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Considerations Regarding the Safety Geometry of the Expansion Loops of the Steam Collectors

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Abstract

In the paper is presented a method for computing the safety geometry of expansion loops of the steam collectors used in petrochemical plants. The safety geometry of the expansion loops are obtained considering only the thermal expansion effect that is the most important one for the steam pipes. We illustrate our approach with a calculus example that includes three steam collectors (3', 4", and 6").

Key words: *loop, thermal expansion, steam collector, stress intensification factor*

General Aspects

The steam collectors used in petrochemical plants have a special geometry in order to avoid the thermal overstress and to behave as good as possible to the external loads such as thermal expansion and occasional loads (wind, earthquake). The main geometrical characteristics of the a steam pipe are the expansion loops that to be large enough in order to limit the maximum thermal stress that appears usually in elbows or in the fixed points (see figure 1).

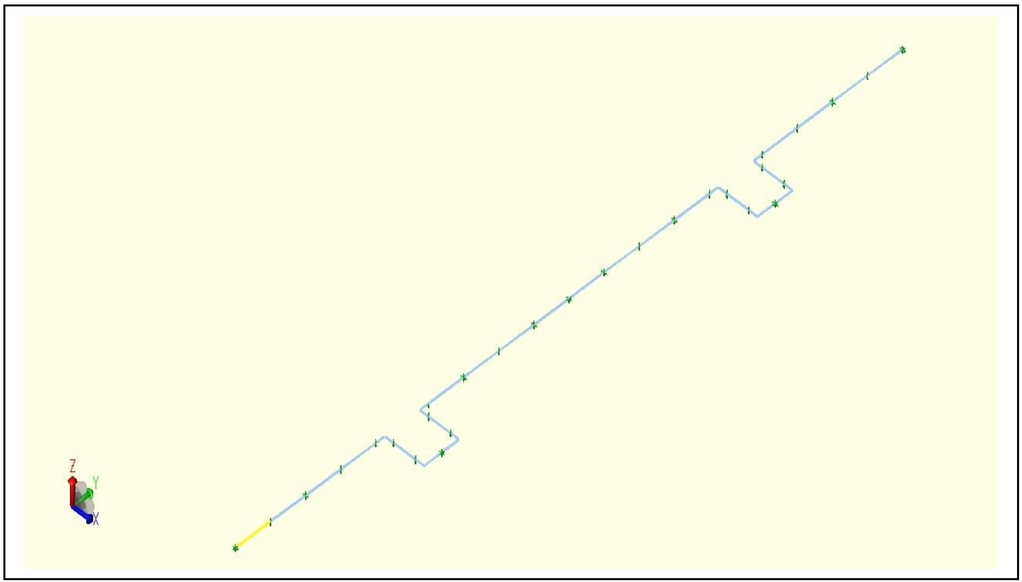


Fig. 1. Steam collector with two expansion loops

The steam collector presented in Figure 1 has two expansion loops and is limited at the ends by two fixed points. Also, between the loops, an axial stop is located, in order to minimize the thermal expansion of the pipe.

The geometry of a single loop between two axial stop points can be designed as a plane beam, embedded at the ends (see figure 2).

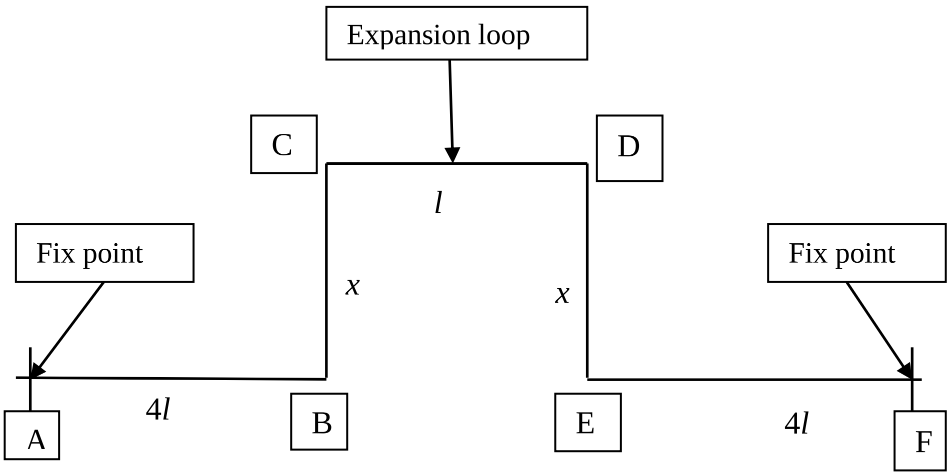


Fig. 2. Strength calculation model for an expansion loop

For the above model it is required to find the x dimension of the loop in order to satisfy the the strength restriction of the pipe: the maximum stress to be above the allowable limit (considering only the thermal loads).

In order to solve this problem a basic system (see figure 3,a) has been used.

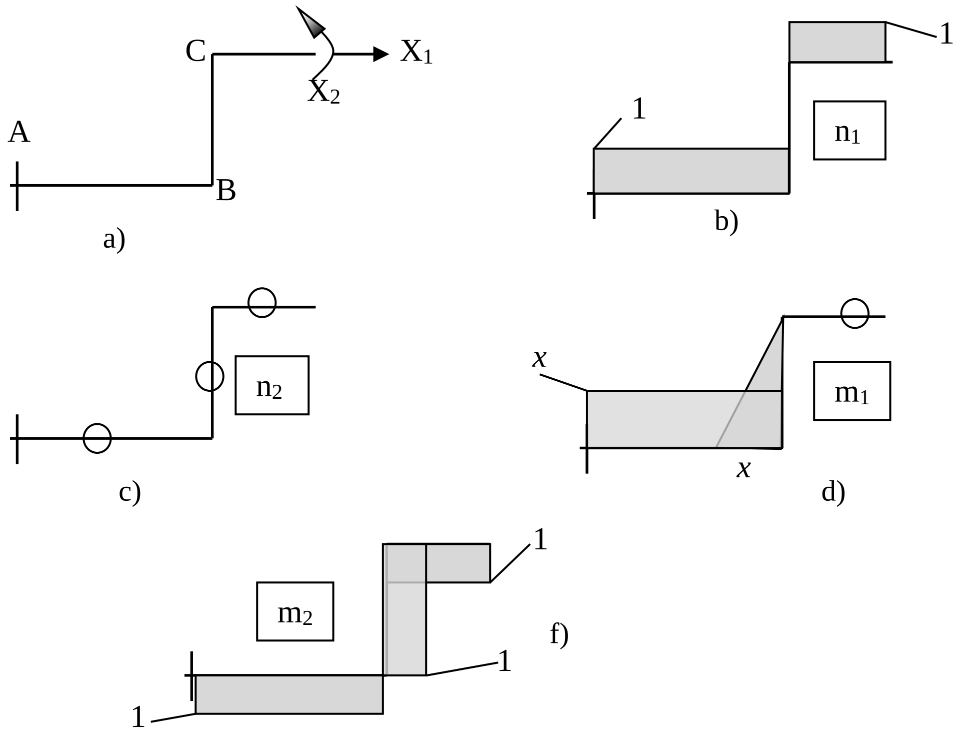


Fig. 3. Main diagrams produced by X_1=1 and X_2=1

Due to symmetry considerations the loop has only to unknown reactions : X_1 and X_2. The main diagrams produced by $X_1=1$ and $X_2=1$ are presented in Figure 3,b..f.

Based on the above diagrams the following displacement coefficients have been calculated :

$$\delta_{11} = \frac{1}{EI}\left(\frac{x^3}{3} + 4 \cdot l \cdot x^2\right); \qquad \text{a)}$$

$$\delta_{22} = \frac{1}{EI}(4.5 \cdot l + x); \qquad \text{b)}$$

$$\delta_{12} = \delta_{21} = \frac{-1}{EI}\left(\frac{x^2}{2} + 4 \cdot l \cdot x\right); \qquad \text{c)} \qquad (1)$$

$$\Delta_{10}^{t} = 4 \cdot l \cdot \alpha \cdot t + 1 \cdot \frac{l}{2} \cdot \alpha \cdot t = 4.5 \cdot l \cdot \alpha \cdot t; \qquad \text{d)}$$

$$\Delta_{20}^{t} = 0; \qquad \text{e)}$$

where *E* represents the Young's modulus of the material and *I* the bending moment of inertia of the cross sectional area of the beam.

Using the above coefficients the following system of equations has to be solved :

$$X_1\left(\frac{x^3}{3} + 4 \cdot l \cdot x^2\right) - X_2\left(\frac{x^2}{2} + 4 \cdot x \cdot l\right) = -4.5 \cdot l \cdot \alpha \cdot t \cdot EI \qquad \text{a)}$$

$$(2)$$

$$-X_1\left(\frac{x^2}{2} + 4 \cdot l \cdot x\right) - X_2(4.5 \cdot l + x) = 0 \qquad \text{b)}$$

Solving the system (2) the solutions for X_1 and X_2 can be written under the form:

$$X_1 = \frac{-4.5 \cdot l \cdot \alpha \cdot t \cdot EI \cdot (4.5 \cdot l + x)}{\frac{x^4}{12} + 2 \cdot x^2 \cdot l^2 + 1.5 \cdot x^3 \cdot l} \qquad \text{a)}$$

$$(3)$$

$$X_2 = \frac{-4.5 \cdot l \cdot \alpha \cdot t \cdot EI \cdot \left(\frac{x^2}{2} + 4 \cdot x \cdot l\right)}{\frac{x^4}{12} + 2 \cdot x^2 \cdot l^2 + 1.5 \cdot x^3 \cdot l} \qquad \text{b)}$$

Using the above solutions it is possible to draw the final efforts diagrams (axial force-N and bending moment-M) produced only by the thermal expansion (see figures 4 and 5).

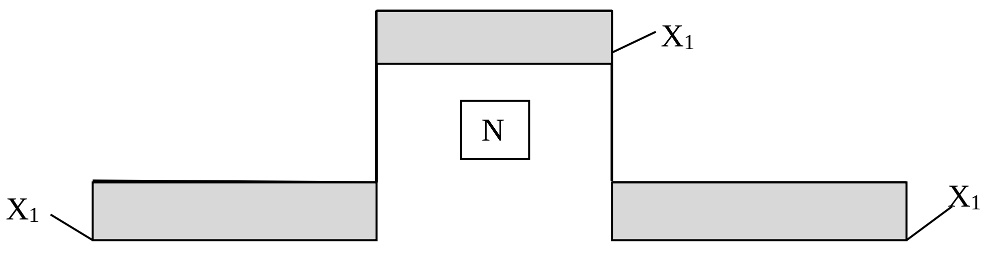


Fig. 4. Axial force diagram

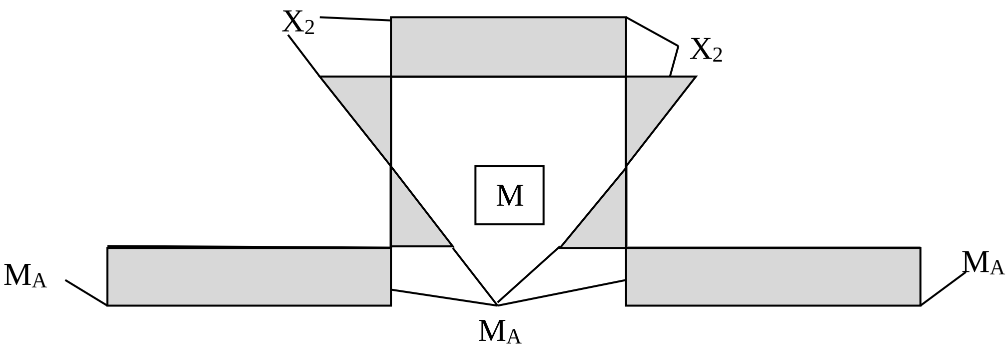


Fig. 5. The bending moment diagram

In the above diagram the moment M_A can be obtained by reducing the forces and moments from the symmetry axis:

$$M_A = X_2 - X_1 \cdot x = \frac{4.5 \cdot l \cdot \alpha \cdot t \cdot EI \cdot \left(\frac{x^2}{2} + 0.5 \cdot l \cdot x \right)}{\frac{x^4}{12} + 2 \cdot x^2 \cdot l^2 + 1.5 \cdot x^3 \cdot l} \tag{4}$$

Comparing the (4) and (3b) expressions it can be noticed that the X_2 moment is greater than M_A, so that the strength restriction for the most loaded sections (points C and D) can be expressed as:

$$\sigma_{\max} = \frac{|X_1|}{A} + \frac{|X_2|}{W} \le \sigma_a \quad , \tag{5}$$

where *A* represents the area of the cross section of the beam, *W* the strength bending modulus of the same section and σ_a the allowable limit of the material of the collector.

Replacing formulae (3) in (5), the following limit equation is obtained:

$$\frac{4.5 \cdot l \cdot \alpha \cdot t \cdot EI}{A} \frac{4.5 \cdot l + x}{\frac{x^4}{12} + 2 \cdot x^2 \cdot l^2 + 1.5 \cdot x^3 \cdot l} + \\ + \frac{4.5 \cdot l \cdot \alpha \cdot t \cdot EI}{W} \frac{\frac{x^2}{2} + 4 \cdot x \cdot l}{\frac{x^4}{12} + 2 \cdot x^2 \cdot l^2 + 1.5 \cdot x^3 \cdot l} = \sigma_a \tag{6}$$

The solution of the equation (6) represents the optimal value of the depth of the loop (x), considering only the thermal loads.

A Numerical Example

In order to evaluate numerically the value of the depth of the loop (x), three sizes of collectors have been considered: 3”, 4” and 6”. The maximum design temperature is 350 ^{o}C and the minimum winter temperature has been considered -29 ^{o}C. The material of the collectors (P235 GH) has at ambient temperature an allowable limit of 119 MPa and at maximum design temperature 79 MPa. The main geometrical and material characteristics are presented below in Table 1.

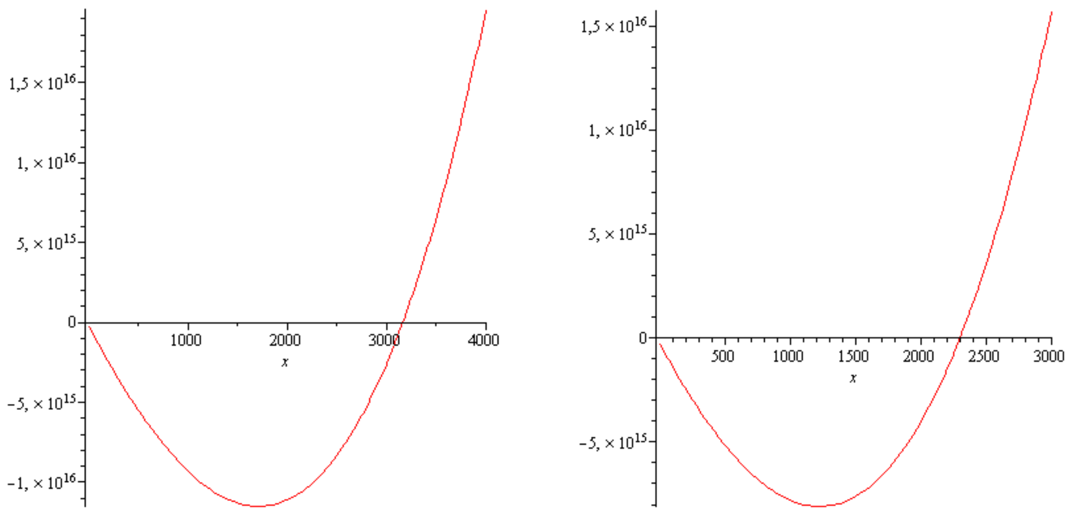
Table 1. Main geometrical characteristics of the steam collectors

Nominal diameter [inches]	External diameter [mm]	Thickness [mm]	Corrosion allowance [mm]	Internal diameter (corroded) [mm]	Area (A) [mm^2]	Strength modulus (W) [mm^3]	Inertia moment (I) [mm^4]
3”	88.9	5	3	84.9	545.73	11592.3	514832.55
4”	114.3	5.6	3	109.1	911.92	27107.54	1549195.8
6”	168.3	6.3	3	161.7	1709.73	70165.44	5904422.1

A specialised program has been designed in order to found the solution of the equation (6). It is important to notice that the solution (x) depends from geometrical characteristics of the collectors but also from the allowable limit of the material.

For every size of the collectors, two cases have been analyzed: one for which the allowable limit is 79 MPa and for another one which is 119 MPa.

The results obtained for the 3” collector are presented in Figure 6,a and b.



a) σ_a = 79 MPa b) σ_a = 119 MPa

Fig. 6. The x values for 3” collector

Analyzing the values presented in Figure 6 it can be noticed that the solutions for the depth of the loop are : 3.2 m (for allowable limit 79 MPa) and 2.3 m (for allowable limit 119 MPa). The values of x are strongly influenced by the allowable limit of the material.

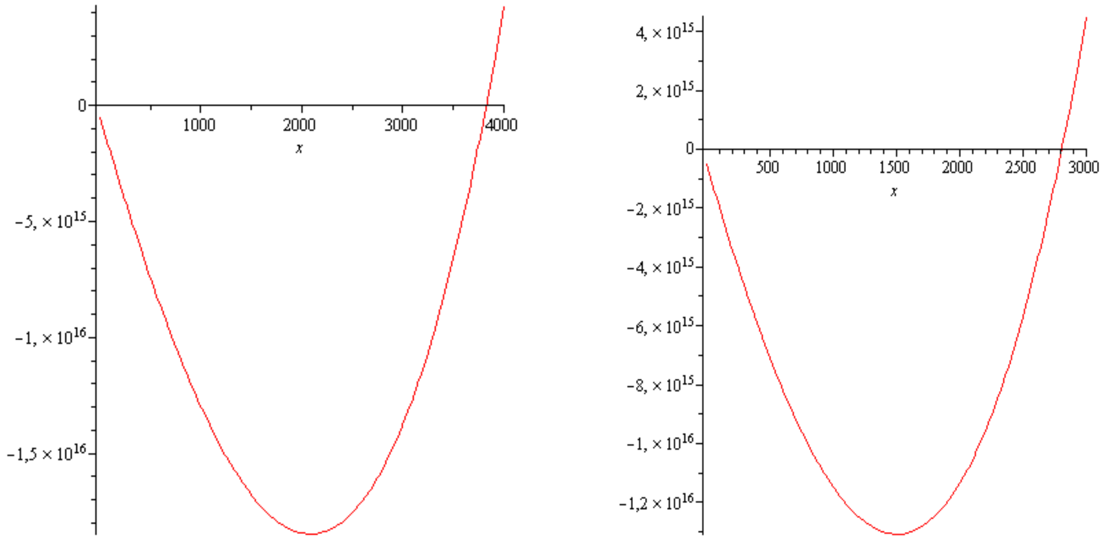
The results obtained for the 4” collector are presented in Figure 7 a and b, in the same way: in Figure 7a for allowable limit 79 MPa and in Figure 7b for allowable limit 19 MPa.

From Figure 7 it can be noticed that, for the 4” collector, the solutions for x are: 3.8 m (if the allowable limit is 79 MPa) and 2.8 m (if the allowable limit is 119 MPa).

The results obtained for the 6” collector are presented in Figure 8 a and b.

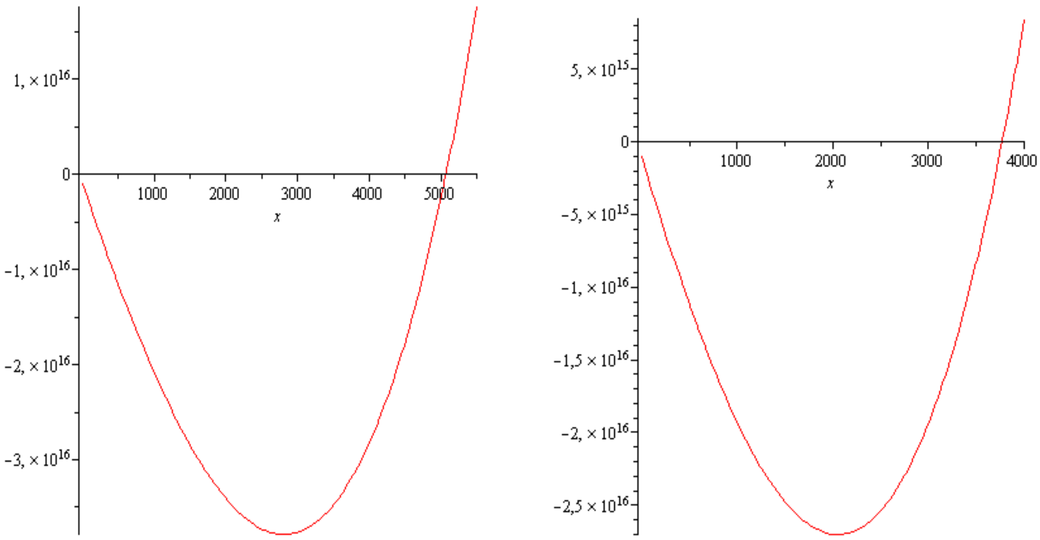
From Figure 8 it can be noticed that, for the 6” collector, the solutions for x are: 5.05 m (if the allowable limit is 79 MPa) and 3.8 m (if the allowable limit is 119 MPa).

It is important to highlight that the above solutions for x are obtained considering only the thermal loads without any intensification factors at bends. If the sustained and occasional loads have to be considered, the depth of the loop (x) have to be increased as a result of a detailed flexibility analysis.



a) σ_a = 79 MPa b) σ_a = 119 MPa

Fig. 7. The x values for 4" collector



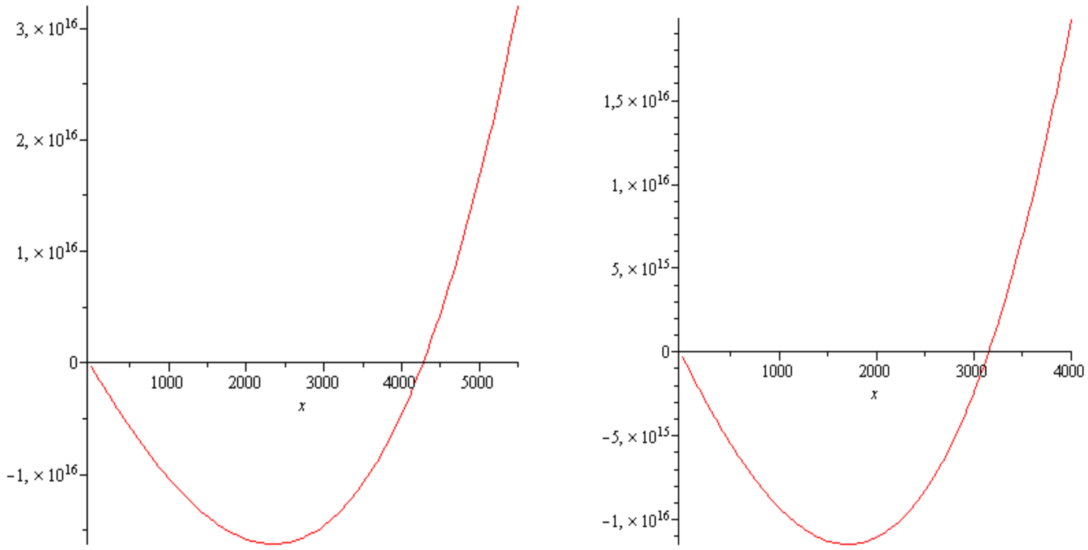
a) σ_a = 79 MPa b) σ_a = 119 MPa

Fig. 8. The x values for 6” collector

If a stress intensification factor (for example 1.5) has to be used, the left member from equation (6) has to be multiplied by the above value of the stress intensification factor.

In this case the solutions of x are presented in Figure 9 (for the allowable limit 79 MPa in Figure 9a and for 119 MPa in Figure 9b).

The value of x for an allowable limit of 79 MPa is 4.25 m. Comparing the Figures 9a and 6a it can be noticed that, in the case of using a stress intensification factor of 1.5, the value of x is increasing 1.33 times.



a) σ_a = 79 MPa b) σ_a = 119 MPa

Fig. 9. The *x* values for 3” collector using a SIF

Conclusions

In this paper we presented an analytical method used for calculation the depth of an expansion loop for a steam collector used in petrochemical plants. The considered external load was only the temperature (in this case the difference between the maximum design temperature and the minimum winter temperature) and the results obtained have been exemplified for three sizes of steam collectors : 3”, 4” and 6”. A specialised program has been developed in order to find the main root of the algebraic equation (6). The depth of the expansion loop (*x*) has been calculated in two cases : when the allowable limit of the material is 79 MPa and 119 MPa.

Also for the 3” collector a stress intensification factor (SIF = 1.5) has been considered for bends, in order to compare the solutions.

The main values for the depth of the expansion loop (*x* – see Figure 2) are presented in Table 2.

Table 2. The solutions for the minimum depth of the expansion loops

Collector size	SIF (at bends)	Minimum depth of the expansion loop (*x*)	
		σ_a = 79 MPa	σ_a = 119 MPa
3”/Sch 5 mm	1	3200 mm	2300 mm
3”/Sch 5 mm	1.5	4250 mm	3100 mm
4”/Sch 5.6 mm	1	3800 mm	2800 mm
6”/6.3 mm	1	5050 mm	3800 mm

The values presented in Table 2 are obtained only from thermal expansion loads and represent minimum values for the depth of the loop (*x*).

In the cases that the sustained and occasional loads have to be considered a specialised flexibility analysis has to be developed.

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Consideraţii privind geometria sigura a lirelor de dilatare a colectoarelor de abur

Rezumat

În lucrare se prezintă o metodă pentru calculul dimensiunilor geometrice sigure ale unui colector de abur utilizat în rafinării. Geometria sigură a lirelor de dilatare este obținută considerând numai efectul temperaturii exterioare, care este și cel mai important. Rezultatele obținute sunt analizate pe trei colectoare (3”, 4”, și 6”).