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Calculating bending finned tubes heat transfer systems

В работе предложена новая методология расчета изгиба оребренных труб для систем теплообмена. Предложенные расчеты и технология изгиба оребренных монометаллических и биметаллических труб позволяют получать качественные изгибы при минимально возможном радиусе изгиба трубы.

***Ключевые слова**: изгиб, оребренная труба, системы теплообмена, технологический процесс.*

У роботі запропонована нова методологія розрахунку вигинання обребрених труб для систем теплообміну. Запропоновані розрахунки і технологія вигинання обребрених монометалічних і біметалічних труб дозволяють отримувати якісні вигини при мінімально можливому радіусі вигину труби.

***Ключові слова**: вигинання, обребрена труба, системи теплообміну, технологічний процес.*

Introduction.Technology bending of smooth pipe in various ways researchers engaged Albov IN, IF Bogachev, Grebenkin VG, Kalachev MM, AD Kovtun, A. Halperin, and other existing methods of bending smooth tubes are divided into three main groups: cold, hot, and bend on stamps [1-3 and others].

The use of technology in the helical rolling of the edges of monometallic and bimetallic pipes of circular cross-section of high-and low-fin gives the coefficient on the fin φ_0= 1 … 20 for the different sizes of finned tubes. To roll the outer helical fins are used as a blank thick-walled seamless tubes of circular cross section, preferably of plastic material.

Statement of the Problem. As the heat-removing elements (cooling) for the construction of systems of heat transfer (CT) are the most promising pipe with outer and inner fins, curved in a coil element (coil). Due to the outer area of the helical fins of heat transfer surface in contact with the cooling medium annulus may be increased in 7 … 20 times, compared with a smooth tube.

Main results. To ensure the compactness of the coiled element and increase the heat transfer characteristics of the CT, it is necessary to bend the pipe with the minimum and the minimum possible radius of curvature [1-6].

These finned tube bending radius depends on its diameter, wall thickness, fin, fin pitch and mechanical properties of pipe material and other factors. Figures 1 and 2 show the scheme to the calculation of bending finned tubes with minimal and minimal bending radii.

In the process of bending of a bimetallic or monometallic finned tubes inside of the fibers of her shortened, lengthened and external. Then the length of the neutral layer of "live" section of finnedtubes is determined by:

$$l_0 = \pi \cdot R_0 \frac{\alpha}{180}. \qquad (1)$$

For this reason the length of the fibers outside of the "living" section of finned tubes after bending is determined by the equation:

$$l_1 = \pi \frac{\alpha}{180}\left(R_0 + r_H\right). \qquad (2)$$

Then the length of the fibers inside of the "living" section of the finned tube after the bend is determined by:

$$l_2 = \pi \frac{\alpha}{180}\left(R_0 - r_H\right), \qquad (3)$$

where $r_{вн}$ – the radius of curvature of the neutral layer finned tubes (at the geometric axis), mm; α – angle of the edges after the bend, in degrees; $r_н$ – the outer radius of finned tubes without fins, mm.

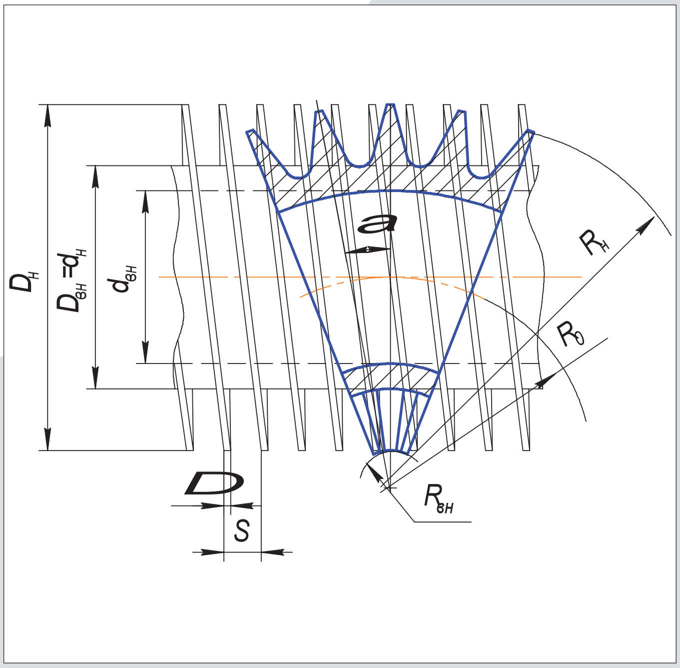

Fig. 1. Scheme to calculate the main parameters of finned tube bending

The average elongation or contraction of the pipe at the bend is determined by obtaining the dependence:

$$\varepsilon_{cp} = \frac{l_1 - l}{l} = \frac{l - l_2}{l} = \frac{r_{вн}}{R_н}. \qquad (4)$$

The arc length in the neutral layer bend measured along the generatrix of the pipe between adjacent two points of the helix fins will be approximately equal to the turn fin tube S. Then the formula (1) takes the form:

$$l_0 = \pi \cdot R_0 \frac{\alpha}{180}. \qquad (5)$$

When bending monometallic and bimetallic finned tubes limiting factor to obtain the minimum and the minimum bending radii possible, be touching the adjacent edges of the inside of the bend pipe (Fig. 2).

The angle of bending of the edges after a finned tube between two adjacent ribs (Fig. 3) is determined by:

$$\frac{\Delta}{R_{\min}} = tg\alpha. \qquad (6)$$

Solving the system of equations consisting of equations (5) and (6) define an internal minimum bend radius of finned tubes:

$$\begin{cases} S = \pi \cdot R_0 \dfrac{\alpha}{180} \\ tg\alpha = \dfrac{\Delta}{R_{\min}} \end{cases}. \qquad (7)$$

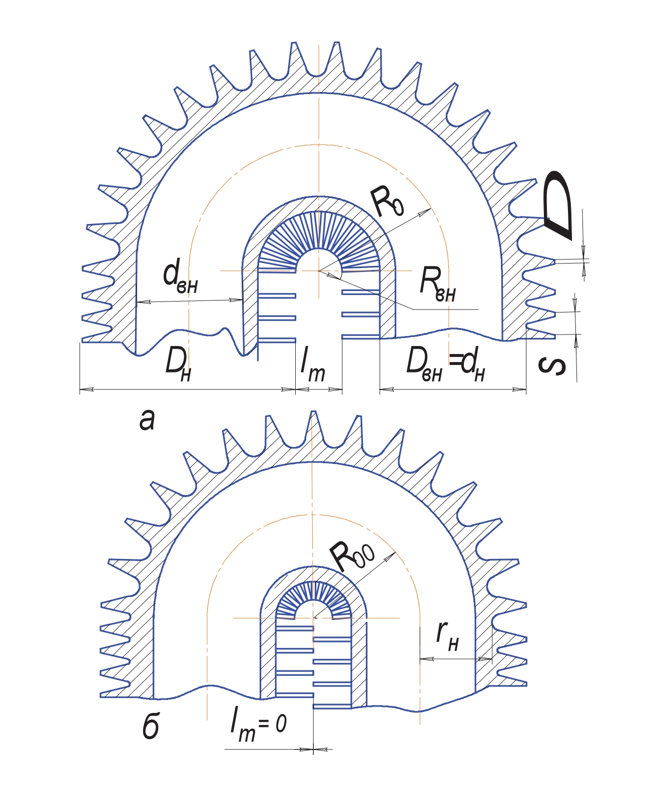

Fig. 2. Scheme to calculate the radius of curvature finned tubes: a – with a minimum, b – with minimal bending radius

From equation (6) $R_{\min} = \dfrac{\Delta}{tg\alpha}$ or as shown in figure 3 $R_{min}=R_0-R_H$.

In view of the slope (Fig. 3a and 3b) for the bending section

$$tg\alpha = \frac{\Delta}{R_{\min}} = \frac{S}{R_0} = \frac{S}{R_{\min} + R_H} = \frac{S}{\dfrac{\Delta}{tg\alpha} + R_H}. \qquad (8)$$

Then $R_{\min} = \dfrac{\Delta}{\dfrac{S}{R_{\min} + R_H}} = \dfrac{\Delta\left(R_{\min} + R_H\right)}{S}$, (9)

where Δ - finned tube fin thickness, mm; R_0 - the minimum bend radius of finned tubes, mm; $R_н$ - the outer radius of the finned tube, mm.

Get rid of the denominator in the last expression, for this we multiply both sides of the expressions on S: if $R_{\min} \cdot S = \Delta \cdot R_{\min} + \Delta \cdot R_H$.

By reducing the expression obtained in the R_{min}, we obtain: $S = \Delta + \dfrac{\Delta R_H}{R_{\min}}$.

From this $R_{\min} = \dfrac{\Delta R_H}{S - \Delta}$. (10)

Then the bending radius in the neutral layer is determined by the formula

$$R_0 = \frac{\Delta R_H}{S - \Delta} + R_H. \qquad (11)$$

To eliminate the intermediate calculations we transform formula (11) so that it included a designation of the diameter of the radius defined by the condition:

$$R_O = \frac{\Delta \dfrac{D_H}{2}}{S - \Delta} + \frac{D_H}{2}. \qquad (12)$$

The coefficient of finning φ is defined as the ratio of external surface area of finned tubes $F_{пн}$ the inner area $F_{пв}$ by the equation: $\varphi=F_{пн}/F_{пв}$, whence $F_{пн}=F_{тр}+F_p$; where $F_{тр}=\pi \cdot D_{вн} \cdot L \cdot l \cdot \Delta$ – unoccupied area of the tube edges of the constant volume, defined as the difference of squares smooth tube and fin area F_p , mm^2; $D_{вн}$ – outer diameter of the pipe at the bottom of the ribs, mm; L - length of the fin tube bending from the land, mm; l – length of the sweep fin tube bending from the land, mm.

The length of the scan profile of fin tubes derive from a parametric equation for the helical surface (spiral) (Fig. 4) $0 \le \gamma \le 2\pi N$:

$$\begin{cases} x = R\cos\gamma \\ y = R\sin\gamma \\ z = \dfrac{\gamma}{2\pi} S \end{cases}, \qquad (13)$$

then the length of the spiral element is obtained from the equations:

$$dl = \sqrt{dx^2 + dy^2 dz^2}, \tag{14}$$

$$\begin{cases} dx = -R\sin\gamma \cdot d\gamma \\ dy = R\cos\gamma \cdot d\gamma \\ dz = \dfrac{S}{2\pi} \cdot d\gamma \end{cases} \tag{15}$$

$$dl = \sqrt{(-R\sin\gamma)^2 + (R\cos\gamma)^2 + \left(\frac{S}{2\pi}\right)^2}\, d\gamma =$$

$$= \sqrt{R\left(\sin^2\gamma + \cos^2\gamma\right) + \left(\frac{S}{2\pi}\right)^2}\, d\gamma \quad ,$$

$$dl = \sqrt{(-R\sin\gamma)^2 + (R\cos\gamma)^2 + \left(\frac{S}{2\pi}\right)^2}\, d\gamma =$$

$$= \sqrt{R\left(\sin^2\gamma + \cos^2\gamma\right) + \left(\frac{S}{2\pi}\right)^2}\, d\gamma,$$

$$dl = \sqrt{R^2 + \left(\frac{S}{2\pi}\right)^2}\, d\gamma, \tag{16}$$

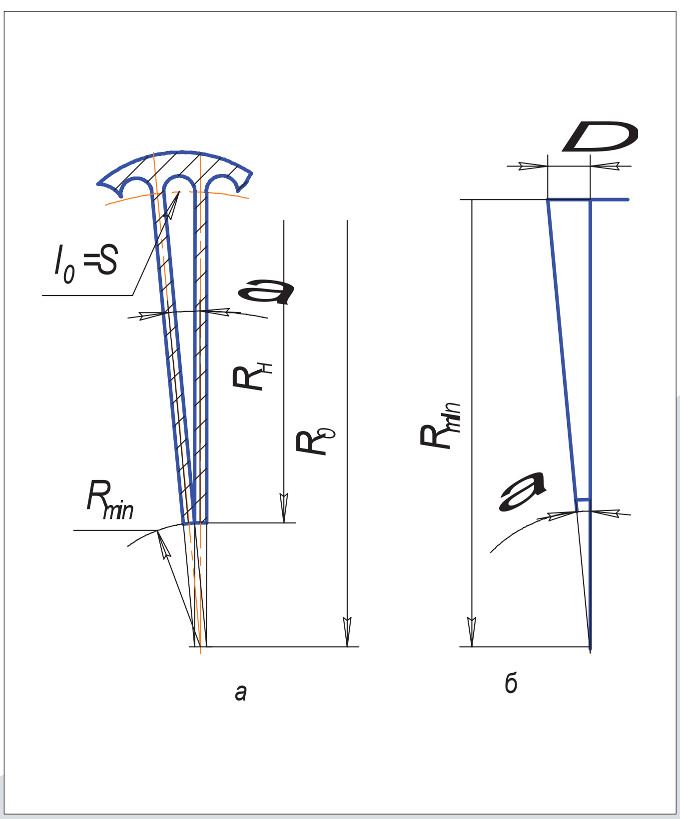

Fig. 3. Scheme of the calculation of the angle of bending of the edges after a finned tube

$$l = \int_{(L)} dl = \int_0^{2\pi N} \sqrt{R^2 + \left(\frac{S}{2\pi}\right)^2}\, d\gamma = \sqrt{R^2 + \left(\frac{S}{2\pi}\right)^2} \cdot \int_0^{2\pi N} d\gamma =$$

$$= \sqrt{R^2 + \left(\frac{S}{2\pi}\right)^2} \cdot 2\pi \cdot N = \sqrt{(2\pi R)^2 + S^2} \cdot N,$$

$$l = \sqrt{(2\pi R)^2 + S^2} \cdot N \text{ or } l = \sqrt{\left(\pi \cdot D_{вн}\right)^2 + S^2} \cdot N, \tag{17}$$

where N – the length of turns of the spiral ribs on the part of the bend, mm: $N = \dfrac{L}{S}$.

Consider the various structural elements of the edges of finned tubes. Lateral surface area finned tube of rectangular cross section of the edge (Fig. 5) is defined as:

$$F_{бр} = 2 \cdot \frac{D_н - D_{вн}}{2} \cdot l_{ср} = \left(D_н - D_{вн}\right) \cdot l_{ср},$$

then

$$\ell_{ср} = \sqrt{\left(2\pi \cdot R_{ср}\right)^2 + s^2} \cdot N, \tag{18}$$

$$R_{ср} = \frac{1}{2}\frac{D_н + D_{вн}}{2},$$

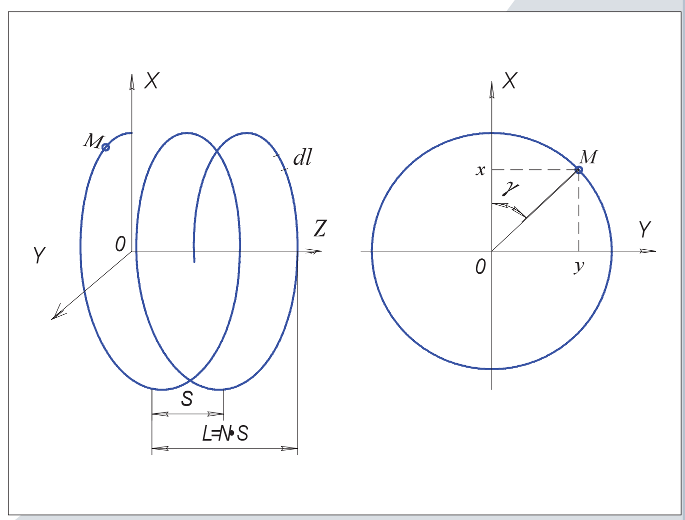

Fig. 4. Scheme to calculate the length of the sweep fin tube

then

$$\ell_{ср} = \sqrt{\left(\frac{\pi \cdot D_н}{2}\right)^2 + \left(\frac{\pi \cdot D_{вн}}{2}\right)^2 + s^2} \cdot N,$$

$$F_{бр} = \frac{N\left(D_н - D_{вн}\right)}{2} \cdot \sqrt{\left(\pi \cdot D_н\right)^2 + \left(\pi \cdot D_{вн}\right)^2 + 4s^2}.$$

Lateral surface area of finned tubes, based on formula (17) for the case of triangular cross-section of the edge (Fig. 6) is determined by: $F_{пн}=F_{тр}+F_р$; $F_{тр}=0$ $F_{пн}=F_р$;

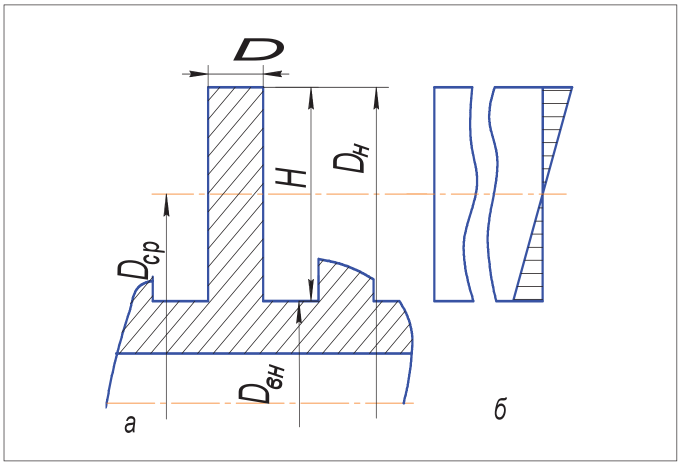

Fig. 5. Diagram to calculate the area of the lateral surface of the finned tube of rectangular section fins

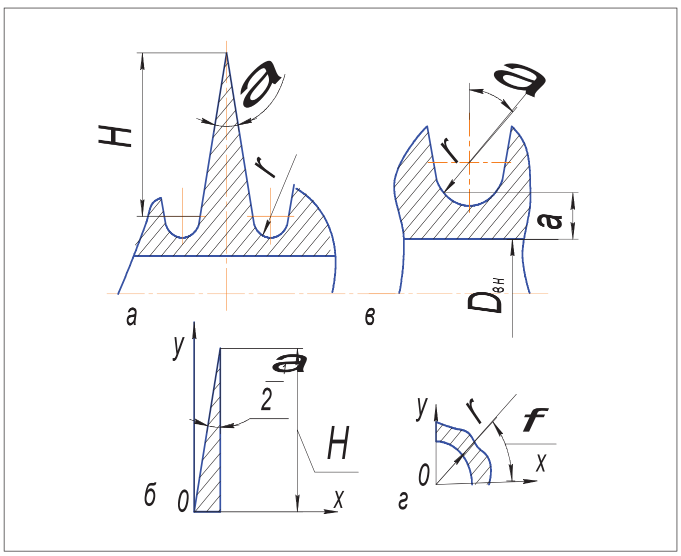

Fig. 6. Scheme to calculate the area of the lateral surface of the finned tubes of triangular section edges

$F_p = F_{б.р.} + F_к$, where $F_{б.р.}$ – lateral surface area of finned ribs , mm²; F_k – surface area of the groove radiused ribbed tube mm².

Determine the length of the finned tube edges of the equations:

$$\begin{cases} x = h \cdot tg\frac{\alpha_1}{2} \\ y = h \end{cases} \text{and} \begin{cases} dx = tg\frac{\alpha_1}{2}dh \\ dy = 1 \cdot dh \end{cases}$$

This element of the expanded length of the edge is defined as:

$$L = \int_0^H \sqrt{1 + tg^2\frac{\alpha_1}{2}}dh = H \cdot \sqrt{1 + tg^2\frac{\alpha_1}{2}} =$$

$$= H \cdot \sqrt{\frac{\cos^2\frac{\alpha_1}{2} + \sin^2\frac{\alpha_1}{2}}{\cos^2\frac{\alpha_1}{2}}} = \frac{H}{\cos\frac{\alpha_1}{2}}.$$

The average length of the expanded helical surface is determined using the formula (17) then:

$$l_{cp} = \sqrt{\left(2\pi \cdot R_{cp}\right)^2 + s^2} \cdot N,$$

where $R_{cp} = \frac{1}{2}\frac{D_н + D_{вн}}{2}$, then write the formula:

$$\ell_{cp} = \sqrt{\left[\frac{2\pi}{2}\left(\frac{D_н + D_{вн}}{2}\right)^2\right] + s^2} \cdot N =$$

$$= \frac{1}{2}\sqrt{\left(\pi D_н\right)^2 + \left(\pi D_{вн}\right)^2 + 4s^2} \cdot N \qquad (19)$$

Then the lateral surface area of finned tubes for the edge of the triangular cross-section is determined by:

$$F_{бр} = 2L \cdot l_{cp} = \frac{H \cdot N}{\cos\frac{\alpha_1}{2}} \cdot \sqrt{\left(\pi D_н\right)^2 + \left(\pi D_{вн}\right)^2 + 4s^2},$$

where H – the height of the edge finned tubes, mm; $R_{cp.}$ – average radius of fin tube , mm.

Determine the length of the radius at the base of the groove edges, that is, a semicircle of radius r for the case of triangular and trapezoidal ribs:

$$\begin{cases} x = r \cdot \cos\varphi \\ y = r \cdot \sin\varphi \end{cases}; \quad \begin{cases} dx = -r \cdot \sin\varphi \cdot d\varphi \\ dy = r \cdot \cos\varphi \cdot d\varphi \end{cases};$$

$$L = \int_0^{\pi/4} \sqrt{\left(-r \cdot \sin\varphi\right)^2 + \left(r \cdot \cos\varphi\right)^2} d\varphi =$$

$$= r\int_0^{\pi/4} \sqrt{\sin^2\varphi + \cos^2\varphi} \cdot d\varphi = r\varphi\Big|_0^{\pi/4} = \frac{\pi}{4}r.$$

Determine the length of the helical lines passing through the point M (Fig. 4), using the formula (14). Here $Rcp = \frac{D_{вн}}{2} + a = \frac{D_{вн} + 2a}{2}$. We obtain:

$$R_{cp} = \frac{1}{2}\left(D_{вн} + 2 \cdot r\left(1 - \cos\frac{\pi}{4}\right)\right) = \frac{1}{2}\left(D_{вн} + 0{,}58 \cdot r\right),$$

$$l_{cp} = \sqrt{\left(\pi\left[D_{вн} + 0.58 \cdot r\right]\right)^2 + s^2} \cdot N.$$

From which we obtain the area of the annular groove of the equation:

$$F_K = 2 \cdot \frac{\pi}{4}r \cdot \sqrt{\left(\pi\left[D_{вн} + 0{,}58 \cdot r\right]\right)^2 + s^2} \cdot N =$$

$$= \frac{\pi}{2}r \cdot \sqrt{\left(\pi\ D_{вн} + \left[0.58 \cdot r\right]\right)^2 + s^2} \cdot N. \qquad (20)$$

Similarly, as in the case of an edge with a triangular cross section (see Fig. 6), lateral surface area of finned tube tapered section fins (Fig. 7) is determined by: $F_{тр}=0$; $F_{пн}=Fp$; $F_p = F_{бр} + F_{рр} + F_к$.

We define $F_{бр}$ by the formula:

$$F_{бр} = \frac{H \cdot N}{\cos\frac{\alpha_1}{2}} \sqrt{\left(\pi \cdot D_н\right)^2 + \left(\pi \cdot D_{вн}\right)^2 + 4 \cdot s^2}\,.$$

Area F_k determined by the formula:

$$F_к = \frac{\pi}{2} r \sqrt{\left(\pi.\left[D_{вн} + 0.58 \cdot r\right]\right)^2 + s^2} \cdot N\,.$$

Determine the area of the edges of the F_{pp} rectangular cross-section for the formula.

$$F_{pp} = \ell_1 \cdot \Delta_1;\ \ell_1 = \sqrt{\left(\pi \cdot D_н\right)^2 + s^2} \cdot N;$$

$$F_{pp} = \Delta_1 \cdot N \sqrt{\left(\pi \cdot D_н\right)^2 + s^2}\,.$$

Then $F_{пн} = F_{тр} + F_p$; $F_p = F_{бр} + F_{pp}$; $F_{бр} = 2 \cdot l_1 \cdot \frac{\left(D_н - D_{вн}\right)}{2}$;

$$F_{pp} = l_1 \cdot \Delta_1 = \sqrt{\left(\pi \cdot D_н\right)^2 + S^2} \cdot N \cdot \Delta_1;\quad F_{нв} = \pi \cdot D_в \cdot L,$$

where $F_{нв}$ – the surface area on the outer diameter of the pipe at the base of the thigh Dвн , mm^2; l_1 – length of the edge of trapezoidal cross-section, mm. $\Delta 1$ – fin thickness, mm.

The sequence of calculating the bending finned tubes with a minimum bend radius (Fig. 2, a) differs significantly from the version of the bend pipe with the minimum possible radius of curvature (Fig. 2 b). Consider the option of bending finned tubes with minimal bending radius of the case where the straight sections of coiled finned element tube in contact with each other. To do this, you must first remove part or all edges on the inside of the intended bending (Fig. 8). In this case all parameters are bending radii decrease by an amount equal to the distance between the straight sections of pipe bending pipe with a minimum radius.

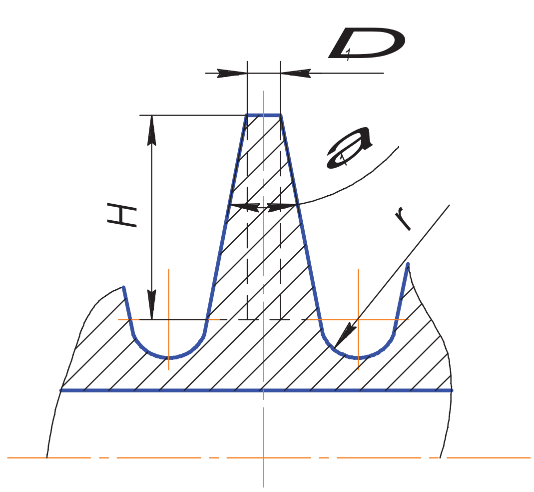

Fig. 7. Diagram to calculate the area of the lateral surface of the finned tube trapezoidal cross-section profile of the edge

Then the minimum possible radius of curvature is determined by:

$$R_{00} = R_0 - l_m = R_0 - 2R_{вн} = \frac{D_H}{2}, \tag{21}$$

where l_m – the distance between the straight sections of pipe, mm.

When bending finned tubes with minimal bending radius (Fig. 8a and b) define the inner radius bend the pipe according to the formula:

$$R_в = R_{00} - \left(R_{00} - t\right) = t. \tag{22}$$

Length of the cutting edges (Fig. 9) define: $l_2 = \pi \cdot t \cdot \kappa_3$, where $R_а$ – radius of the remote edges of the sample mm; l_2 – length of the cutting edge, mm; κ_3 – safety factor for the length of the cut edges of the site.

Thus, the depth of cut on the edges of t will be equal to the inner radius bend finned tubes $R_{вн}$.

Payment schemes for finding the depth of cut and to determine the minimum possible radius of curvature are shown in Fig. 8 and 9. We present a system of equations in accordance with Fig. 8 then:

$$\begin{cases} S = \pi \dfrac{D_H}{2} \cdot \dfrac{\alpha}{180}. \\ t = \dfrac{\Delta}{tg\alpha} \end{cases} \tag{23}$$

From the first equation in the system of equations (22) we express the angle α between two adjacent ribs as:

$$\alpha = \frac{S \cdot 360}{\pi \cdot D_H}.$$

Length of the cutting edge is defined as the length of the arc radius equal to the outer diameter of the tube without fins, turned on the bending angle γ. The proposed method of calculation the main technological parameters of bending monometallic and bimetallic finned tubes with minimal and minimal bending radii, allows to make the necessary calculations to establish patterns of performance of the process of bending finned tubes and to establish patterns of influence of the radii of curvature on the formation of the bend in the pipe coil element:

$$l_{c.p} = \frac{\pi \cdot d_H \cdot \gamma}{180}. \tag{24}$$

Stranded coiled elements of the finned tubes are used in a variety of CT, such as centrifuges, evaporators, and others.

Constructions of twisted coil elements can be single-start and multistart with the desired outer diameter and winding pitch. Precision manufacturing of twisted coil elements depends on the requirements for the design of PT.

When you assign modes for pipe-bending equipment is necessary to determine the value of the required bending moment depending on the known parameters of the tube (dimensions and yield strength of the pipe material, hardening modulus and the bending radius and other parameters). If we assume for the hardened material finned tube conventional stress-strain diagram in cross-section finned tube, you can get with a high degree of accuracy, the formula for determining the bending moment.

For clarity, finned tubes in the plane of bending rotated (Fig. 10). The horizontal distance of fibers deposited metal pipe from the neutral sheet and the corresponding deformation, and vertical – normal stresses in the cross section finned tube.

We introduce the following notation: y – coordinate of the current point on the midline of the cross section of a finned tube, mm; y_T – coordinate of the border zone of plastic finned tubes, mm; M_T – the bending moment corresponding to the onset of plastic deformation, $N{\cdot}m$; ω_T – a central angle of border zone of the elastic cross-section of finned tubes, in degrees; R_1 – average radius of the tube without fins $R_1 = \frac{d_H - d_{вн}}{2}$, mm; R_2 – the average radius of the tube, taking into account the fins $R_2 = \frac{D_H - d_{BH}}{2}$, mm .

From the equilibrium conditions of the bending moment is equal to the moment of internal forces, so

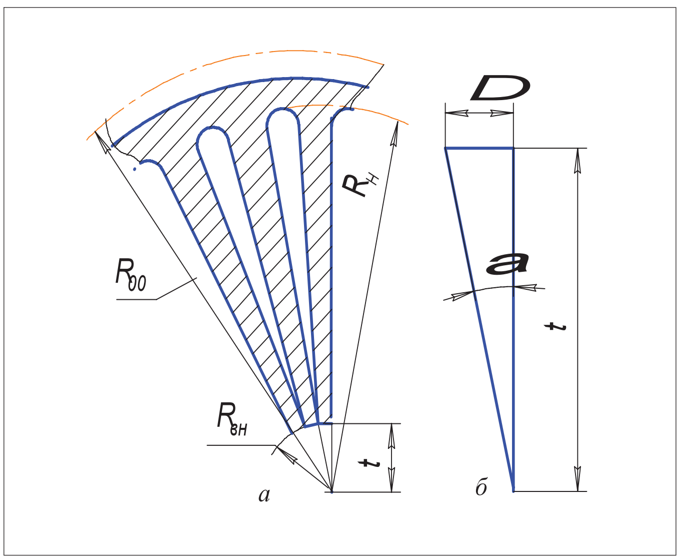

Fig. 8. Diagram to calculate the minimum possible radius of curvature finned tubes

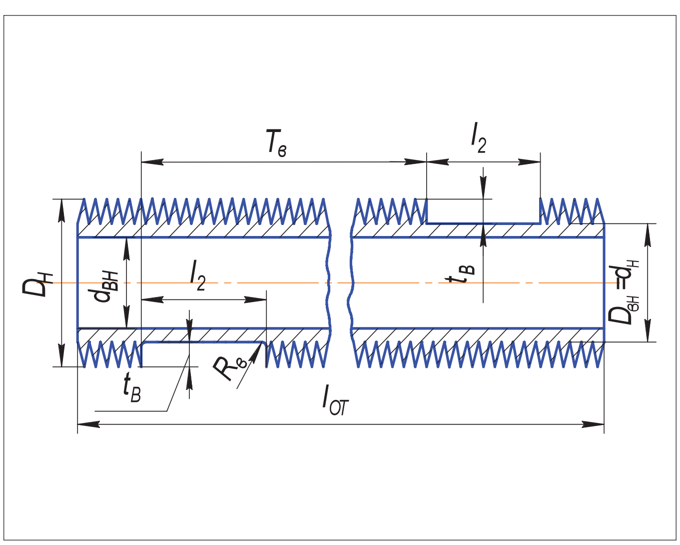

Fig. 9. Diagram to calculate the depth of the cut edges of the section finned tube bending

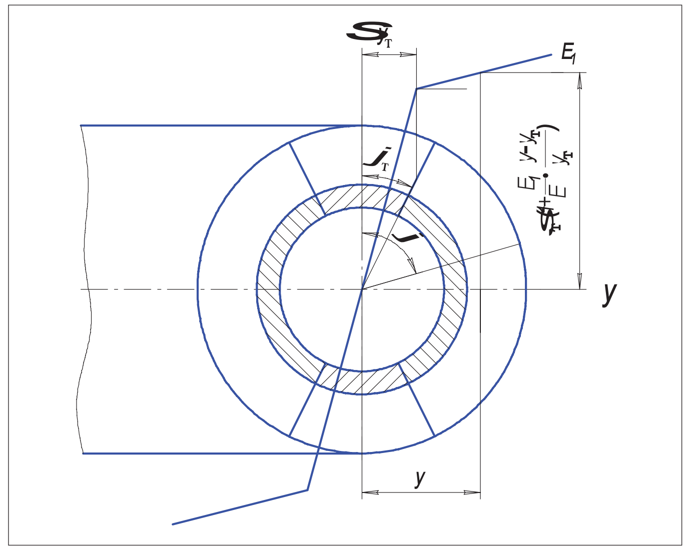

Fig. 10. Diagram of distribution of normal stress – strain in the cross section of the tube bending

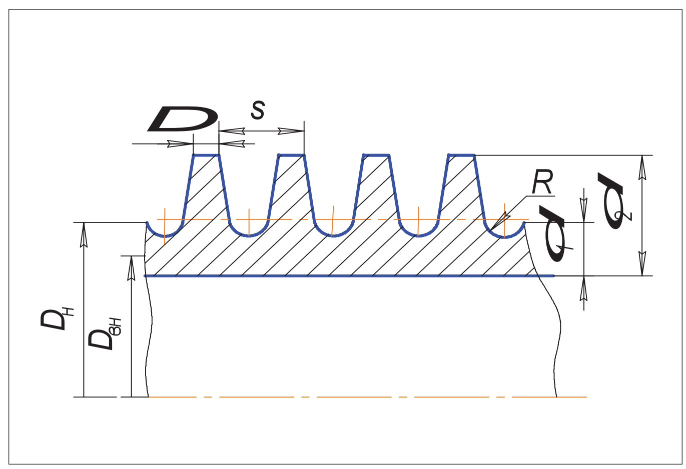

Fig. 11. Element finned tubes used in the calculation of the bending moment

$$M = \int_{F_{уп}} \sigma_{уп}\, y\, dF + \int_{F_{пл}} \sigma_{пл}\, y\, dF \quad . \tag{25}$$

Elementary area of the pipe $dF = R\delta d\omega$, where δ_2 – pipe wall thickness in view of the fins, mm; δ_1 – the thickness of the pipe wall without fins, mm.

If we accept the hypothesis of plane sections, the elongation is proportional to the distance of fiber from the neutral line: $\frac{\varepsilon}{\varepsilon_T} = \frac{y}{y_T} = \frac{R\cdot\sin\omega}{R\cdot\sin\omega_T}$.

In the zone of elastic deformations $\frac{\varepsilon}{\varepsilon_т} = \frac{\sigma_{уп}}{\sigma_т}$; $\sigma_{уп} = \varepsilon E$; $\sigma_{уп} = \sigma_T \frac{\varepsilon}{\varepsilon_T}$; $\sigma_T = \varepsilon_T E$.

In the zone of plastic deformation $\sigma_{пл} = \sigma_T + \left(\varepsilon - \varepsilon_T\right)E_1 = \sigma_T \left(1 + \frac{E_1}{E}\cdot\frac{y - y_T}{y_T}\right)$.

When calculating the total bending moment bending moment is represented as the sum of bending moments for a smooth tube and fins, taking into account the quantitative characteristics of each component. In this case, substituting the previously obtained values in the formula (25) we obtain:

$$M_1 = \frac{S}{\Delta}\left\{\int_0^{\omega_T} \sigma_T \frac{\sin 2\omega}{\sin \omega_T} D_1^2\, \delta_1 d\omega + \int_{\omega_T}^{\frac{\pi}{2}} \sigma_T D_1^2 \delta_1 \sin \omega d\omega + \right.$$

$$\left. + \int_{\omega_P}^{\frac{\pi}{2}} \sigma_T \frac{E_1}{E} D_1^2 \delta_1 \frac{\sin 2\omega}{\sin \omega_T} d\omega - \int_{\omega_T}^{\frac{\pi}{2}} \sigma_T \frac{E_1}{E} D_1^2 \delta_1 \sin \omega d\omega \right\} \cdot K_{пэ}$$

$$M_2 = \frac{S}{\Delta}\left\{\int_0^{\omega_T} \sigma_T \frac{\sin 2\omega}{\sin \omega_T} D_2^2\, \delta_2 d\omega + \int_{\omega_T}^{\frac{\pi}{2}} \sigma_T D_2^2 \delta_2 \sin \omega d\omega + \right.$$

$$\left. + \int_{\omega_P}^{\frac{\pi}{2}} \sigma_T \frac{E_1}{E} D_2^2 \delta_2 \frac{\sin 2\omega}{\sin \omega_T} d\omega - \int_{\omega_T}^{\frac{\pi}{2}} \sigma_T \frac{E_1}{E} D_2^2 \delta_2 \sin \omega d\omega \right\} \cdot K_{пэ}$$

$$M = M_1 + M_2 =$$

$$= \frac{S}{\Delta}\left\{\int_0^{\omega_T} \sigma_T \frac{\sin 2\omega}{\sin \omega_T} D_1^2\, \delta_1 d\omega + \int_{\omega_T}^{\frac{\pi}{2}} \sigma_T D_1^2 \delta_1 \sin \omega d\omega + \right.$$

$$\left. + \int_{\omega_P}^{\frac{\pi}{2}} \sigma_T \frac{E_1}{E} D_1^2 \delta_1 \frac{\sin 2\omega}{\sin \omega_T} d\omega - \int_{\omega_T}^{\frac{\pi}{2}} \sigma_T \frac{E_1}{E} D_1^2 \delta_1 \sin \omega d\omega \right\} +$$

$$+ \frac{S}{\Delta}\left\{\int_0^{\omega_T} \sigma_T \frac{\sin 2\omega}{\sin \omega_T} D_2^2\, \delta_2 d\omega + \int_{\omega_T}^{\frac{\pi}{2}} \sigma_T D_2^2 \delta_2 \sin \omega d\omega + \right.$$

$$\left. + \int_{\omega_P}^{\frac{\pi}{2}} \sigma_T \frac{E_1}{E} D_2^2 \delta_2 \frac{\sin 2\omega}{\sin \omega_T} d\omega - \int_{\omega_T}^{\frac{\pi}{2}} \sigma_T \frac{E_1}{E} D_2^2 \delta_2 \sin \omega d\omega \right\} \cdot K_{пэ}$$

or after integration

$$M = \frac{S}{\Delta}\left(-\frac{1}{2}\sigma_T \cdot D_1^2 \cdot \delta_1 \frac{\cos\omega_T \cdot \sin\omega_T - \omega_T}{\sin\omega_T} + \right.$$

$$+ \cos\omega_T \cdot \sigma_T \cdot D_1^2 \cdot \delta_1 + \frac{1}{4}\pi\sigma_T \frac{E_1}{E} D_1^2 . \frac{\delta_1}{\sin\omega_T} +$$

$$\left. + \frac{1}{2}\sigma_T \cdot E_1 \cdot D_1^2 \cdot \delta_1 \cdot \frac{\cos\omega_T \cdot \sin\omega_T - \omega_T}{E \cdot \sin\omega_T} - \cos\omega_T \sigma_T \cdot \frac{E_1}{E} \cdot D_1^2 \cdot \delta_1 \right)$$

$$+ \left(-\frac{1}{2}\sigma_T \cdot D_2^2 \cdot \delta_2 \frac{\cos\omega_T \cdot \sin\omega_T - \omega_T}{\sin\omega_T} + \cos\omega_T \cdot \sigma_T \cdot D_2^2 \cdot \delta_2 + \right.$$

$$+ \frac{1}{4}\pi\sigma_T \frac{E_2}{E} . D_2^2 . \frac{\delta_2}{\sin\omega_T} + \frac{1}{2}\sigma_T \cdot E_1 \cdot D_2^2 \cdot \delta_2 \cdot \frac{\cos\omega_T \cdot \sin\omega_T - \omega_T}{E \cdot \sin\omega_T} -$$

$$\left. - \cos\omega_T \sigma_T \cdot \frac{E_2}{E} \cdot D_2^2 \cdot \delta_2 \cdot \right) \cdot K_{пэ} \; .$$

After simplification

$$M = -\frac{S}{4\Delta}\sigma_M \cdot D_1^2 \cdot \delta_1 \times$$

$$\times \frac{-2\cos\omega_T E \cdot \sin\omega_T - 2E\omega_T - \pi E_1 + 2 \cdot \cos\omega_T \cdot E_1 \cdot \sin\omega_T + 2E_1\omega_T}{E\sin\omega_T} -$$

$$-\frac{\Delta}{4S}\sigma_M \cdot D_2^2 \cdot \delta_2 \times$$

$$\times \frac{-2\cos\omega_T E \cdot \sin\omega_T - 2E\omega_T - \pi E_1 + 2 \cdot \cos\omega_T \cdot E_1 \cdot \sin\omega_T + 2E_1\omega_T}{E\sin\omega_T} \cdot K_{ПЭ} \qquad (26)$$

Imposed common factor outside the brackets, then the bending moment is determined from the equation

$$M = \frac{s}{4\Delta} \cdot \sigma_m \cdot \times$$

$$\times \frac{2\cos\omega_m \cdot E\sin\omega_m + 2E\omega_m + \pi E_1 - 2\cos\omega_m \cdot E_1 \sin\omega_m - E_1\omega_m}{E\sin\omega_m} \times$$

$$\times\left(D_{вн}^2 \cdot \delta_1 + D_н^2 \cdot \delta_2 \cdot K_{п.э} \right) \cdot \qquad (27)$$

Ratio of the reinforcing effect $K_{п.э}$ finned tube at the bottom edge hardening of the edges as they roll, obtained experimentally: for aluminum alloys – $K_{п.э}$ = 1.1 … 1.3, for copper and copper-nickel alloys – Кп.э = 1.2 … 1.4; for brass – $K_{п.э}$ = 1.3 … 1.7.

Conclusions

Thus, the developed methodology allows for the necessary calculations to determine the basic parameters of the process of bending of finned tubes. The proposed technology of bending monometallic and bimetallic finned tubes, produces quality bends with a minimum and the minimum possible radius of the bend pipe.

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