The compensator's calculation for the pipe in complex systems

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Abstract**—** This article shows the results of such a study, which has been triggered by a technological incident: the wrenching from the compensator and its axial shifting of a large diameter air pipe in a wastewater treatment plant, event that occurred after many years of normal operating. The phenomenon that occurred can be justified only as a result of action of some axial forces, taking into account that axial shifting of rectilinear pipe sectors is not impeded by any special blocking device, but only by the friction of the pipe on its supports (axially) and by the resistance torque generated by its own weight (in the supports of the perpendicular sectors).

Keywords**—**friction force, deformation arrow, inertia momentum, pressure force, temperature, weight force

I. Introduction

The behaviour in time of fluid pipes is determined by numerous quantifiable factors took into account by corresponding values of a quasi-normal operating in specific conditions of locations. During operation may occurred situations which, due to unusual combinations of factors, lead to serious loss of balance which impacts on the structures' stability and eventually leads to serious or less serious incidents. Assessing such events and identifying their causes bring useful information which can optimize models and criteria used in design process and furthermore, may lead to enhancing of safety and efficiency of respective systems, [1].

The study is also very valuable because all plant's personnel was believed that the accident has been caused by the relatively high temperature of transported air in the pipe and hence by large temperature variations. Subsequently these theories have been proven to be false.

The most probable causes have been identified through a study of the structure's mechanical behaviour, under the complex stresses that impacted it at the existing conditions of the accident and considering also the way of how these have evaluated. The proof of identified causes is made by the fact that, in the system's evolution, all corresponding circumstances have occurred only in the moment when the incident took place, [2].

The physical and mechanical characteristics of the air pipe are provided by the topographic measurements and the current pipe route, constructive details of materials, $d_e \times s$, the compensators' features, flanges and bolts, the mounting temperature (t_m = 15^{o}C) and certain specific properties of the fixings which support the pipe.

The conditions are represented by the parameters of operational ratings for the air plant: flow Q = 9.500 ÷ 21.000 Nm^3/h per blower; 1 ÷ 3 active blowers; pressure p = 0,6 ÷ 0,8 bar; fluid's operating temperature t = 50 ÷ 70^o C; maximal variation of pipe's temperature Δt < 100^o C. The climatic features of geographical area are: minimal recorded temperature –30,6^o C; maximal recorded temperature: +40,0^o C; annual average number of snowy days: 134 d/yr; average thickness of snow layer: 310 mm - in December and January; main winds blowing on North-West direction (22,8 %) and on East direction (14,5 %); NW wind monthly average velocity: 4,9 ÷ 6,7 m/s; 1/10 frequency maximal wind velocity: 27 m/s.

II. Problem Definition

Circumstances in which the incident occurred: last week of year 2009; frosty weather and sleet; plant operating on auto mode, by night.

Incident consisted of a detachment of the air pipe from the C2 compensator which is located in the aeration tank area (Fig. 1) and the shifting of the upstream pipe sector on approximately 60 cm distance.

After replacing the pipe on position, with hydraulic jacks, the coupling with the compensator has been re-mounted with o-shaped seals.

Stability of the pipe sector has been provided by blocking the axial motion with a metallic shaft supported against the secondary clarifier's structure present nearby the pipe, section D.

According to personnel's' statements the phenomenon started with air leaks on the compensator's o-shaped seal. These leaks slowly developed, while pipe sector C1 - D was getting deformed and while pipe sector C2 - D was axially shifting, Fig. 2. The acute phase (detachment from compensator and shifting) occurred by night when the blower plant was on auto mode. The air leaks being heavier and heavier, the air flow need grow on and on till the second blower automatically has been started up by the system. The two blowers, parallel operating, led to a serious rise of air pressure which eventually triggered the start up of the third blower. All these conditions led to the acute phase above described.

Given the extent of pipe's shifting (approximately 60 cm) and the circumstances of the event (frost, sleet, snow) this cannot be directly declared to be caused by temperature

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variation because, even at $\Delta t = 100^oC$, the main's length variation (on the aeration tank) would never exceed $\Delta L = 10$ cm.

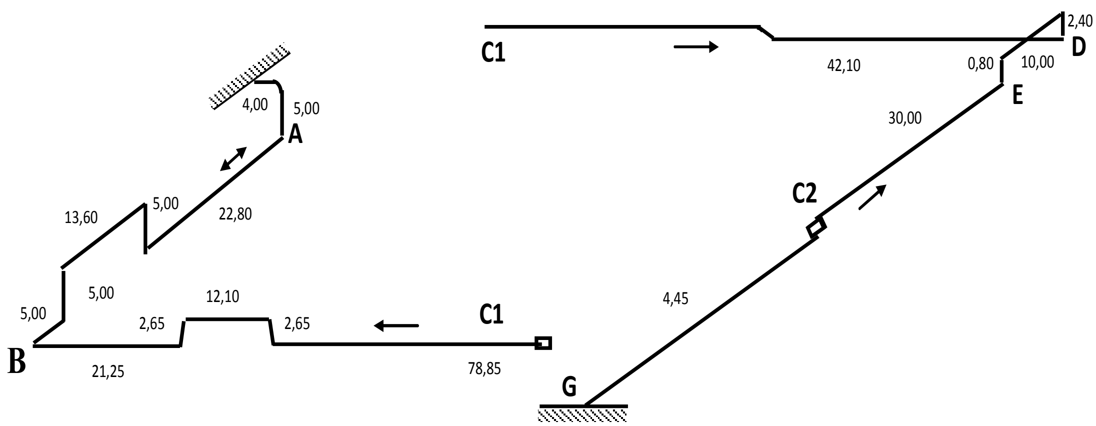

Fig. 1. Diagram of relevant pipe sectors study.

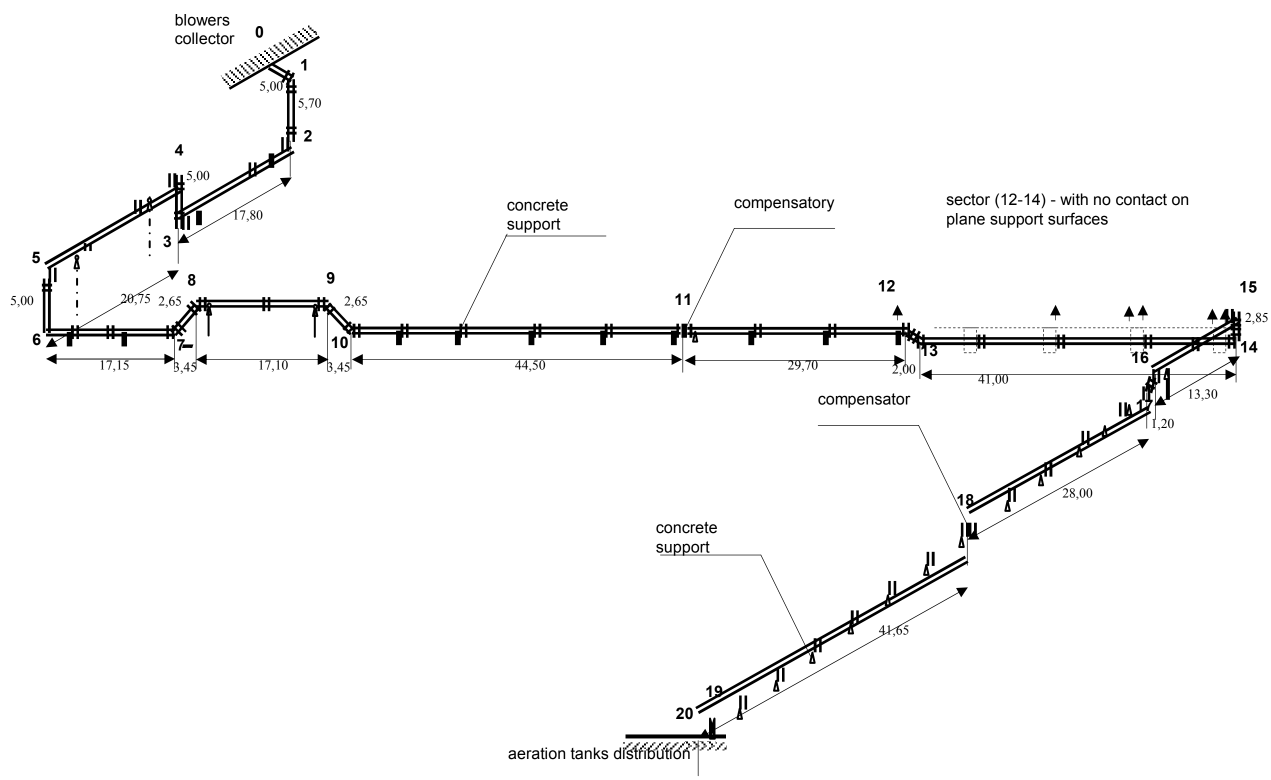

Fig. 2. Isometrical diagram of air main Dn 1200 mm

The phenomenon can only be explained as a result of action of axial stresses, in the conditions when axial shifting of rectilinear pipes is not impeded by any stopping device but only by the friction of the main against its supports (on axial direction) and by the resisting torque developed (on the supports of perpendicular pipe sectors) by the pipes' own weights, [4, 5].

So that the phenomenon to be explained it has to be stated that, because the presence of the two compensators, the air pipe in question can be illustrated in terms of mechanical behaviour as is shown in Fig. 3.

Considering the air main configuration, the axial forces occurring in bends are balancing themselves two by two, their result being null on each of the system's pipe sectors, [5].

When system is operated balance of axial horizontal forces is provided by (Fig. 3):

- Friction force between pipe and pipe sector's supports on which direction it occurs.
- Horizontal reactions in supports of the perpendicular pipe sector, on which it acts.
- Resilience of consoled pipe sectors, between the applying point and first active support.

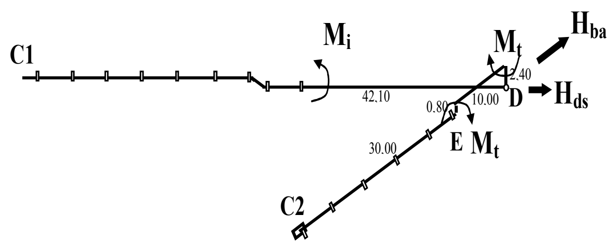

Fig. 3. Stresses that might induce axial shifting of air main's C2 - D sector.

The consoled pipe sector C1 - D, which limits axial shifting of sector C2 - D, will be deformed by bending stresses, according to its length and its resilience modulus of the pipe's transverse section, depending on the force that act upon the free end. This deformation of the consoled sector will allow an axial shifting of the perpendicular pipe sector, which will be equal to the arrow of the free end *f*.

Considering the items above the study of the main's mechanical stability included the following:

- Calculation of main loads that act upon studied system: weight forces G, pressure forces P, hydrodynamic forces in bends F_x and friction forces in supports Q_f.
- Calculation of axial horizontal forces in unbalanced bends.
- Calculation of vertical and horizontal forces that occur in supports.
- Checking the stability to rolling of the pipe, on its support.
- Calculation of unitary efforts and calculation of sectors' deformation in console.
- Assessing axial shifting of perpendicular pipe sector.
- Checking distance between supports.
- Calculation of maximal variation of rectilinear sectors' lengths when temperature varies during operation.
- Establishing the number of compensators needed to prevent the main's loss of tightness and their type.

The console sector which is the weak link that impacts on the system's stability is located in the pipe sector laid on the metallic manholes of the clarifier, area in which some 30 m of pipe is literally suspended (with no contact with supports). Study has been developed on MathCAD and MathLAB software, with classic methods of the field.

III. Experimental Results

The even distributed head of main's weight (kN/m) during operating period corresponds to the pipe's diameter and to its wall thickness, respectively to the air density (kg/m^3), depending on pressure, Table I.

TABLE I
VARIATION OF AIR DENSITY, AIR WEIGHT AND PIPE WEIGHT

Air density	1,0	1,1	1,2	1,3	1,4
Air weight	0,011	0,012	0,013	0,014	0,015
Pipe weight	3,059	3,060	3,061	3,062	3,063

In calculation the average value is adopted G_c = 3,061 kN/m. Weight of a flanged coupling is G_f = 2,326 kN/buc. Pressure force in bend (A = 1,128 m^2) varies depending on air pressure in main, between P = 56,379 kN, at pressure p = 0,5 bar and P = 90,207 kN, at p = 0,8 bar, Table II.

TABLE II
VARIATION OF PRESSURE FORCE *P* DEPENDING ON AIR PRESSURE *P*

air pressure p [bar]	0,5	0,6	0,7	0,8
pressure force P [kN]	56,379	67,655	78,931	90,207

Hydro dynamical force in the 90^o bend varies very little compared to air density and flow in the main, depending, as the pressure force does, on the operating pressure, Table III.

TABLE III
PRESSURE *P* VARIATION DEPENDING ON AIR FLOW *Q*

pressure [bar] / air flow [m^3/s]	0,6	0,7	0,8
5	67,686	78,962	90,238
10	67,779	79,055	90,331
15	67,934	79,210	90,486
20	68,152	79,427	90,703

For an air density ρ_{aer} = 1,4 kg/m^3, when an average 10 m^3/s flow is transported, hydrodynamic force takes values between F_x = 67,779 kN, at p = 0,6 bar and F_x = 90,331 kN, at pressure p = 0,8 bar, (Fig. 4):

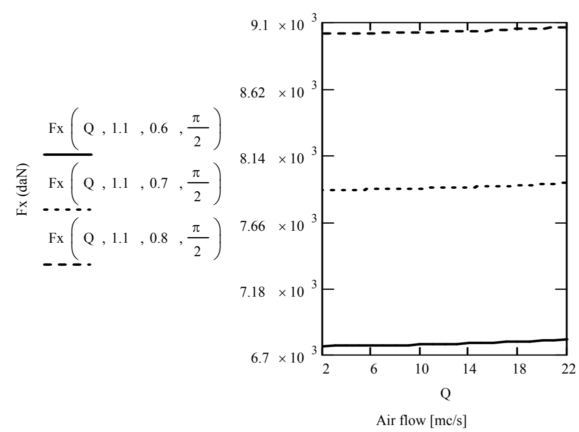

Fig. 4. Horizontal hydraulic force F_x depending on air flow Q for bend at 90^o.

1. *Friction forces on supports* correspond to the total weight of the studied pipe (length and number of flanged couplings) and to the friction factor between pipes and supports. For friction factors having values $\mu = 0{,}1 \div 0{,}4$ the friction force that impedes the axial shifting takes different values from a sector to another as it follows Table IV.

2. *Horizontal axial forces in vertical bends* D *and* 6*: a*xial forces that act upon bends correspond to the action's direction is sensibly depending of friction factor between mains and supports. Assuming the following values $\rho_{aer} = 1{,}4$ kg/m^3, Q = 10 m^3/s, $\alpha = 90^o$ and $\mu = 0{,}1 \div 0{,}4$, axial forces in bends D and *6* take the values shown in Table V.

When monitoring the variation of the active axial force in bends which depends on the air pressure within the pipe, for different values of the friction factor, we may observe the following:

- in case of bend 6, when friction factor drops down to $\mu = 0{,}2$, the force will have values which will not exceed 10 ÷ 15 kN, even if air pressure boosts to 0,9 ÷ 1 bar; in the exceptional situation when friction factor drops down to μ = 0,15, the values are not exceeded at air pressures of 0,7 ÷ 0,8 bar, [3].

TABLE IV.
FRICTION FORCES ON SUPPORTS Q_F AND F_R VARIATIONS DEPENDING ON FRICTION FACTORS μ.

μ	sector D – C2 L = 45,35 m; n_{fl} = 11; n_r = 5		sector C1 - D L = 72,70 m; n_{fl} = 10; n_r = 5		sector 1 – C1 L = 139,9 m; n_{fl} = 30; n_r = 14	
	Q_f	F_r	Q_f	F_r	Q_f	F_r
0,1	16,44	3,288	24,58	4,916	49,80	3,557
0,2	32,88	6,576	49,16	9,832	99,60	7,114
0,3	49,32	9,864	73,74	14,748	149,40	10,672
0,4	65,76	13,152	98,32	19,663	199,21	14,229

TABLE V
AXIAL FORCES VARIATION DEPENDING ON PRESSURE P AND FRICTION FACTORS μ.

	Direction C2 - D L = 86,35 m; n_{fl} = 11; n_r = 5			direction C1 - D L = 118,05 m; n_{fl} = 10; n_r = 5			direction C1 - 6 L = 139,9 m; n_{fl} = 30; n_r = 14		
p μ	0,6	0,7	0,8	0,6	0,7	0,8	0,6	0,7	0,8
0,1	38,789	50,65	61,341	29,318	40,594	51,87	17,978	29,254	40,530
0,2	9,799	21,075	32,351	-9,142	2,133	13,41	-31,82	-20,55	-9,271
0,3	-19,19	-7,915	3,361	-47,60	-36,33	-25,05	-81,62	-70,35	-59,07
0,4	-48,18	-36,91	-25,63	-86,06	-74,79	-63,51	-131,4	-120,1	-108,9

- In case of bend D, active axial force will take values sensibly superior compared to those above soon as $\mu < 0{,}25$ (on direction C1 - D) and even if $\mu = 0{,}30$ (on direction C2 - D), and this at lower pressures within the main (0,65 ÷ 0,85 bar, on direction C1 - D, respectively 0,5 ÷ 0,8 bar, on direction C2 - D).

3. *Vertical force on supports V* corresponds to the quasi-even distribution of the total weight of the free shifting sector, on the n_r supports that exist on its route, Table VI:

TABLE VI
VERTICAL FORCE ON SUPPORT V VARIATION

Pipe sector	length L [m]	flanges silver n_f	support	vertical force on support $V(L,n_f,n_r)$ [kN]
1 – C1	139,90	30	D	35,572
C1 – C2	118,50	21	C1	37,415

$$V(L,n_f,n_r) = \frac{L \cdot G_c + n_f \cdot G_f}{n_r} \tag{1}$$

4. *Horizontal axis-normal force in supports H*: generated by the active axial force applied by the perpendicular sector, the horizontal force that acts upon supports, in a direction normal to axis, results from, Table VII:

$$H(p,\mu,L,n_f,n_r) = \frac{F_{a1}(p,\mu,L,n_f)}{n_r} \tag{2}$$

5. *Pipe roll-over stability on supports c* is provided by over-unitary values for the safety coefficient:

$$c(p,\mu,L,n_f,n_r) = \frac{V \cdot a}{H(p,\mu,L,n_f,n_r) \cdot b} \tag{3}$$

The inertia momentum I_x and the resilience modulus of the annular section W_x having $d = D_i/D_e = 0{,}983$, being:

$$I_x = \pi \cdot \frac{D_e^4}{64} . \left(1 - d^4\right) = 7{,}177 \cdot 10^5 \ \ [\text{cm}^4], \tag{4}$$

Respectively:

$$W_x = \pi \cdot \frac{D_e^3}{32} \cdot \left(1 - d^4\right) = 1{,}177 \cdot 10^4 \quad [\text{cm}^3], \tag{5}$$

Corresponding to the axial load with which acts the perpendicular pipe sector C2 - D, within the embedding C1, will generate a bending momentum M_i:

$$M_i = 10^{-1} \cdot F_{a1} \cdot L, \ [\text{MN.cm}], \tag{6}$$

which will next generate an unitary effort σ_x, [6]:

$$\sigma_x = 10^2 . \frac{M_i}{W_x}, \ [\text{N/mm}^2], \tag{7}$$

Maximal arrow f in D sector is calculated with following form: [7]:

$$f = \frac{10^9 \cdot F_{a1} \cdot L^3}{3 \cdot E \cdot I_x}, \ [\text{cm}] \tag{8}$$

The deformed angle φ has the mathematical relation:

$$\varphi = \tan^1 \left[\frac{10^7 \cdot F_{a1} \cdot L^2}{2 \cdot E \cdot I_x} \right], \ [\text{rad}]. \tag{9}$$

Variation of the arrow function of the axial active load in node D (Fig. 6), correlated with its dependence on air pressure and support friction factor, leads to the conclusion that when the axial shifting on direction C2 - D is not impeded, section D will sensibly shift as soon as the air pressure exceeds 0,8 bar, even in normal conditions of support friction. Subsequently the phenomenon occurs at lesser and lesser pressures even when the friction factor takes values below $\mu = 0{,}25$.

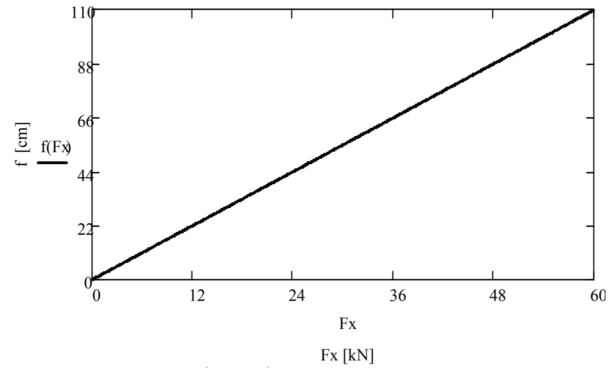

Fig. 6. Arrow variation f depending on horizontal hydraulic force F_x .

If accept an elastic modulus $E = 2{,}02.10^7$ N/cm^2, for sector C1 - D, having a length $L = 43$ m, the main characteristics of the bending stress occurring in section C1, under the active axial forces in range from 0 to 60 kN, are shown in Table VII.

The pipe sector comprised between section E and bend D also do not have any supporting point. Therefore this sector works such as an annular beam of diameters D_e, D_i and a length L, embedded at one end E, and stressed at the other end by a concentrated active force corresponding to the active axial force F_{a1}, applied by the perpendicular sector C1 - D.

The inertia momentum and the resilience modulus of the annular section having $d = D_i/D_e = 0{,}983$, being the same as in the previous case (I_x = 7.177.10^5 cm^5, respectively W_x = 1,177.10^4 cm^3), corresponding to the axial load with which the perpendicular sector C1 - D acts, in the embedding E will occur a bending momentum M_{iE}, which generates:

- the unitary effort σ_{x17} [N/mm^2],
- the maximal arrow in D, f_D [cm],
- the deformation angle φ_E [rad],

Which, accepting an elastic modulus $E = 2{,}02.10^7$ N/cm^2 and a length for sector E - D, $L = 15$ m, for active axial forces in the range of 0 to 60 kN, takes the values shown in the Table VIII.

TABLE VII

AXIAL FORCE F_{A1} , BENDING MOMENTUM M_{iC1} , UNITARY EFFORT σ_{xC1} , ARROW F_D , DEFORMED ANGLE φ_{C1} VARIATIONS BETWEEN C1 – D BENDS

F_{a1}	kN	0	10	20	30	40	50	60
M_{iC1}	MN.cm	0	43	86	129	172	215	258
σ_{xC1}	N/mm^2	0	36,52	73,04	109,55	146,07	182,59	219,10
f_D	cm	0	18,3	36,6	54,8	73,1	91,4	109,7
φ_{C1}	Grd.	0	0,37	0,73	1,07	1,46	1,83	2,19

TABLE VIII

AXIAL FORCE F_{A1} , BENDING MOMENTUM M_{iE} , UNITARY EFFORT σ_{xE} , ARROW F_D , DEFORMED ANGLE φ_E VARIATIONS BETWEEN E – D BENDS

F_{a1}	kN	0	10	20	30	40	50	60
M_{iE}	MN.cm	0	15	30	45	60	75	90
σ_{xE}	N/mm^2	0	12,74	25,48	38,22	50,96	63,69	76,43
f_D	cm	0	0,78	1,55	2,33	3,10	3,88	4,66
φ_E	grd.	0	0,04	0,09	0,13	0,18	0,22	0,27

IV. Conclusion

Deformation occurring in the console pipe sector allows an axial shifting of the perpendicular sector, corresponding to the arrow in its free end *f*.

In normal conditions the friction force that opposes to the axial load takes values Q_f = 65,76 kN - on sector D- C2; Q_f = 98,32 kN – on sector C1- D and Q_f = 199,21 kN – on sector 1 - C1.

Axial shifting of a main is allowed only by bending deformation of the perpendicular sector and will correspond to the arrow generated in their free end, *f*.

Admissible distance between supports is conditioned by:

- Calculation distributed load, generated by the own operating pipe's weight, including the weight of flanges.
- The resilience modulus of the annular main section.

The admissible tension for wind and weight generated loads of the material of which the main is made (OLT35 K, σ = 145,8 N/mm^2 [1]), is respected in the case of the air main having D_e = 121,9 cm, and D_i = 119,83 cm, even on sector C1 - D which is not supported on the plane supports existing nearby on the clarifier.

The necessary number of compensators matches the maximal temperature variation which occurs during operating ΔT, the length of straight main on which they are mounted L and the compensation capacity stated by the supplier ΔL, respectively the linear thermal dilatation factor for steel (α_d = 11,10^{-6} m/m. ^{o}C).

Keeping the same number of compensators on the two long sectors of the air main it results that at a maximal temperature variation ΔT = *100* ^{o}C, the main must undertake a length variation of ΔL = 9,5 ÷ 12 cm.

The phenomenon that occurred can be justified only as a result of action of some axial forces, taking into account that axial shifting of rectilinear pipe sectors is not impeded by any special blocking device, but only by the friction of the pipe on its supports (axially) and by the resistance torque generated by its own weight (in the supports of the perpendicular sectors) (see Fig. 3).

Presence of compensators C1 and C2 may lead to axial unbalanced forces that might induce shifting of rectilinear pipe sectors; this may occur in (Fig. 2):

- Bend *6* (pipe sector *B*, Fig. 2), action towards the exterior, on direction *11-6*;
- Bend *14* (pipe sector *D*, Fig. 2), action towards the exterior, on direction *11-14*;

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