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Contributions to the Calculus of Mechanical Stresses Generated by Temperature within a Pipe Section

Viorel Nicolae

Universitatea "Petrol-Gaze" din Ploiesti, Bd. Bucuresti 39, Ploiesti
e-mail: nicolae_viorel@upg-ploiesti.ro

Abstract

This paper presents an original method for the calculus of mechanical stresses generated by the temperature within a pipe section through which warm products are transported. The proposed method, theoretically underlined, takes into account the variation of temperature from a pipeline section, starting with its charging point.

Key words: *calculus, mechanical stresses*

Introduction

In practice, the calculus of mechanical stresses generated by temperature within piping systems is realized taking into account that along the pipeline the transported fluid has a constant temperature. Although this simplified calculus method is quite good, yet it is uneconomic. It leads to an overestimation of the thermal extensions states, and of the mechanical stresses generated by temperature, also to an excess of thermal insulation and compensation schemes of thermal extensions.

In this paper an original calculus method for the mechanical stresses generated by temperature is suggested, considering that the temperature varies along a pipeline section, starting from its supplying component.

Theoretical Basis of Calculus

The warm pipes work at different temperatures from assembly temperature (T_m = 293 K), this temperature variation leading to a pipe size changing. The pipe volume expands in all three directions, but taking into account that the ratio between the pipe length and other dimensions is very high, very interesting being only axial extension of the pipe. When the walls temperature increases, they expand and in order to ensure the pipeline normal function it is necessary to provide special measures that will allow taking over or compensation of these thermal deformations or extensions.

The value of thermal extension of the pipe in the point "i" of the T_i temperature will be [2]:

$$\Delta l^{T_i} = \alpha^{T_i} L \Delta T_i^m \tag{1}$$

α^{T_i} - the coefficient of linear extension of piping material, with the temperature of point "*i*", in m/mK;

L – the straight length of pipe ends, in m;

ΔT_i^m - the difference between the temperature T_i and mounting system temperature T_m = 293 K;

The thermal specific deflection $\left(\varepsilon_x^T\right)$, which is a specific lengthening, for free extension of the pipe is [2]:

$$\varepsilon_x^T = \frac{\Delta l^{T_i}}{L} = \alpha^{T_i} \Delta T_i^m \tag{2}$$

Preventing, however, the extension (the real case of open-wire line), specific thermal deflection is a deflection alike a compression one, developing in the wall of the tubular material (pipe) mechanical stresses generated by the temperature σ_x^T:

$$\sigma_x^T = E^T \cdot \varepsilon_x^T \tag{3}$$

and the point "*i*" along the section of pipe:

$$\sigma_x^{T_i} = E^{T_i} \cdot \alpha^{T_i} \Delta T_i^m = E^{T_i} \alpha^{T_i} \left(T_i - T_m\right) \tag{4}$$

E^{T_i} - the longitudinal elasticity module of pipe material at the temperature T_i , in N/m^2.

To determine the mechanical stresses generated by temperature within the pipeline system is necessary to know the temperature distribution T_i along the pipeline system.

The thermal axial force, corresponding to the pressure $\sigma_x^{T_i}$ will be:

$$F_x^{T_i} = E^{T_i} \alpha^{T_i} \Delta T_i^m \text{, in N} \tag{5}$$

A – the resistance section of the pipe, in m^2.

This force is a tension force if the extension isn't prevented and a compression force if the extension is prevented.

If the following condition is fulfilled:

$$F_x^{T_i} \langle F_{cr} \tag{6}$$

the pipe doesn't buckle and the thermal axial force will be transmitted to the fixed points of the pipeline system or to the equipment to which the pipe is connected.

F_{cr} - critical buckling force that can be determined by Euler's relation.

The critical value of temperature difference for which there is no danger of buckling, in which case the pipe can function without compensating pipe, is:

$$\Delta T_i^m \langle \Delta T_{cr}^i = \frac{\pi^2 I_{min}}{\alpha^{TL} A l_f^2} \tag{7}$$

I_{min} - inertia moment of resistance section, in m^4;

l_f - buckling critical length, in m.

To calculate the temperature distribution within the pipeline system, using this method, it is necessary to specify the following initial data:

- dimensional characteristics of the pipe: outside diameter D_T, in m; inside diameter, d_T, in m; the pipe wall thickness, s_1, in m; thickness of the outside thermal insulation pipe, s_{iz}, in m; outside diameter of the insulated pipe, D_{exiz}, in m; length of the pipeline system along which the temperature distribution is determined, L, in m;
- thermal conductivity of the pipe material, λ_m, in W/mK, depending on the pipeline's material, which depends a little on temperature, being a constant measure;
- thermal conductivity of the insulation material, used in the outside thermal insulation, λ_{iz} in W/mK, depends on the material type used to make insulation, which depends a little on temperature, being a constant measure;
- product transport characteristics through pipeline system: the product, for the calculus application from this paper, is the superheated steam, with the flow D, in m^3/s and transmission speed, v, in m/s; pressure p, N/m^2 and initial temperature of the steam at the input in the considered section T_1, in K;
- depending on the pipeline location (ground, air) we have to mention the average air temperature next to the pipeline, T_0, in K, and average wind speed next to the pipeline, W, in m/s.

Starting from the initial data, it is considered a pipeline system of length "*L*" (Fig. 1), and we have an element of length dx. During the elementary time interval $d\tau$, the elementary quantity of heat dQ_1 enters in the pipe, the elementary quantity of heat dQ_2 gets out, the losses to the outside through the insulating layer being characterized by the elementary quantity of heat dQ_p (Fig. 2).

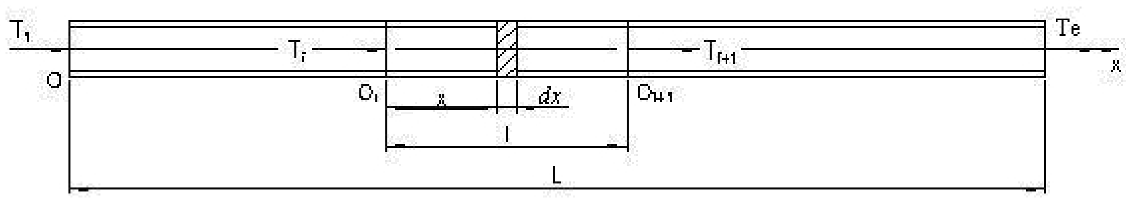

Fig. 1. Pipeline system

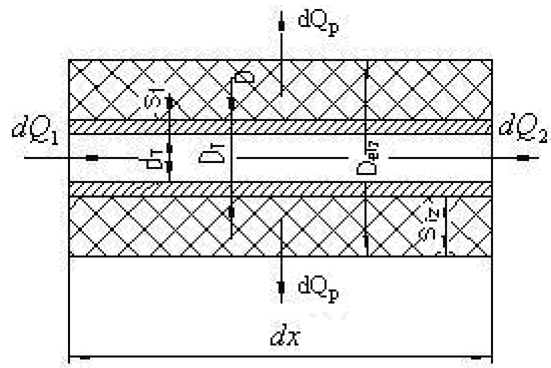

Fig. 2. Element of length dx from the pipeline system

The thermal balance pipe element is:

$$dQ_1 = dQ_2 + dQ_p \tag{8}$$

The expressions of elementary quantities of heat are:

$$dQ_1 = \rho \cdot S \cdot v \cdot c \cdot T \cdot d\tau \qquad \text{a)}$$

$$dQ_2 = \rho \cdot S \cdot v \cdot c\left(T + \frac{dT}{dx}dx\right) \cdot d\tau \qquad \text{b)} \qquad (9)$$

$$dQ_p = k_G \cdot \pi \cdot D_{eiz} \cdot dx\left(T - T_0\right) \cdot d\tau \qquad \text{c)}$$

ρ - steam density, in kg/m^3;
c – steam specific heat, in J/KgK;
S - range of steam flow through the pipeline, in m^2:

$$S = \frac{\pi d_T^2}{4} \qquad (10)$$

k_G - overall coefficient of heat transfer from the pipe steam to the atmosphere, in W/mK.

Substituting equation (8) with (9), results:

$$\rho SvcTd\tau = \rho Svc\left(T + \frac{dT}{dx}\right)d\tau + k_G \pi D_{eiz} dx \cdot \left(T - T_0\right)d\tau \qquad (11)$$

Because:

$$D = S \cdot v \qquad (12)$$

it results:

$$\frac{dT}{T - T_0} = -\frac{\pi \cdot D_{eiz} k_G}{\rho D \cdot c} dx \qquad (13)$$

Equation (13) is the differential equation characterizing the temperature variation steam along pipe element *dx*.

Integrating the equation (13) at the temperature range of T_i and T_{i+1} it results:

$$\int_{T_i}^{T_{i+1}} \frac{dT}{T - T_0} = \int_0^l \left(-\frac{\pi D_{eiz} k_G}{\rho D \cdot c}\right)dx \qquad (14)$$

It results:

$$T_{i+1} = T_0 + \left(T_i - T_0\right) \cdot e^{-\frac{\pi D_{eiz} k_G}{\rho Dc} l}, \text{ in } K \qquad (15)$$

$$\Delta T_i = T_i - T_{i+1} = \left(T_i - T_0\right)\left(1 - e^{-\frac{\pi D_{eiz} k_G}{\rho Dc} l}\right), \text{ in } K \qquad (16)$$

Noting $k_1 = \pi D_{eiz} k_G$, the formulas (15) and (16) become: (17)

$$T_{i+1} = T_0 + \left(T_i - T_0\right) \cdot e^{-\frac{k_1 l}{\rho Dc}}, \text{ in } K \qquad (18)$$

$$\Delta T_i = T_i - T_{i+1} = \left(T_i - T_0\right)\left(1 - e^{-\frac{k_1 l}{\rho Dc}}\right) \qquad (19)$$

The formulas (18) and (19) are final formulas used to determine the steam temperature distribution in the symmetry axis of the pipeline within the section considered.

Thus, if the pipe, of length L, is divided in "n" sections, of length l, and the input steam temperature from the first section is T_1 in K, using the formula (19) the steam temperature variation within the first section is calculated. This difference being determined, the steam temperature at the output of the first section is calculated. This is the input temperature in the second section and so on, and in this way are determined the input and output temperatures in each of the n sections, which represent the distribution of steam temperature within the pipeline.

In formulas (15), (16), (18), (19), the ρ density and the c specific heat of steam were considered constant within the section of length l, although the steam temperature varies (decreases). The length of the section l chosen for calculus has to be sufficiently small to avoid excessive errors of this approximation (errors are inevitable, because the equations are very complicated if we consider the density and specific heat depending on temperature).

The overall heat transfer coefficient k_G is determined [3] with the formula:

$$k_G = \frac{1}{D_{eiz}\left(\frac{1}{\alpha_i d_T} + \frac{1}{2\lambda_m} ln\frac{D_T}{d_T} + \frac{1}{2\lambda_{iz}} ln\frac{D_{eiz}}{D_T} + \frac{1}{\alpha_e D_{eiz}}\right)} \quad (20)$$

and the coefficient K_1, according to the formulas (10) and (13) will be:

$$k_1 = \frac{\pi}{\frac{1}{\alpha_i d_T} + \frac{1}{2\lambda_m} ln\frac{D_T}{d_T} + \frac{1}{2\lambda_{iz}} ln\frac{D_{eiz}}{D_T} + \frac{1}{\alpha_e D_{eiz}}}, \text{ in W/K} \quad (21)$$

In formulas (20) and (21), α_i is the inside heat transfer coefficient from the steam from the pipe to the inside wall of the pipe, in W/m^{2}K. The determination of the coefficient α_i is done taking into account the particularities of the heat transfer process from the steam to the inner wall of the pipe. Thus, although the steam is overheated because the temperature of the inner wall of the pipe is lower than the steam saturation temperature, at the pipe pressure, small amounts of steam condensation are produced near the wall, forming a layer of condensation (water) which is moving with the steam. The heat transfer from steam pipe to the inner wall of the pipe is produced by convection from the steam to the water layer and by convection and conduction from the water layer to the inner surface of the pipe. The appropriate transfer coefficient, according to [3] is:

$$\alpha_i = \frac{R_{el}}{(T_s - T_p)d_T} \cdot \frac{r_l \cdot \rho_l \cdot \upsilon}{144000} \quad (22)$$

T_s - steam saturation temperature, at the pipe pressure, in K;

T_p – temperature of inner surface of the pipe;

r_l - specific latent heat of water vaporization, at the pipe pressure and at the average temperature of the water layer (liquid), T_l, expressed in J / kg;

ρ_l – water density at the temperature T_l;

υ – kinematics viscosity of the steam, at the steam temperature in the symmetry axis, T_i, expressed in m^2/s;

R_{el} – Reynolds similarity criterion for steam flow, is considered, however, for the temperature of the water layer, T_l, determined by the formula:

$$R_{el} = \frac{v \cdot d_T}{\upsilon} \quad (23)$$

T_l – average temperature of the water layer, given by the formula:

$$T_l = \frac{T_i^a + T_p}{2}, \text{ in [K]} \quad (24)$$

T_i^a - steam temperature in the symmetry axis of the pipe.

External heat transfer coefficient, α_e, from the outside surface of the insulated pipe, to the atmosphere, in W/m^{2}K is according to [4]:

$$\alpha_e = 3{,}8953 \frac{w^{0,6}}{D_{eiz}^{0,4}} \quad (25)$$

Due to the fact that the heat transfer is achieved by a complex mechanism, we consider that the temperature varies linearly from the symmetry axis of the pipe (where the steam temperature is T_i^a) to the outside surface of the insulated pipe (Fig. 3).

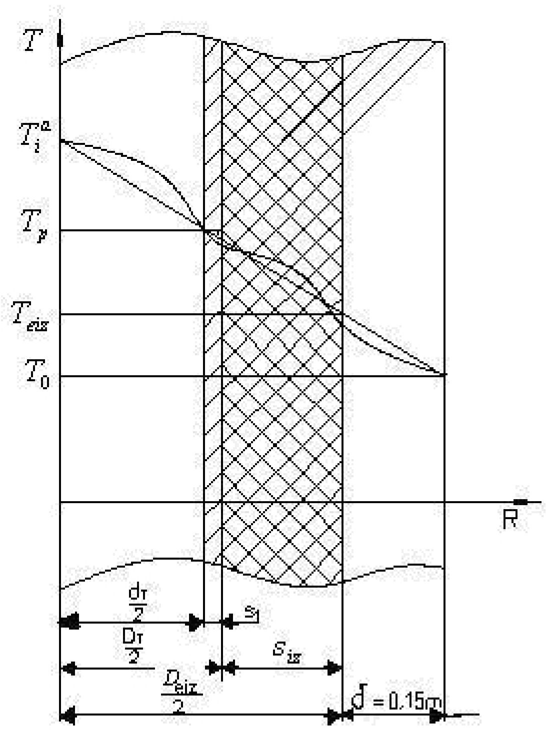

Fig. 3. The drawing of the temperature variation from the symmetry axis to the outside surface

Taking into account that the free air temperature, T_0, is reached, at a distance δ_0 = 0.150 m to the outside surface of the insulated pipe (Fig. 3), the temperature at the inner surface of the pipe wall, T_p, is given by:

$$T_p = T_i^a - \frac{d_T}{D_{eiz} + 0{,}300} \cdot \left(T_i^a - T_0\right), \text{ in [K]} \quad (26)$$

The Determination of the Different Degrees of the Steam and Water Physical Properties According to the Temperature

In order to realize the applied calculus, the relations of dependence between steam and water physical properties according to the temperature must be established.

- Water density:

In the paper [5] the values of water density with temperature are tabulated. Based on these values, using least-squares method [6], the dependence from the water density and temperature was determined with the formula: $\rho_l(T) = A \cdot T^2 + BT + C$ (27)

It results: $$\rho_l(T) = 2{,}6475 \cdot 10^{-3} T^2 + 1{,}27533T + 851{,}7047 \qquad (27')$$

measured in Kg/m^3.

- Steam density:

Being saturated and overheated, the steam transported by pipeline is similar to an ideal gas. From the ideal gas theory, we obtain the relation for steam density:

$$\rho = \frac{p}{R_{abur} \cdot T} \qquad (28)$$

Because: $p = 12 \cdot 10^5$ N/m^2

$R_{abur} = 8314/18 = 461{,}889$ J/KgK

$\rho = 2598{,}03/T$, in Kg/m^3 (29)

- Specific heat of water and steam:

In the paper [5] specific heat values of water and steam are tabulated according to the temperature. Using the least-squares method, the dependence of specific heat and temperature was determined:

$$c(T) = 1{,}8147 \cdot 10^{-2} \cdot T^2 - 12{,}30233T + 6255{,}546 \qquad (30)$$

measured in J/KgK.

- Latent heat of water vaporization:

For the pressure p = 12 • 105 N/m^2, in [5], the values of specific latent heat of water vaporization for different values of temperature are tabulated. Using the least-squares method, the dependence between the latent heat of vaporization and temperature was determined, in the following way:

$$r_l(T) = -11{,}86969 \cdot T^2 + 7292{,}5851 \cdot T + 1147180{,}5 \qquad (31)$$

- Steam dynamic viscosity:

The dependence between the steam dynamic viscosity and temperature is given by Southerland's relation [7]:

$$\eta(T) = 1{,}70 \cdot 10^{-8} \cdot T^{1{,}116}\text{, measured in Kg/m}^2\text{s} \qquad (32)$$

- Water kinematics viscosity:

The dependence between the water kinematics viscosity and temperature is given by Poisenille's relation [7]:

$$v_l(T) = \frac{1{,}78 \cdot 10^{-6}}{1 + 0{,}0337 \cdot (T - 273) + 0{,}00022(T - 273)^2}\text{, in m}^2\text{/s} \qquad (33)$$

The Determination of the Different Degrees of the Physical and Elastic Characteristics of the Piping Material According to the Temperature

- Linear extension coefficient:

In the paper [8] linear extension coefficient values depending on temperature are tabulated for steel pipes. Using the least-squares method, the dependence between the linear extension coefficient and temperature is determined:

$$\alpha(T) = 5 \cdot 10^{12} T^2 + 7{,}75 \cdot 10^{-10} T + 11{,}51528 \cdot 10^{-6}, \text{ in m/mK} \quad (34)$$

- Longitudinal elastic modulus:

In the paper [8] longitudinal elastic modulus values depending on temperature are tabulated for steel pipes at high temperatures. Using the least-squares method, the dependence between the longitudinal elastic modulus and temperature is determined:

$$E(T) = 5{,}4999 \cdot 10^5 T^2 - 7{,}7529992 \cdot 10^8 T + 45{,}566593 \cdot 10^{10} \quad (35)$$

Numerical Application

To apply in practice the suggested method, we need to determine temperature variation and thermal stresses within a pipe section mounted above ground, knowing: the transported product, superheated steam, D = 0.5 m^3/s, υ = 9.95 m/s, p = 12 • 10^5 N/m^2, T_1 = 523 K, T_s = 463 K, D_T = 0.273 m, d_T = 0.253 m, s_T = 0.010 m, s_{iz} = 0.060 m, $D_{e,iz}$ = 0.393 m, pipe length 2000 m , quality of pipe material - steel, λ_m = 45 W/mK, external thermal insulation material - glass wool, λ_{iz} = 0.05 W/mK, T_0 = 293 K, w = 10 m/s.

Calculus results are presented in Table 1.

Table 1. The obtained results for the numerical application

Nr crt	x [m]	T_i [K]	T_{pi} [K]	T_{li} [K]	$E^{Ti} \cdot 10^{10}$ [N/m^2]	$\alpha^{Ti} \cdot 10^{-6}$ [m/mK]	$\Delta T_i^m = T_i - 293$ [K]	$\sigma_x^{Ti} = E^{Ti}\alpha^{Ti}\Delta T_i^m 10^8$ [N/m^2]
1	0	523	439	481	20,0649	13,2882	230	6,1324
2	100	521,387	438	479,7	20,0973	13,2785	228,387	6,0947
3	200	519,788	436,9	478,4	20,1297	13,2689	226,788	6,0574
4	300	518,201	435,9	477,1	20,1622	13,2595	225,201	6,0205
5	400	516,626	434,9	475,8	20,1947	13,2501	223,626	5,9838
6	500	515,064	433,9	474,5	20,2271	13,2408	222,064	5,9431
7	600	513,515	433,0	473,3	20,2596	13,2317	220,515	5,9113
8	700	511,977	432,0	472,0	20,2921	13,2226	218,577	5,8754
9	800	510,452	431,1	470,8	20,3246	13,2136	217,452	5,8399
10	900	508,939	430,04	469,5	20,3570	13,2047	215,939	5,8046
11	1000	507,437	429,1	468,3	20,3895	13,1959	214,437	5,7695
12	1100	505,948	428,2	467,1	20,4220	13,1872	212,948	5,7348
13	1200	504,471	427,3	465,9	20,4544	13,1786	211,471	5,7004
14	1300	503,005	426,3	464,7	20,4868	13,1701	210,005	5,6662
15	1400	501,551	425,4	463,5	20,5192	13,1617	208,551	5,6322
16	1500	500,108	424,5	462,3	20,5516	13,1533	207,108	5,5985
17	1600	498,677	423,6	461,1	20,5839	13,1451	205,677	5,5651
18	1700	497,257	422,7	460,0	20,6163	13,1369	204,237	5,5312
19	1800	495,849	421,8	458,8	20,6485	13,1288	202,849	5,4990
20	1900	494,452	420,9	457,7	20,6814	13,1206	201,422	5,4656
21	2000	493,066	-	-	-	-	-	-

Analyzing the results achieved for thermal mechanical stresses σ_x^{Ti}, results that they have values that exceed the admitted limit of piping material. In this case, we have to divide the pipe section in compensation blocks (CTB), equipped with special devices named compensating pipe, working at the temperature of the CTB that's determined in order to increase the elasticity of the pipe system so that thermal mechanical stresses be below the admitted piping material.

Conclusions

Based on this paper, the following significant issues can be underlined:

- the presented method in this paper is original and easy to use with computers;
- the method is efficient from the economic point of view, determining the real temperature along a pipe section, leading to the establishment of the mechanical stresses generated by temperature;
- the method provides an economic sizing of the thermal insulation and compensation systems of the thermal extensions.

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Contribuții privind calculul tensiunilor mecanice generate de temperatură în lungul unui tronson de conductă

Rezumat

Această lucrare prezintă o metodă originală de calcul al tensiunilor mecanice generate de temperatura din conductele prin care produsele calde sunt transportate. Metoda propusă, prezentată teoretic, ia în considerare variația de temperatură pe un tronson de conductă, începând cu punctul de alimentare al acestuia.