rolling is a promising direction for fixing small diameter pipes in conditions where high strength of joints is required at minimum time expenditures.

The results considered in the work can be useful for improvement of technological processes of production and operation of heat-exchange apparatuses. Application of the obtained data allows to increase not only reliability and durability of the equipment, but also its economic efficiency, which is especially important in the conditions of modern industrial requirements.

***Keywords**: heat-exchange, thick-walled tubes, step-by-step reaming, continuous reaming, evaluation, tightness of joints, tube grids.*

Introduction. In the conditions of modern industrial enterprises, heat exchange apparatuses represent one of the key components of technological processes [1]. Their reliability determines the efficiency of heat exchange, safety of the production process and durability of the equipment [2]. One of the most important elements of such apparatuses are pipe grids, which combine a large number of pipes, providing the maximum heat exchange area [3]. The most common material for tubes is alloy steels such as A335 Grade P12 steel, which provide high corrosion resistance and mechanical strength [4].

Due to the increased demands on equipment performance and durability, designers are increasingly faced with the need to use thick-walled tubes in tube array designs [5]. This is due to the fact that such tubes have a higher resistance to internal pressure, which allows them to retain their operational properties under more severe operating conditions. At the same time, the use of thick-walled tubes requires the use of specialized fastening methods, which has become the main problem in the production of modern heat exchangers.

One of the most common methods of securing tubes in tube arrays is flaring. Flaring is a process of plastic deformation of pipe ends in order to tightly connect them to the holes in the grid. This method provides a high degree of tightness of the joint, which is critical for equipment operating under high pressure [6].

In practice, various methods of reaming are used, among which step-by-step and continuous reaming occupy a special place. Step-by-step reaming is performed using a set of rollers, each of which has a larger diameter than the previous one. The pipe is reamed sequentially with each roll, starting with the smaller diameter [7]. This method has proven to be one of the most reliable, but its main disadvantage is its high labor intensity and considerable time consumption.

The aim of this study is to comparatively evaluate two methods of reaming: stepwise and continuous. The objective is not only to evaluate the strength and tightness of the joints, but also to consider the time required to perform each method and to identify their advantages and disadvantages depending on the operating conditions.

Materials and experimental methods. The research was carried out on the basis of the production unit of the engineering company Yuzhenergo LLC, Dnipro city, Ukraine.

In the course of the study were used pipes from alloy steel A335 Grade P12, which are widely used in the manufacture of heat exchangers and other high-temperature apparatus. This material was chosen because of its high resistance to corrosion when exposed to hot media, as well as its ability to withstand significant mechanical loads during operation. The pipes had a nominal outside diameter of 25 mm and a wall thickness of 4 mm. Pipes with different characteristics in terms of the ratio of inner and outer diameters were selected for the study, which allowed us to evaluate the influence of these parameters on the reaming processes and the subsequent quality of joints.

A516 Grade 55 steel plates with high strength and impact toughness were used to fabricate the pipe grids. These plates are used in high-pressure applications and in contact with aggressive media, making them the optimal choice for heat exchangers. The plates had a thickness of 185 mm and a hole diameter of 25.4 mm to ensure a tight connection to the pipes.

The flattening process was performed using PowerMaster's P-1000 (Fig. 1), 800 (Fig. 2) and V Series (Fig. 3) specialized flattening tools, which are widely used for mechanically securing pipes in heat exchangers. The 800 and 1000 Series extended adjustable rollers were used for stepwise reaming, providing control over roller penetration depth and contact pressure. Continuous reaming was performed using V Series screw rollers, which allow the entire length of the pipe to be deformed in a single pass.

Fig.1. Rollers Series P-1000 powermaster [8]

Fig.2. Rollers Series 800 powermaster [9]

Fig.3. Rollers Series V powermaster [10]

An MPG-3 roll drive equipped with torque control system was used to drive the rolls. This equipment allows precise control of the reaming process, preventing the redistribution of stresses in the pipe metal and ensuring uniform distribution of contact pressures over the entire joint surface.

Mineral oil was used for cooling and lubrication during the reaming process, which was fed into the contact zone between the rollers and the pipe, preventing tool overheating and reducing friction.

Two types of specimens were prepared for the study: multi-pipe and single-pipe specimens.

Multi-pipe specimens - each specimen contained 18 pipes fixed in a 185 mm thick pipe grid (Fig. 4). These specimens were used to evaluate the strength of the joints by means of press-out tests.

Single-pipe specimens - the specimens consisted of a single pipe fixed in a pipe grid (Fig. 5). This type of specimens was used to evaluate the tightness of the joints.

Technological process of reaming. Step-by-step reaming was carried out in several stages. Five separate passes of the rolling tool were used for each pipe. In the process of the research the rollers of 800 and 1000 series were used (Fig. 1, 2) The first pass of the rollers of 1000 deformed the pipe near its end, and each subsequent pass of the rollers of 800 series moved along the pipe, deforming it at the next section. In this way, a consistent uniform deformation of the pipe along the entire length of its contact with the pipe grid was ensured. This method allows for precise control of metal deformation, preventing its destruction and ensuring uniform distribution of contact pressures.

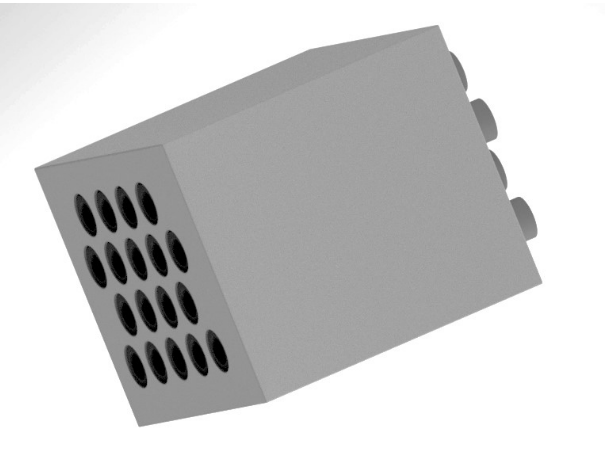

Fig. 4. Multi-pipe specimen

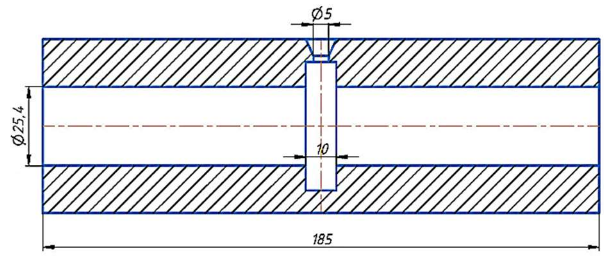

Fig. 5. Sketch of the pipe grid for a single-pipe specimen

Continuous reaming can be accomplished either in a single pass or by using tapered rollers that deform the pipe gradually as the tool advances. The V Series helical rollers (Fig. 3) deformed the entire length of the pipe simultaneously, which significantly reduced the time required to complete the operation. However, this method required more precise adjustment of the equipment, as the slightest errors in adjustment could result in uneven deformation and reduced joint tightness.

For each pipe, the time required to perform reaming was recorded, including equipment set-up, pipe installation, and execution of the operation. Time for tool preparation and lubrication was recorded separately, allowing for an accurate assessment of the performance of each method.

Strength Testing. Strength tests were performed on a Holzmann WP 100H hydraulic press (Fig. 6), which develops a force of up to 100 kN. M20 thread was cut into each specimen inside the protruding pipe ends to install plugs. Strength tests consisted of gradually increasing the axial force on the pipe until it was pressed out of the pipe grid. This made it possible to determine the maximum force at which the joint failed.

Fig. 6. Holzmann hydraulic press WP 100H

Tightness tests. Tightness tests were carried out using a hydraulic press with pressures up to 160 MPa. In each sample, the inner surface of the pipe had an annular groove into which water was applied. The pressure was increased step by step, with a 5-minute dwell time at each stage. The moment of depressurization was recorded by the appearance of moisture on the surface of the sample, as well as by the change in pressure on the manometer. These data allowed us to evaluate the tightness of the joints for each method of reaming.

Results and discussion. The following data were obtained from the results of the strength tests for both groups of specimens (stepwise and continuous reaming) (Table 1).

The average press-out force values for the stepwise method were 67 kN with a variation of ± 4 kN and for the continuous method were 69 kN with a variation of ± 6 kN, indicating that the stepwise reaming method is more stable. It can also be said that, on average, continuous reaming achieves slightly higher joint strengths, but the variation was greater for this method.

Table 1

Pressing forces from pipe grids

Stepwise reaming				Continuous reaming			
No.	Force pressing force, kN	No.	Force pressing force, kN	No.	Force pressing force, kN	No.	Force pressing force, kN
1	80,5	16	57,0	1	74,5	16	98,0
2	72,0	17	63,0	2	73,5	17	78,5
3	92,0	18	63,5	3	65,5	18	76,0
4	95,5	19	54,0	4	60,5	19	72,5
5	71,5	20	70,0	5	48,5	20	59,0
6	52,0	21	51,0	6	79,0	21	85,2
7	41,5	22	60,0	7	79,5	22	39,0
8	70,0	23	60,5	8	64,5	23	51,5
9	66,5	24	63,0	9	74,2	24	76,0
10	51,5	25	54,0	10	48,0	25	58,5
11	61,0	26	87,5	11	73,5	26	53,5
12	64,5	27	69,5	12	66,4	27	67,0
13	44,0	28	70,0	13	40,0	28	66,5
14	51,0	29	39,0	14	53,5	29	59,0
15	55,0	30	53,5	15	22,5	30	70,0

Table 2

Depressurization pressures of joint samples

Stepwise reaming				Continuous reaming			
No.	Depressurization pressure, MPa	No.	Depressurization pressure, MPa	No.	Depressurization pressure, MPa	No.	Depressurization pressure, MPa
1	55	11	51	1	43	11	54
2	62.7	12	48	2	52	12	55
3	48	13	53	3	53	13	41
4	48	14	57	4	49	14	49
5	60	15	54	5	47	15	37
6	52	16	47	6	49	16	50.9
7	54	17	45	7	51	17	52
8	49	18	30	8	55	18	49
9	55	19	47	9	44	19	48
10	59	20	55	10	49	20	47

For incremental reaming, the press-out forces ranged from 39 kN to 95.5 kN, which shows the stability of this method. The minimum values remain quite high, indicating a more predictable behavior of the joints when using the stepwise technique. This is also confirmed by the small deviations from the median (62.0 kN), which emphasizes the uniformity of the force distribution.

The range of values was wider for continuous reaming, from 22.5 kN to 100 kN. This variation can be explained by the fact that the continuous method requires more precise equipment setup and is subject to more factors that can affect the results. The lower values of press-out forces in some cases may be due to non-uniform deformation of the pipe, which results in lower joint strength.

The coefficient of variation for step-by-step reaming was 10%, indicating a high degree of predictability and stability of the method. For the continuous method, this coefficient was higher at 15%, indicating a large variation in the extrusion forces. This can be explained by the fact that with continuous reaming it is more difficult to control the uniformity of deformation of the pipe along its entire length.

Tightness tests (Table 2) showed that stepwise reaming provides higher average depressurization pressures than continuous reaming. The average pressure value for the stepwise method was 51.5 MPa, with a deviation of ±3 MPa, whereas for the continuous method it was 49.0 MPa, with a higher deviation of ±5 MPa. This indicates that stepwise reaming is better suited for applications where leak tightness is critical and is more predictable in its results.

The minimum depressurization pressure values for the step-by-step method were 30.0 MPa, which is also higher than the minimum values for the continuous method (37.0 MPa). The maximum pressure values for both methods were quite close: 62.7 MPa for the stepwise method and 55.0 MPa for the continuous method. These data indicate that both methods can provide high leak tightness values, however, stepwise reaming is more predictable and reliable in this respect.

In order to identify the existence of a significant difference between the presented methods, we will perform a mathematical treatment of the data. The analysis model will present the dependence of depressurization pressure of joint samples at two different methods of pipe reaming: step-by-step and continuous methods. Let's calculate the average values of depressurization pressures for each group and determine.

For each reaming method it is necessary to calculate the average values of depressurization pressures:

Average value for the step-by-step reaming process $P_{av.st}$:

$$P_{av.st} = \frac{\sum P_{st}}{n_{st}}, \quad (1)$$

where P_{st} - is the pressure for each sample, $n_{st} = 20$ - number of samples.

Average value for continuous reaming method $P_{av.con}$:

$$P_{av.con} = \frac{\sum P_{con}}{n_{con}}, \quad (2)$$

where P_{con} - is the pressure for each sample, $n_{con} = 20$.

To analyses the quality of the two methods, we also calculate the variance and standard deviation.

Dispersion for the stepwise method D_{st}:

$$D_{st} = \frac{1}{n_{st} - 1} \sum \left(P_{st} - P_{av.st} \right)^2. \quad (3)$$

Dispersion for the continuous method D_{con}:

$$D_{con} = \frac{1}{n_{con} - 1} \sum \left(P_{con} - P_{av.con} \right)^2. \quad (4)$$

To test whether there is a significant difference between the two methods of unmolding, we apply Student's criterion (t-test) for two independent samples:

$$t = \frac{P_{av.st} - P_{av.con}}{\sqrt{\frac{D_{st}}{n_{st}} + \frac{D_{con}}{n_{con}}}}, \quad (5)$$

where t - statistic, $P_{av.st}$ and $P_{av.con}$ - are mean values, D_{st} and D_{con} - dispersions, n_{st} and n_{con} - number of samples.

The results of the calculations are presented in table 3.

Table 3

Average depressurization pressures of each group

Average value of depressurization pressure, MPa - for the step-by-step method	51.49
- continuous method	48.75
Dispersion: - for the step-by-step method	48.64
- continuous method	21.88
Importance of statistics, t	1.46

Critical t value for significance level α=0.05 amounts to 2.02.

Since the calculated t-statistic of 1.46 is less than the critical value, the difference between the mean depressurization pressures for the two reaming methods is not statistically significant at a significance level of 0.05.

In Fig. 7 and Fig. 8, we present the obtained data, for a better understanding of the difference between the methods.

Fig. 7 shows a histogram of the depressurization pressure distribution: The blue histogram shows the pressure distribution for stepwise reaming. The orange one is for continuous depressurization. It can be seen that the pressure distributions for both methods have similar trends, although the stepwise flattening has more emissions, which correlates with the previously described processes.

Fig. 8 shows the Scatter Diagram: It shows the medians, quartiles and outliers for each method. It can be seen that the medians of both methods are close, but the stepwise unmolding shows a larger variation in pressures. These visualizations confirm the results of the statistical analysis: there are no significant differences between the methods.

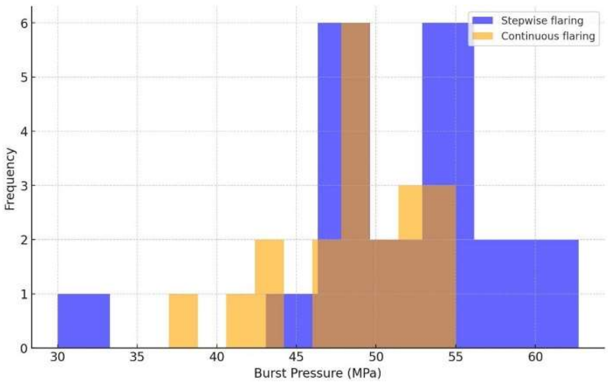

Fig. 7. Distribution of burst pressures by flaring methods

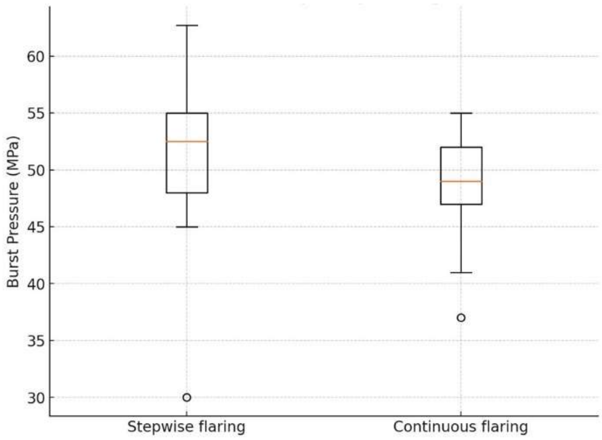

Fig. 8. burst pressure boxplot by flaring methods

The calculated data and plots showed that there is not enough evidence to claim that one method is better than the other based on these data.

Time cost analysis. In terms of time costs (Table 4), continuous reaming has a clear advantage over step reaming. On average, it took 131 minutes to perform a single reaming operation using the continuous method for 18 pipes, while step reaming took 251 minutes (Fig. 9). This can be explained by the fact that step-by-step reaming requires several passes of the tool on each pipe, while continuous reaming performs the entire operation in one pass.

Thus, continuous reaming is more productive in mass production applications where time constraints are critical. However, for joints when leak tightness is critical (e.g. in systems with high pressures or aggressive media), the step-by-step method remains preferable.

Table 4

Time costs for each method

Method, time (minutes)							
Continuous				Stepwise			
1	142.64	11	126.44	1	211.70	11	252.32
2	129.00	12	139.54	2	259.80	12	255.67
3	134.78	13	132.61	3	262.96	13	236.68
4	147.40	14	126.21	4	238.86	14	220.28
5	143.67	15	129.43	5	284.04	15	244.78
6	115.22	16	128.33	6	228.18	16	252.34
7	134.50	17	139.94	7	250.68	17	268.45
8	123.48	18	122.94	8	247.19	18	268.03
9	123.96	19	128.13	9	272.99	19	244.19
10	129.10	20	116.45	10	272.04	20	245.46
Average value							
130.69				250.83			

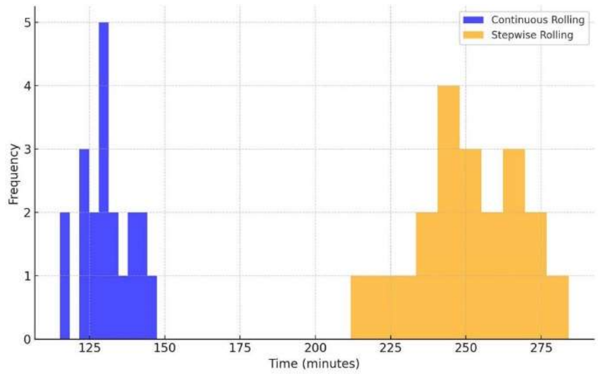

Fig 9. Comparison of time costs between rolling methods

Effect of reaming methods on the surface condition of the pipes. Visual inspection of the samples revealed that the stepwise reaming resulted in a slight delamination of the metal layers on the inner surface of the pipes (“flaking”), which may be due to metal riveting during repeated deformation. No such defects were found in the samples rolled by the continuous method, indicating that taper rolling causes a more uniform and gentle deformation, preventing excessive metal riveting.

Nevertheless, this tinning phenomenon is unlikely to have a significant effect on joint strength, but may be critical for equipment operating in high temperature or corrosive environments where defects on the internal surface can accelerate corrosion.

Conclusions. The results of the conducted research allow us to draw the following conclusions:

1 Both methods of reaming - step-by-step and continuous - provide high strength of pipe joints with the pipe grid. The average values of press-out forces for both methods were similar (62.8 kN for stepwise and 64.5 kN for continuous reaming). However, the step-by-step method showed greater

stability and predictability in terms of extrusion forces, making it preferable for use in applications where precise performance is critical.

Continuous reaming, although showing slightly higher maximum force values, showed a wider variation in the data. This may be a result of the difficulty in controlling the deformation of the pipe while simultaneously reaming the entire length of the pipe, as well as the heterogeneity of the pipe material. Consequently, the continuous method requires more fine-tuning and skilled equipment maintenance to minimize the risk of weak joints.

2 Step-by-step reaming showed the best results in terms of tightness, providing an average depressurization pressure of 51.5 MPa. This is especially important for equipment operating at high pressures or with aggressive media where leaks can cause significant losses or accidents. The average value for the continuous method was 49.0 MPa, which is also a good result, but inferior to that of step-by-step reaming.

For applications where absolute tightness is required, such as heat exchangers used in the chemical or petrochemical industries, step reaming is the preferred method. However, if the requirements for tightness are not as high, such as in systems with less aggressive media or at low operating pressures, continuous reaming may be a more cost-effective alternative due to the lower time required.

3 Continuous reaming is far superior to step reaming in terms of speed. The turnaround time for a single reaming operation using the continuous method averaged 130.69 minutes for 15 pipes, while stepwise reaming required 250.83 minutes. This makes the continuous method preferable for mass production where time resources are critical.

However, it must be taken into account that the high productivity of the continuous method is accompanied by higher demands on the accuracy of equipment setup and process control. In environments where even small defects in connections can lead to accidents or damage, the reduction in lead time may not justify the risks.

4 Visual inspection of the samples showed that step reaming causes tinning of the inner surface of the pipe, which is due to the riveting of the metal during repeated deformation. This phenomenon, although it does not significantly affect the strength of the joints, can be critical in conditions of operation at high temperatures or under the influence of aggressive media. Under such conditions, defects on the inner surface of the pipe can accelerate corrosion damage of the metal.

Continuous reaming does not cause such defects, making it preferable for use in applications where minimizing damage to the inside of the pipe is required.

5 For high-volume production facilities, continuous reaming can significantly reduce the time required to complete operations. However, in applications where there may be high losses due to poor quality connections (e.g. chemical industry), the additional time for step reaming may be justified.

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Стовпник О.В., Кирилюк В.О. Оцінка ефективності методів розвальцювання товстостінних труб в трубній решітці теплообмінників

Робота присвячена експериментальному дослідженню методів розвальцьовування товстостінних труб у товстих трубних решітках, що застосовуються в сучасних теплообмінних апаратах. Ефективність роботи промислових систем багато в чому залежить від надійності обладнання, основним елементом якого є кожухотрубчасті теплообмінники. Останнім часом набирає популярності використання товстостінних труб, що забезпечує більш високі показники міцності і герметичності з'єднань. Однак, використання таких труб вимагає застосування методів попередньої деформації кінців труб під кутом, який відповідає конічній поверхні отворів у трубній решітці. Це забезпечує більш щільне з'єднання перед подальшим зварюванням і розвальцюванням по всій товщині решітки.

Основна мета роботи полягє в порівняльному аналізі покрокового і безперервного методів розвальцьовування, які широко застосовуються в промисловості. Ці методи істотно різняться за своєю продуктивністю, якістю та часовими витратами. Оцінка цих параметрів дає змогу виявити переваги та недоліки кожного з них, що стає основою для подальшого вибору оптимального методу залежно від умов виготовлення. Під час дослідження особливу увагу приділяли ключовим показникам, таким як міцність і герметичність з'єднань, а також стан поверхонь розвальцьованих ділянок труб. Дослідження проводилися на базі виробничого підрозділу ТОВ Юженерго, м. Дніпро.

Експериментальні дані отримані на основі досліджень з'єднань труб, виготовлених зі сталі A335 Grade P12 з різними параметрами діаметрів і товщини стінок. У процесі роботи також проведено кількісну оцінку часу, що витрачається на виконання операцій розвальцьовування кожним методом. Результати досліджень показали, що безперервне вальцювання є пріоритетним напрямком для закріплення труб малого діаметру в умовах, коли потрібна висока міцність з'єднань за мінімальних витрат часу.

Розглянуті в роботі результати можуть бути корисними для поліпшення технологічних процесів виробництва та експлуатації теплообмінних апаратів. Застосування отриманих даних дає змогу підвищити не тільки надійність і довговічність обладнання, а й його економічну ефективність, що особливо важливо в умовах сучасних промислових вимог.

Ключові слова: *теплообмін, товстостінні труби, покрокове вальцювання, безперервне вальцювання, оцінка, герметичність з'єднань, трубні решітки.*

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