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EXPERIMENTAL RESEARCH ON DETERMINATION OF DRAG COEFFICIENT OF THE GREENHOUSES LOCATED ON ROOFS OF BUILDINGS

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Abstract: *This paper presents the results of the experimental research carried out on the drag aerodynamic forces and on total drag coefficients of five models of greenhouses under the wind action. The five models have equal base surfaces and heights, but differ in terms of their forms, the number of slopes and angles of the roofs' slope. The research was conducted at different values of the speed of the wind such as 10, 15, 20, 25, 27.5 and 30m/s, and under its frontal and lateral directions on the greenhouses.*

Key words: *drag aerodynamic force, drag coefficient, greenhouses on rooftops, wind.*

1. Introduction

An important component of the concept of 'green city' refers to the cultivation of plants on the roofs and balconies of buildings in major cities in order to improve the quality of the air and to give a more human aspect of these cities [3]. A solution which is lately used more frequently consists in the location of greenhouses on the roofs of old and new buildings. Thus, flowers, vegetables or ornamental shrubs not only contribute to the environment protection but also have an economic effect and can benefit the residents of those buildings [7], [8]. When designing these constructions should be taken into account not only the urban regulations, but also their resistance to the mechanical stresses provoked by the climatic factors such as wind, snow and rain. Many universities from the US and Canada, but also from Japan and China [9], [10], [12], [13] are undertaking ample researches regarding the greenhouses located on the tops of buildings. In Europe such kind of research is in its early stages, and some projects developed in Romania are considering the protection and cleanliness of green spaces in cities alongside encouraging people to cultivate ornamental plants on the balconies and terraces of buildings.

Most of the researches refer to the

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variety of the cultivated plants, the materials used for the construction of the greenhouses' floors and superstructures, and the ways of ensuring the plants' growing factors such as light, heat, water, air, nutrients, etc. The mechanical solicitations faced by these buildings so that they are safe at a light weight, but also at the action of any natural phenomena are less studied nowadays [5].

The general guide which is used by all the designers of such greenhouses in Romania is called 'Design code: Evaluation of the action of wind on buildings', indicative CR 1-1-4 / 2012 [17]; it stipulates to technical regulations in this area. The designed features of the greenhouses located on rooftops justify the need of further research such as those undertaken in this paper so that their functionality and safety to be at a high level. Of great interest in this sense is the knowing of the coefficient of aerodynamic drag of a large number of constructive models of greenhouses that could be located on the roofs of many buildings in large cities [17].

The drag concept in the context of fluid dynamics refers to forces that act on a solid object in the direction of the relative flow velocity (note that the diagram below shows the drag in the opposite direction to the flow) [11]. The aerodynamic forces on a body come primarily from differences in pressure and viscous shearing stresses. Thereby, the drag force on a body could be divided into two components, namely frictional drag or viscous drag and pressure drag or form drag. The net drag force could be decomposed as follows (Figure 1). Flow across an aerofoil showing the relative impact of drag force to the direction of motion of fluid over the body. This drag force gets divided into frictional drag and pressure drag. The same aerofoil is considered as a streamlined body if friction drag or viscous drag dominates pressure drag and is considered a bluff body when pressure drag or form drag dominates friction drag.

The aerodynamic drag force F_d is defined by the formula (1):

$$F_d = \frac{1}{2} \cdot \rho \cdot c_d \cdot A \cdot v^2 \tag{1}$$

where: ρ is the density of air, kg/m^3; A – the area of the building exposed to the wind, m^2; c_d – the overall aerodynamic drag coefficient of building under the wind action; v - wind speed, m/s.

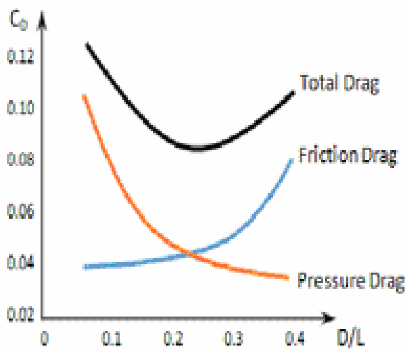

Fig. 1. *Trade-off relationship between pressure drag and friction drag* [1]

In turn, the c_d can be written as (2) [11]:

$$c_d = \frac{2F_d}{\rho v^2 A} = c_p + c_f = \underbrace{\frac{1}{\rho v^2 A} \int_S (p - p_o).\hat{n}.\hat{\imath} dA}_{c_p} + \underbrace{\frac{1}{\rho v^2 A} \int_S T_w.\hat{t}.\hat{\imath} dA}_{c_f} \tag{2}$$

where: c_p is the pressure drag coefficient; c_f - the friction drag coefficient; t – the tangential direction to the surface with area dA; n – the normal direction to the surface *dA*; T_w - the shear stress acting on the surface *dA*; p_0 - the pressure far away from the surface *dA*; *p* - the pressure at surface *dA*; *i* - the unit vector in the normal direction to the surface *dA*, forming a unit vector *dA* [11].

Therefore, for the experimental determination of the global coefficient of aerodynamic drag of the buildings must be computed: the amount of down force wind, *Fd*; the surface area of the model to the direction of action of the wind, *A*; the speed of wind, *v* and density of air, *ρ*.

2. Materials and Methods

The materials used in this experimental research are:

• Five models of greenhouses of equal base surfaces and heights, but of different number of roof slopes and angles which form these slopes (Figure 2) [1], [2]. The geometrical characteristics of these models are presented in Table 1.

Fig. 2. *The models used for the experimental researches*

The notations in Table 1 have the following meanings: α_1 - the angle of main slopes of the roof, °; α_2 - the angle of front slopes of the roof, °; A_b – the base surface, cm^2; *H* – the height of model, *cm*; *V* – the internal volume of greenhouse model, cm^3; A_{fv} – the front vertical surface, cm^2; A_{fac} – the front roof surface, cm^2; A_{lv} – the lateral vertical surface, cm^2; A_{lac} – the lateral roof surface, cm^2; A_t – the total area of greenhouse's superstructure, cm^2.

• The aerodynamic tunnel HM 170 Educational Wind Tunnel which is manufactured by G.U.N.T. Gerätebau GmbH; it was used for measuring the pressing forces on the greenhouse models at different wind speeds (Figure 3) [6].

The aerodynamic tunnel is a subsonic wind tunnel with open circuit, air speed up to Mach 0.1; the air is taken from outside and expelled all outside, with increased speed.

Fig. 3. *The Wind Tunnel* [6]

The geometrical characteristics of models used for the experimental researches Table1

Model no.	α_1 [°]	α_2 [°]	A_b [cm^2]	H [cm]	V [cm^3]	A_{fv} [cm^2]	A_{fac} [cm^2]	A_{lv} [cm^2]	A_{lac} [cm^2]	A_t [cm^2]
1.	110	-	400	20	6600	330	-	260	240	1660
2.	120	-	400	20	7000	350	-	300	220	1740
3.	90	-	400	20	6000	300	-	200	280	1560
4.	115	120	400	20	5600	250	80	250	180	1520
5.	100	100	400	20	5200	250	120	250	120	1480

Figure 4 shows the structure of the wind tunnel, which allows determining the ways in which forces that are exerted by the wind on the surfaces of various corps are measured, in this case the front and lateral surfaces of the five models of greenhouses.

The experimental model 1 is fastened to the measurement section 2. The air is absorbed into the tunnel from the feeding hopper 5 and a laminar flow is ensured through the section 4 (any transverse components of air flow are reduced to zero). The laminar flow of the air is accelerated by approximately 3.3 times in section 3. In section 6 of the tunnel the deceleration of the air speed is performed and after that the air is given out through the fan 7 [4].

The measurement of the forces is achieved through the force transducer 8, which is integral with the experimental mode 1 (Figure 4) [6]. Through this transducer the measurements inside the tunnel can be made after 2 directions, drag and lift regarding: forces, speeds, pressures, pushing aerodynamic coefficient (drag) and lift aerodynamic coefficient (elevator). The measured values of the forces are displayed on the screen of the amplifier 9 (Figure 5).

The speed of the air in the measurement section 2 can be read on the inclined manometer tube 10. The control panel 11 contains a main switch ON/OFF power supply, emergency stop button, a button for adjusting the air flow (converter in frequency) and an ON/OFF commutator of the fan [6].

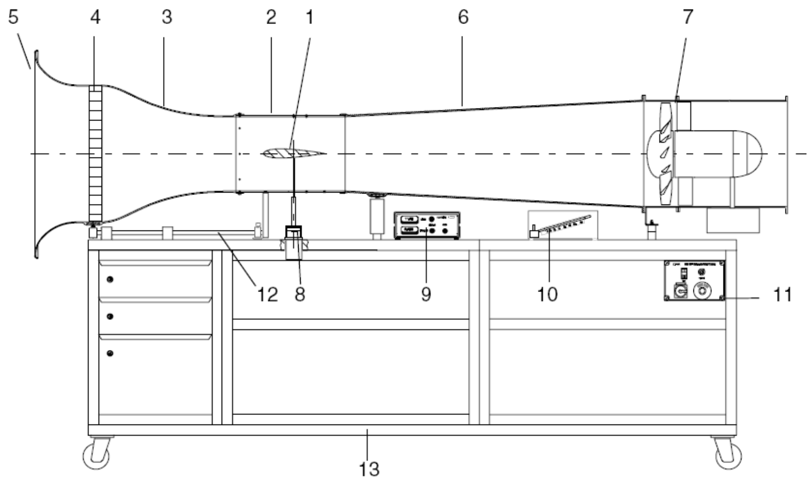

Fig. 4. *The structure of aerodynamic wind tunnel* [6]

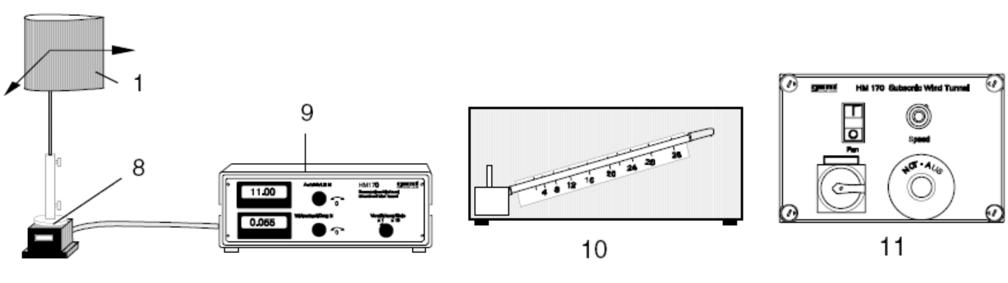

Fig. 5. *The measurement system with manometer tube and control panel* [6]

The rail 12 allows the displacement of lateral wall of measurements section and the access to the inside part of the section. The system is placed on the frame 13, provided with a roller.

• Thermal anemometer with probe for measuring the speed of the wind (Figure 6).

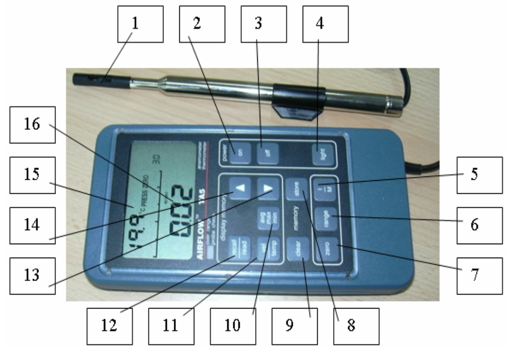

Fig. 6. *The thermal anemometer* [6]

Thermal anemometer has the following features: 1 - a type strain gauge sensor; 2 - ON button; 3 - OFF button; 4 – a button of screen light; 5 – a button for computing the average value measured; 6 – a setting button of the measurement unit; 7 – a button for calibration; 8 – a memory button; 9 – a delete button of the stored values; 10 – a button to display the minimum, maximum, average measured and activation button ON; 11 – a button to display the measured temperature; 12 – a button to display the measured wind speed; 13 – a scroll down button; 14 – a button scroll up; 15 – a measured temperature value displaying; 16 – a measured wind speed value displaying.

Aerodynamic models for which a force measurement is to be performed must have a model holder with a shaft diameter of *Ø4 mm*. To obtain the correct lever arm for the force measurement, the length of the holder should be 190 mm measured from the centre of the model. This simultaneously positions the model in the centre of the measurement section (Figure 7).

Before inserting model in two-component force transducer, set angle scale to zero. Insert model and carefully secure with upper knurled screw. In doing so set model to a distance of exactly 302 mm between centre of bending beam and centre of model. The force measuring device is calibrated to this lever arm.

Fig. 7. *The device for fixing of normalized stem in greenhouses models*

Set desired angle of attack by loosening the - lower knurled screw and turning the angle scale. Re-tighten knurled screw. Other models and devices, such as instability model for aerofoils, models for investigating boundary layers or different measurement probes can be attached to the holes in the measurement section.

Lever arms other than a = 302 *mm* involve correction of the displayed force F as shown in the relation (3):

$$Fcor = F\frac{302}{a} \quad (3)$$

with a in *mm*, and $F_{cor} = F_d$.

3. Results and Discussions

The results obtained in measuring of the drag forces F in the case of the five greenhouses models, at wind speeds of 10, 15, 20, 25, 27.5 and 30 m/s, in case it acts on the front and lateral directions of the greenhouses are presented in Table 2 (front) and Table 3 (lateral).

Table 4 and Table 5 presents the values of aerodynamic drag forces corrected according to the equation (3).

With $T = 18°C$, $p = 1026$ *mbar* and a relative humidity level of 60%, the air density is 1.225 kg/m^3. The drag coefficient can be thus calculated by using the formula (2). The results are presented in Tables 6 and 7, on the two directions of the action of the wind.

These values are comparable to the values found in the literature [17].

It is found that in case of the front action of the wind, the lower drag coefficients are registered at the models no. 4 and no. 5; at these models the roof consists of four slopes, compared with the models in which the roof is formed by two slopes. To the lateral action of the wind, the lower drag coefficients are registered at the models no. 2 and no. 3; in these cases the roof consists of two slopes.

The values of drag forces recorded to the front action of the wind, N Table 2

Model\ Wind speed	10 [m/s]	15 [m/s]	20 [m/s]	25 [m/s]	27.5 [m/s]	30 [m/s]
1	2.0	4.5	5.8	6.6	7.2	8,0
2	2,0	4.3	5.7	6.6	7.2	7.9
3	1.8	3.9	5.9	6.5	6.9	7.6
4	1.7	3.5	5.1	6.3	6.5	7.2
5	1.7	3.7	5.6	6.4	6.8	7.6

The values of drag forces recorded to the lateral action of the wind, N Table 3

Model\ Wind speed	10 [m/s]	15 [m/s]	20 [m/s]	25 [m/s]	27.5 [m/s]	30 [m/s]
1	2.5	5.5	6.3	7.5	8.1	8.9
2	2.6	5.3	6.2	7.3	7.9	8.8
3	2.3	5.0	5.9	6.9	7.6	8.5
4	2.0	4.3	5.7	6.7	7.2	8.0
5	1.7	3.7	5.6	6.4	6.8	7.6

The corrected values of drag forces to the front action of the wind, N Table 4

Model\ Wind speed	10 [m/s]	15 [m/s]	20 [m/s]	25 [m/s]	27.5 [m/s]	30 [m/s]
1	4.0	9.0	11.6	13.2	14.4	16.0
2	4,0	8.6	11.4	13.2	14.4	15.8
3	3.6	7.8	11.8	13.0	13.8	15.2
4	3.4	7.0	10.2	12.6	13.0	14.4
5	3.4	7.4	11.2	12.8	13.6	15.2

The corrected values of drag forces to the lateral action of the wind, N Table 5

Model\ Wind speed	10 [m/s]	15 [m/s]	20 [m/s]	25 [m/s]	27.5 [m/s]	30 [m/s]
1	5.0	11.0	12.6	15.0	16.2	17.8
2	5.2	10.6	12.4	14.6	15.8	17.6
3	4.6	10.0	11.8	13.8	15.2	17.0
4	4.0	8.6	11.4	13.4	14.4	16.0
5	3.4	7.4	11.2	12.8	13.6	15.2

The values of the drag coefficients at the front action of the wind Table 6

Model\ Wind speed	10 [m/s]	15 [m/s]	20 [m/s]	25 [m/s]	27.5 [m/s]	30 [m/s]	Average value
1	1.98	1.98	1.44	1.05	0.94	0.88	**1.38**
2	1.87	1.78	1.33	0.99	0.89	0.82	**1.28**
3	1.96	1.89	1.60	1.13	0.99	0.92	**1,41**
4	1.68	1.54	1.26	1.00	0.85	0.79	**1.19**
5	1.50	1.45	1.24	0.90	0.79	0.75	**1.10**

The values of the drag coefficients at the lateral action of the wind Table 7

Model\ Wind speed	10 [m/s]	15 [m/s]	20 [m/s]	25 [m/s]	27.5 [m/s]	30 [m/s]	Average value
1	1.63	1.60	0.98	0.78	0.70	0.65	**1.05**
2	1.63	1.48	0.97	0.74	0.66	0.62	**1.02**
3	1.56	1.51	1.00	0.75	0.68	0.64	**1.02**
4	1.51	1.45	1.08	0.81	0.72	0.68	**1.04**
5	1.50	1.45	1.24	0.90	0.79	0.75	**1.10**

4. Conclusions

1. According to the 'Code of design. Evaluation of the action of wind on buildings, indicative CR 1-1-4/ 2012', in order to evaluate the action of the wind on buildings and their reactions can be used as well the results of tests in the wind tunnel and/ or numerical methods, using adequate models of the buildings and actions of the wind. Also, in order to conduct experimental tests in the wind tunnel, the wind action must be modelled as such the profile of the average speed of the wind and the turbulence characteristics in the location of the construction to be respected. These requirements have been fully met in this paper.

2. The models of greenhouses that can be placed on the roofs of buildings have such forms that take into account the existence of the real buildings in different parts of the world. Depending on the local climatic characteristics and crop needs, the model that best satisfies those needs can be chosen.

3. The aerodynamic drag coefficient at the action of the drag forces at different speeds of the wind has higher values in the case of the frontal action of the wind (1.41...1.10), compared to the situation in which the wind acted in the lateral direction (1.10...1.02). On the frontal direction, the vertical walls are predominant, while on the lateral direction the roof surfaces have a significant share.

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