ANNALS of the ORADEA UNIVERSITY.
Fascicle of Management and Technological Engineering, Volume VII (XVII), 2008

EXPERIMENTAL INVESTIGATION OF THE WIND LOADS ON A SINGLE AND A SLUDGE-DIGESTION TANK ENSEMBLE

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KEYWORDS: Wind tunnel, local pressure, aerodynamic force and momentum coefficients.

ABSTRACT
The paper describes the experimental investigation on models placed in the experimental vena of an aerodynamic boundary layer wind tunnel (BLWT) regarding the wind loads on the sludge-digestion tanks (SDT) of the waste water treatment plant serving Bucharest municipality. The purpose of the research was to determine the static load generated by the wind on two rigid models. To achieve this aim, measurements on the model of a single SDT (scale 1:100) and for an ensemble of five SDT, the technological buildings and control tower were made (scale 1:150).

1. INRODUCTION

The aim of the experimental investigation was the determination on models placed in the experimental vena of the aerodynamic boundary layer wind tunnel (BLWT) of the wind loads on the sludge-digestion tanks (SDT), process steps 1 and 2 of the Bucharest municipality waste water treatment plant. For an efficient, economically and unmistakable designing this experimentally studies were considered necessary to underlain more rigorous the chosen solution and to offer the necessary data to the civil engineers. The purpose of the experimental tests was to determine the local pressure coefficients C_P distributions on the envelope of the SDT, necessary for an optimum design of the coating elements, and the aerodynamic forces coefficients $(C_x, C_y \text{ and } C_z)$ and the global aerodynamic momentum coefficients $(C_{M_x} \text{ and } C_{M_y})$ which act on the SDT.

2. SIMILITUDE CRITERIA

Based on the Navier-Stokes and continuity (mass conservation) equation and applying the Ruark transform yields, the similitude criteria (Euler, Reynolds and Froude) and therefore the similitude criteria for models with static response, namely Eu = idem. Re = idem. and Fr=idem. finally result.

Taking into account that the Froude similitude can be neglected in comparison with the Reynolds similitude and that this last assures the Euler similitude too, the only demanded condition is Re = idem. This condition is impossible to be accomplished for experimental measurements in the BLWT. Therefore, the correctness of the experimental tests was secured using the auto modeling phenomena with respect to the Reynolds criteria.

3. AERODYNAMIC BOUNDARY LAYER WIND TUNNEL. EXPERIMENTAL MODELS. MEASUREMENT EQUIPMENT

Experiments were performed on rigid models of the SDT, placed in the experimental zone of the BLWT belonging to the Aerodynamics and Wind Engineering Laboratory (AWEL) of the Technical University of Civil Engineering Bucharest.

This is an open circuit aerodynamic tunnel, with a long guided experimental vena. The BLWT is 27200 mm long with a 1750 x 1750 mm experimental vena cross section. The effective experimental zone is 20850 mm long and includes the simulated boundary layer forming zone, the experimental zone and the viewing zone. In this tunnel the boundary layer can be simulated as mean velocity profile and also as turbulent structure. The air flow inside the tunnel is produced with an axial fan driven by an electric motor with adjustable rotation speed, which ensures a velocity adjustment of the experimental vena at a desired value.

For the present experiments, by using of a BLWT it was created an atmospheric boundary layer mean velocity profile simulation at the scale of the studied models. This was made by placing obstacles on a sufficient length of the experimental zone to obtain the desired roughness respectively the mean velocity profile of the desired wind.

To express the mean velocity $U(z)$ with the altitude z, an empirical power law called Davenport's law was adopted:

$$U(z) = G\left(\frac{z}{\delta}\right)^{\theta}, \tag{1}$$

Where θ is Davenport's exponent, δ is the boundary layer thickness and G is the gradient wind velocity in the studied structure area. For the zone were the SDT structures will be placed, a Davenport's exponent $\theta = 0.23$ and a boundary layer thickness δ over 300 m were considered.

Figure 1 shows the mean velocity profile in the experimental zone of the BLWT, used in this case.

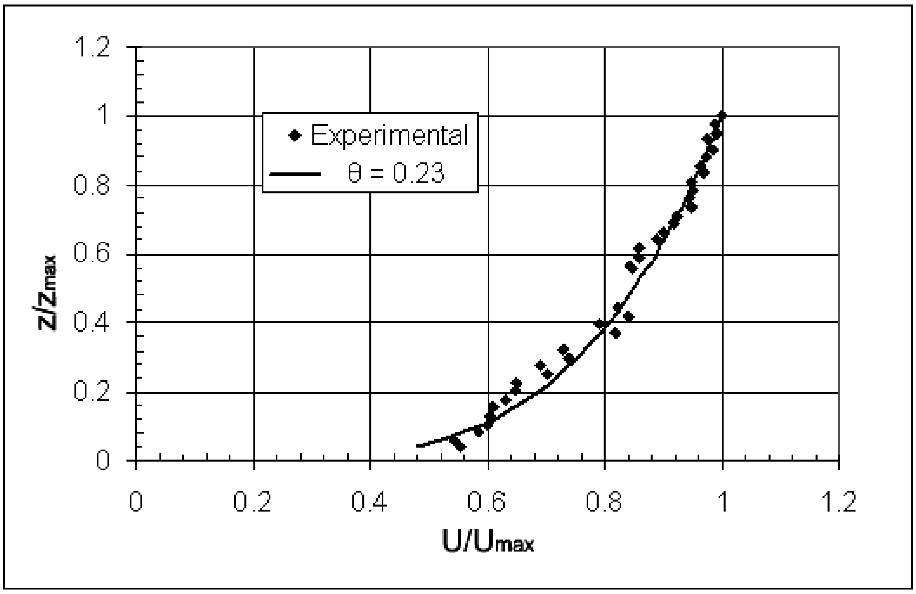

Figure 1 Mean velocity profile in the experimental zone of the BLWT

It is necessary to mention that this type of profile was adopted based on wind field measurements carried out by specialists from the Meteorology and Hydrology Department of the University of Bucharest in the SDT area.

The studies were performed for two types of models with static response, placed in the experimental vena of the aerodynamic wind tunnel. These models are:

– Individual SDT experimental model at a 1:100 scale (figure 2).
– SDT ensemble including the five tanks, the technological buildings and the access tower, at a 1:150 scale (figures 3).

Figure 2 Iindividual SDT - experimental model at 1:100 scale

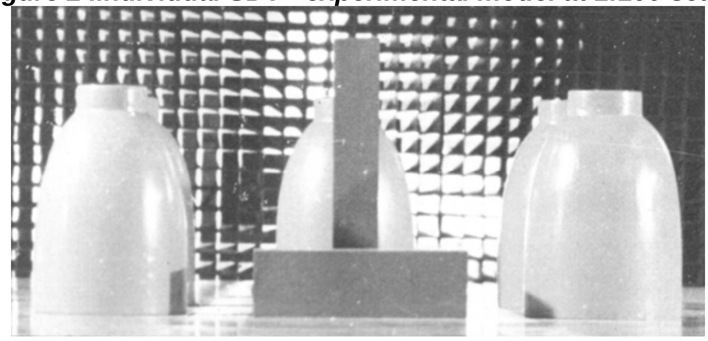

Figure 3 SDT ensemble - the five tanks, the process building and the access tower (1:150 scale)

The individual SDT model (figure 2) is an active one (provided with pressure taps on the lateral surface), with a base cross section diameter $D = 235\,mm$, a top cross section diameter $d = 107\,mm$ and a total high $h = 333.7\,mm$.

The model was provided with 40 pressure taps, placed on four generating lines, occupying a quarter of its lateral surface. The determination of the local pressure coefficients C_p in 160 points (denoted 1, 2…160) on the model surface, was made by rotating the model after the air stream direction.

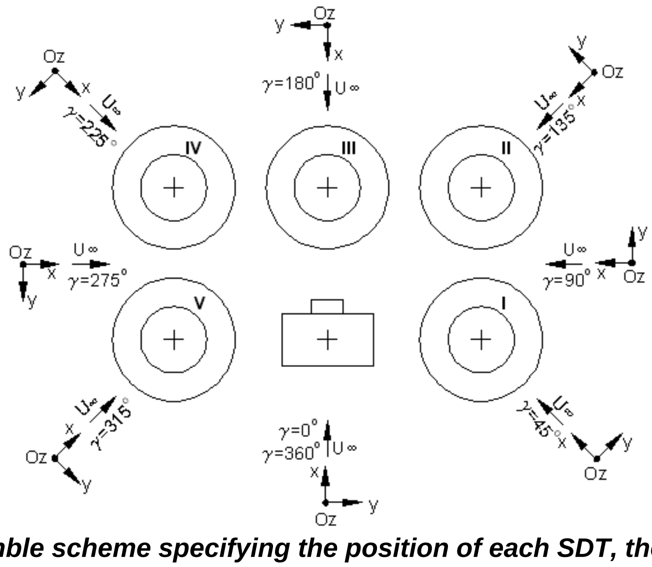

Figure 4 Modeled ensemble scheme specifying the position of each SDT, the other buildings and the wind-SDT incidence angles γ

The SDT ensemble (figures 3 and 4) consists of an active SDT model and four passive models (without pressure taps) and the passive model of the technological buildings and access tower. The active SDT model can be placed in all five positions of the ensemble (I, II, III, IV, and V). This model is provided with 40 pressure taps placed on eight generating lines (denoted 1, 2…40), occupying approximate uniform the entire lateral surface. The dimensions for each of the five SDT models of the ensemble are: $D = 156.6\,mm$, $d = 71.3\,mm$ and $h = 222.4\,mm$.

The pressure taps were coupled in groups to a SIMULTEC scanning valve with 48 gates. Two of them are reserved for the total pressure p_t and static pressure p_∞ measured with a Pitot-Prandtl tube placed upstream of the model (figure 5).

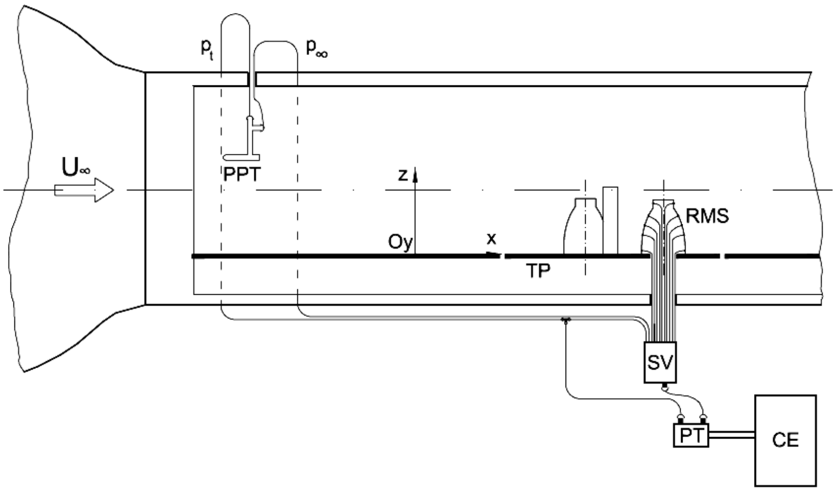

Figure 5 Experimental setup utilized for wind loads measurements on the SDT rigid models 1:150 placed in the BLWT-AWEL: PPT – Pitot-Prandtl tube; RMS – rigid model at reduced scale; SV - scanning valve; PT – pressure transducer; CE – computing equipment: p_t - total pressure; p_∞ – static pressure

After passing through a tap shifter the measured pressure are transmitted successively to the low pressure adapter of a differential transducer type AUTO TRAN model 600D – 011, with 0 and 1” Water Head measuring range. The total pressure p_t of the experimental vena upstream of the model measured by the total pressure tap of the Pitot-Prandtl tube is plugged at the high pressure lead-in of the device (figure 5).

4. EXPERIMENTAL TESTS

For both models (SDT 1:100 and 1:150) were developed tests used for determining local pressure p_{M} on the lateral surfaces of the model. Based on this measured values, the local pressure coefficients C_p were computed as follows (the index **M** refers to the model):

$$C_p = \frac{p_{\mathrm{M}} - p_{\infty,\mathrm{M}}}{\frac{\rho U_{\infty,\mathrm{M}}^2}{2}}, \tag{2}$$

Were $p_{\infty,\mathrm{M}}$ and $U_{\infty,\mathrm{M}}$ are the hydrodynamic pressure and the reference velocity upstream the model at a reference height.

Knowing the local pressure coefficients values C_{pi} on the lateral surface of a tank, by decomposing after the O x y z axe system attached to the air stream, results the $C_{p_{xy}}$ (in the O x y plan) C_{p_x}, C_{p_y} and C_{p_z} coefficients. With the aid of those local coefficients, integrating on the lateral surface A_{M}, the force and momentum aerodynamic coefficients can be computed using the following relationships:

$$C_x = \frac{1}{A_{\mathrm{M}}}\int_{A_{\mathrm{M}}} C_{p_x}\mathrm{d}A, C_y = \frac{1}{A_{\mathrm{M}}}\int_{A_{\mathrm{M}}} C_{p_y}\mathrm{d}A,\ C_z = \frac{1}{A_{\mathrm{M}}}\int_{A_{\mathrm{M}}} C_{p_z}\mathrm{d}A \tag{3}$$

$$C'_{M_x} = \frac{1}{A_{\mathrm{M}} R_{\mathrm{M}}} \int_{A_{\mathrm{M}}} C_p b_x \mathrm{d}A \,, C'_{M_y} = \frac{1}{A_{\mathrm{M}} R_{\mathrm{M}}} \int_{A_{\mathrm{M}}} C_p b_y \mathrm{d}A \,,\ C'_{M_z} = \frac{1}{A_{\mathrm{M}} R_{\mathrm{M}}} \int_{A_{\mathrm{M}}} C_p b_z \mathrm{d}A \qquad (4)$$

were C_x, C_y and C_z represents the drag, drift and lift coefficients, C'_{M_x}, C'_{M_y} and C'_{M_z} the momentum coefficients expressed with the lateral area A_{M} with respect to the Ox, Oy and Oz axes, R_{M} the base cross section ray of the SDT and b_x, b_y and b_z the corresponding moment arm of the elementary forces perpendicular to the lateral surface element $\mathrm{d}A$ related to Ox, Oy and Oz axes. The origin of the coordinate axes corresponds to the center of the bottom area. Using the projection of the tank $A_{p,\mathrm{M}}$ on a cross-cut plane of the air stream as a characteristic surface, by multiplying of the C'_M coefficients with the ratio $A_{\mathrm{M}}/A_{p,\mathrm{M}}$ results the mathematical expression of the momentum coefficients expressed with the projected area:

$$C_{M_x} = \frac{1}{A_{p,\mathrm{M}} R_{\mathrm{M}}} \int_{A_{\mathrm{M}}} C_p b_x \mathrm{d}A \,,\ C_{M_y} = \frac{1}{A_{p,\mathrm{M}} R_{\mathrm{M}}} \int_{A_{\mathrm{M}}} C_p b_y \mathrm{d}A \,,\ C_{M_z} = \frac{1}{A_{p,\mathrm{M}} R_{\mathrm{M}}} \int_{A_{\mathrm{M}}} C_p b_z \mathrm{d}A \qquad (5)$$

As a result of the fact that the auto modeling phenomena with respect to the Reynolds criteria is ensured, we can admit, with an acceptable error, that the values of the local pressure C_p, aerodynamic force coefficients $(C_x, C_y \text{ and } C_z)$ and aerodynamic momentum coefficients $(C_{M_x}\ C_{M_y} \text{ and } C_{Mz})$ determined on the model, are equal to those of the prototype structure, at natural scale.

Therefore the local pressure p_{N} values on the lateral surface of the real structure can be computed using the following relationship (the N index refers to the prototype):

$$p_N = C_p \frac{\rho U_{\infty,\mathrm{N}}^2}{2} = C_p \frac{\rho U_{10}^2}{2} \left(\frac{z_{U\,\infty,\mathrm{N}}}{10} \right)^{2\theta} \qquad (6)$$

were $U_{\infty,\mathrm{N}}$ is the wind velocity at the reference height corresponding those at real scale $z_{U_{\infty,\mathrm{N}}}$, and U_{10} is the standard velocity at 10 m above the ground, provided by the Meteorology and Hydrology Department of the University of Bucharest.

The aerodynamic forces and momentum which acts on the SDT prototype (**N**) can be computed using the aerodynamic force and momentum coefficients with the following formulas:

$$F_{x,\mathrm{N}} = C_x A_{p,\mathrm{N}} \frac{\rho U_{\infty,\mathrm{N}}^2}{2} \,,\ F_{y,\mathrm{N}} = C_y A_{p,\mathrm{N}} \frac{\rho U_{\infty,\mathrm{N}}^2}{2} \qquad (7)$$

$$M_{x,\mathrm{N}} = C_{M_x} A_{p,\mathrm{N}} R_{\mathrm{N}} \frac{\rho U_{\infty,\mathrm{N}}^2}{2} \,,\ M_{y,\mathrm{N}} = C_{M_y} A_{p,\mathrm{N}} R_{\mathrm{N}} \frac{\rho U_{\infty,\mathrm{N}}^2}{2} \,,\ M_{z,\mathrm{N}} = C_{M_z} A_{p,\mathrm{N}} R_{\mathrm{N}} \frac{\rho U_{\infty,\mathrm{N}}^2}{2} \qquad (8)$$

5. RESULTS

The tests have been made on both models (individual SDT model scale 1:100 and SDT ensemble scale 1:150) at various incidence angles γ which values are in the range of 0° to 360°. A number of 48 tests have been made, 8 of them for the SDT model scale 1:100 and 40 for the SDT model scale 1:150. Due to the fact that the SDT is an axial-symmetric structure, for the first model type, the experimental tests do not depend on the incidence angle. In the second case (SDT scale 1:150) the purpose of the tests was to determine the wind loads for each of the five tanks of the ensemble (I, II, III, IV, and V) at different incidence angles γ varying with 45° in a range between 0° and 360° (figure 4).

First of all in all foregoing cases there was determinate the local pressure coefficients C_p distributions on the lateral surface of the SDT. The values of those coefficients were plotted. The negative values of the coefficients represent underpressure and the positive one overpressure. To represent the local pressure coefficients C_p were used a vertical cross section of the SDT. Thus, for the 1:100 scale SDT model eight vertical characteristic cross sections were made and four vertical for each 1:150 scale SDT model. Figures 6 and 7 show some of those graphical representations. For the individual 1:100 scale model, figure 6 shows the local pressure coefficients C_p variation for two vertical cross sections. In case of the modeled SDT ensemble (scale 1:150) figure 7 shows the distributions of the C_p coefficients for two vertical cross sections both for the SDT I, and corresponding to an incidence angle $\gamma = 0^o$.

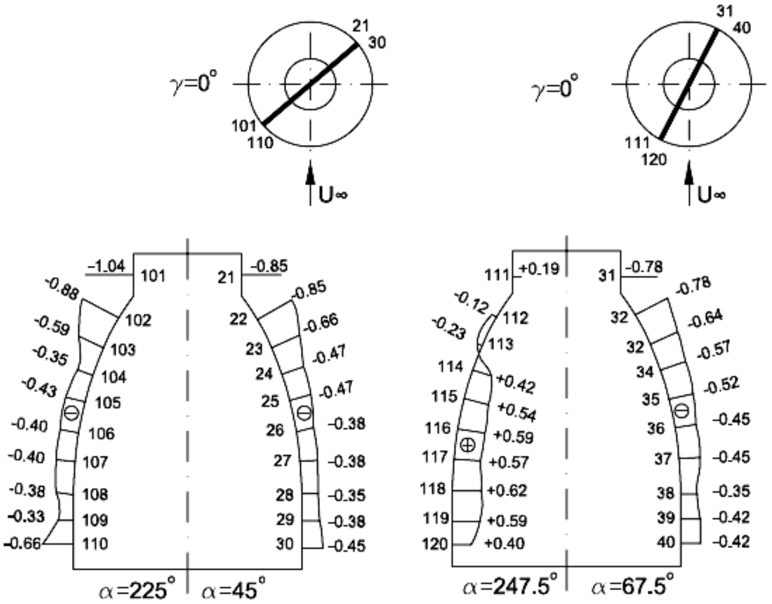

Figure 6 Vertical cross section plots of the local pressure coefficients C_p distributions for the single SDT 1:100 scale model

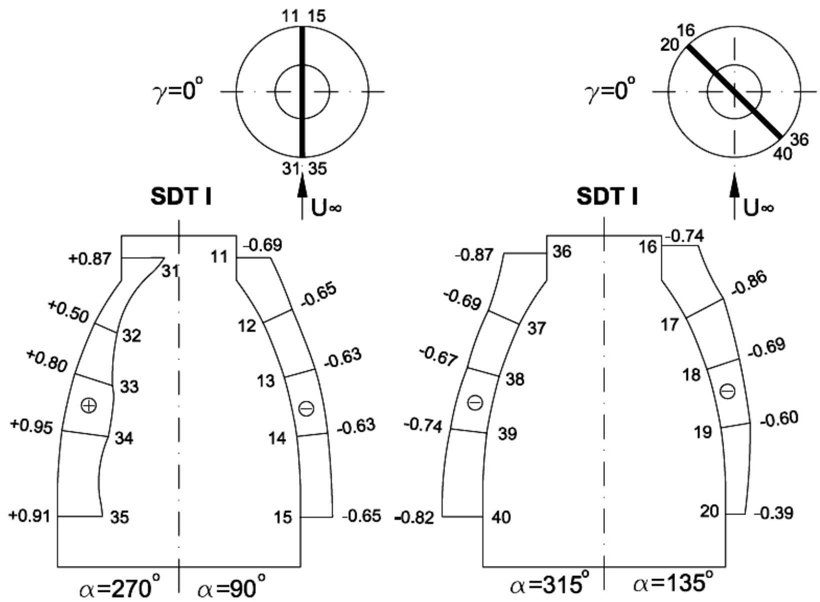

Figure 7 Vertical cross section plots of the local pressure coefficients C_p distributions for the active SDT I of the model ensemble 1:150 scale

The coefficients C_{p_x}, C_{p_y} and C_{p_z} were computed starting from the local pressure coefficients C_p values. Their sign corresponds to the chosen coordinate system $Oxzy$.
The aerodynamic force coefficients (C_x, C_y and C_z) and aerodynamic momentum coefficients (C_{M_x}, C_{M_y}) were computed aid the C_{p_x}, C_{p_y} and C_{p_z} coefficients and relationships (3) and (5) using a numerical integration method. For example the graphical representations of the aerodynamic force and momentum coefficients C_x and C_{M_x} variations with respect to the incidence angle γ for each of the five SDT of the ensemble (scale 1:150) are presented relative to the same values in the case of de individual SDT model (scale 1:100) in figures 8 and 9.

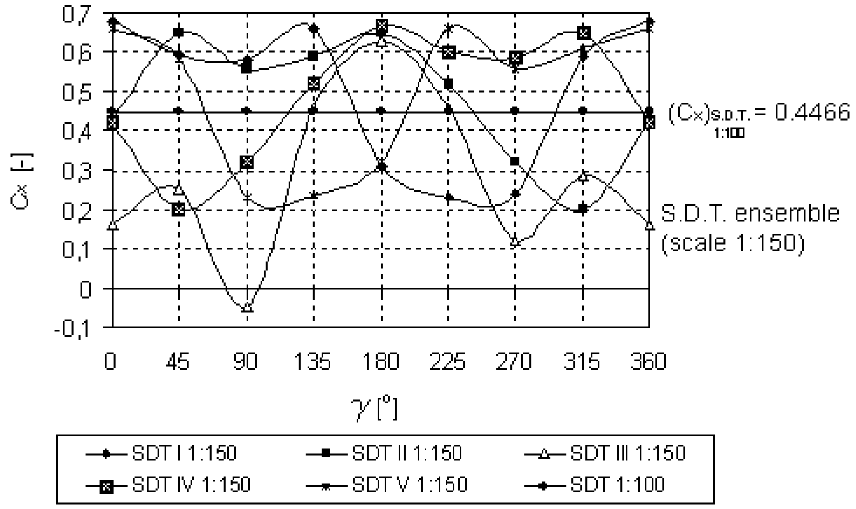

***Figure 8** Graphical representation of the aerodynamic drag C_x, coefficient variation with respect to the incidence angle γ and the SDT position in the ensemble*

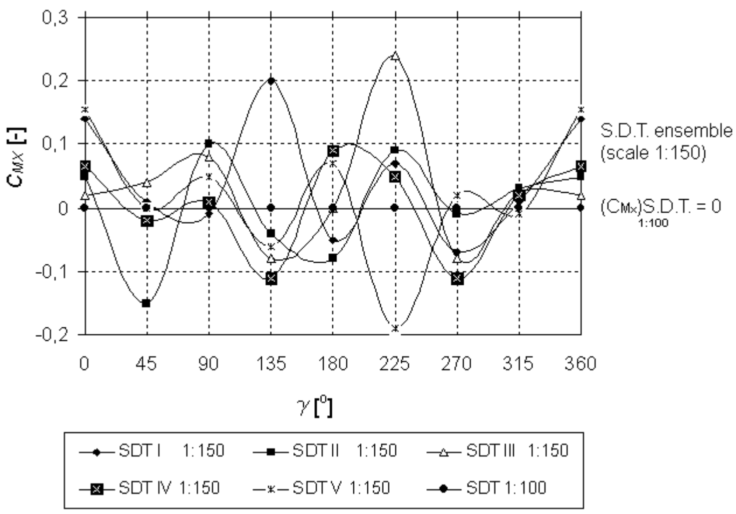

***Figure 9** Variation graph of the aerodynamic momentum coefficient C_{Mx} with respect to the incidence angle γ and the SDT position in the ensemble*

6. CONCLUSIONS

Based on the analysis of the experimental results the following conclusions concerning the pressure coefficients distribution and aerodynamic force and momentum coefficients values:

- the local pressure C_p coefficient distribution emphasizes the fact that on the greatest area of the lateral surface of the SDT the pressure coefficients have negative values excepting a relative small area located in the zone of the generating line placed in the air flow direction, were the C_p values are in general positive;
- C_p coefficient repartition shows that the greatest part of the coating elements is subjected to pulling out forces as a result of a suction effect. Thus, the designer must take care about these forces by the anchorage calculus. The other elements are subjected to pushing forces with an eventual distortion tendency;
- for the individual SDT model (1:100) the resulted C_p positive coefficients values (in the overpressure areas) are in the range between +0.19 and +0.97; the negative values of the C_p coefficients (underpressure areas) are between -0.12 and -2.62; in case of the modeled SDT ensemble the positive values of the C_p coefficients are between +0.02 and +0.98 and the negative one between -0.02 and -1.91;
- the negative pressure coefficients C_p distribution on the lateral area of the single SDT model (1:100) is more unfavourable that those on the SDT model placed in the ensemble (1:150); the selected computing values from the obtained results for the first model are secured;
- based on the analysis of the aerodynamic force and momentum coefficients resulted values, the conclusion is that by performing of the structural design taking into account the additional loads generated by the wind on the entire surface of the SDT, it is proper to use the results obtained for the SDT ensemble (1:150) those are unfavourable in the most of the cases comparing to those obtained in the case of a single SDT (1:100) model.

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