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A PROCEDURE FOR EVALUATING NATURAL VENTILATION POTENTIAL OF URBAN SITES

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ABSTRACT

This paper describes synthetically the work carried out by the Polytechnic University of Turin within the CE-funded Research *Project PRECis*, aimed at evaluating the effect of urban form on heating and cooling energy saving potential. A sensitivity analysis based on the parameter *urban wind pressure drag* was performed using the thermal simulation program ESP-r. The methodology used and a first set of results are presented.

KEYWORDS

Theoretical annual energy saving potential; thermal urban factor; drag coefficient; ventilation urban score.

INTRODUCTION

The contribution of Polytechnic University of Turin within the European Research *Project PRECis* (Assessing the Potential for Renewable Energy in Cities) is specifically oriented to evaluate the effect of urban form on the *Theoretical Annual Energy Savings Potential ($TAESP_{nv}$)* due to wind-driven natural ventilation in buildings.
The present paper describes an excerpt of the work carried out related to the effect of varying urban *drag coefficient* on airflow rates as well as on *energy loads* (winter thermal losses through air infiltration and summer cooling load reduction by opening windows). Five locations, representing a typical climate variation range for Europe, from N-W to S-E, were chosen as references.
The effect of the interaction between wind and urban form geometry on the heating and cooling energy loads of buildings was evaluated using the multi-zone thermal program *ESP-r* and the model *$CpCalc_{urban}$*.

DEVELOPMENT OF A PROCEDURE FOR EVALUATING THE VENTILATION POTENTIAL OF URBAN SITES

A procedure for evaluating wind driven ventilation potential of buildings in urban areas was developed considering the following phases:

a) calculation of urban form parameters such as *plan area density (PAD),* average building dimensions, wind-facing projected frontal area, azimuth and aspect ratio, from 2-D graphical or digital representation using NIH's imaging-processing program (Grosso, M., Giordano, R., et Al., 2000);

b) development of the model *$CpCalc_{urban}$*, extension of *$CpCalc^{+}$* (Grosso, M., 1992), aimed at calculating the *drag coefficient C_d* (Parisi E., D'Elia I., 2000) of urban areas. C_d was used to define the influence of the above described urban form parameters as well as of environment characteristics such as wind velocity and direction, and terrain roughness, on the wind pressure drag and, hence, on airflow through buildings;
c) regression analysis of data from ESP-r simulations, aimed at evaluating the thermal effect of urban drag for selected reference zones;
d) definition of a *Ventilation Urban Score (VenUS)* characterizing an urban area in terms of annual net saving potential due to natural ventilation.

Thermal simulation

A first set of simulations was carried out on a monozone cube-shaped building cell – volume 27 m³ (dimensions: 3×3×3 m) – with equal openings of 1 m² size on the opposite walls facing the wind direction (see Fig. 1).
Input envelope characteristics were: walls made of a 25 cm thick full brick layer with 4 mm plaster on each side; single glass windows; horizontal concrete floor and roof, three types of insulation (U-value = 1.5, 0.76, and 0,4 W/m²K) and two levels of air leakage characteristics (crack thickness of 0.5 and 3 mm).
The airflow network was composed of three nodes (one internal and two external, on the north and south sides), located at 1.5-m height from the floor, and the two relevant connections through the windows. Wind direction was measured clockwise from the north axis.
Five locations were simulated for the coldest day – Trondheim, London (Kew), Turin, Catania, and Athens. An analogous procedure was followed for the hottest day on the same locations, except Trondheim. ESP-r and Meteonorm climate input reference data were used, changing the values related to wind velocity in order to perform the parametrical analysis. Constant direction (0° N) and four wind velocities (0.5, 1, 2, and 3 m/s) were considered.
The following controllers were set to calculate energy loads:

- closed windows all day in winter for all considered locations (air leakage through cracks of 0.5-mm × 4-m, and 3mm × 4 m, for each window);
- windows totally open in Turin, Catania, Athens, and 50% open in London, when external temperature is lower than the summer set-point temperature;
- summer and winter set-point temperatures, respectively, of 26 and 19 °C.

Internal gains (30 W/m² in Turin and 50 W/m² in London, since no cooling load was detected for lower values) were also considered for the summer period in order to highlight the cooling contribution of natural ventilation, particularly in climates where external temperatures are almost always below the summer set-point temperature even in the hottest day (London).

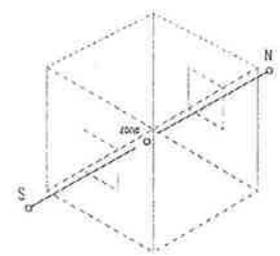

Fig.1. Reference building cell

An analogous set of simulations was performed on a 12 m-side 4-storeys cube-shaped building with 1728 m³ of total volume, comprising 8 double-zone cells, each with equal openings of 1 m² size on the opposite walls facing the wind direction. Envelop characteristics and types of insulation as well as wind direction are the same as for the monozone simulation. The cell airflow network is composed of four nodes, two internal (one for each zone) and two external (one on the north, and the other on the south side).

Oblique wind (45°) was also considered for one location in order to check the influence of C_d on single side ventilation.

Analysis of results

Among the various airflow and thermal parameters that could be correlated to the drag coefficient as a dependent variable, two parameters – one for airflow, the other for thermal effect - were chosen in order to represent synthetically the variations generated by urban form:

- *ACH = Air volumes Changed per Hour*, averaged within 24 hours in winter, and for the number of hours with open windows, in summer (summer natural ventilation rates are expressed in ACH/m² of net open area, as winter infiltration rates could be given in ACH/m of crack length);
- TUF_{nv} = *Thermal Urban Factor*, defined as the thermal flux generated by natural ventilation per degree-hour and floor square meter [W/(dh m²)], divided in a $TUF_{nv(H)}$, when referred to air infiltration winter losses, and $TUF_{nv(C)}$, when related to summer cooling load, respectively calculated as follow:

$$TUF_{nv\,(H)} = \frac{TL_{inf}}{dh_{ref\,(H)}} \qquad [W/dh_{(H)}m^2] \qquad (1)$$

$$TUF_{nv\,(C)} = \frac{CE_{ow}}{dh^*_{ref\,(C)}} \qquad [W/dh_{(C)}m^2] \qquad (2)$$

Where TL_{inf} = thermal losses due to air infiltration for the coldest day;

CE_{ow} = cooling energy at open window for the hottest day;

$dh_{ref(H)}$ = heating degree hours for the coldest day = $\sum_{1}^{24}(19-Te)^+$

$dh_{ref(C)}$ = cooling degree hours for the hottest day = $\sum_{1}^{24}(Te-26)^+$

$dh^*_{ref(C)}$ = corrected in order to take the degree-hours during ventilation into account = $dhref_{(C)} / \sum_{1}^{hnv}(26-Te)^+$

Te = outdoor air temperature.

An analysis of the monozone simulation results regarding *winter conditions* is reported in the following section. $TUF_{nv(H)}$, and ACH values were found to be very close in all locations, for each wind velocity, as expected. Thus, location-averaged values, related to the higher air leakage characteristics, were chosen as references (Table 1 and Fig. 2a and 2b). As expected, data and fittings show an increase in airflow rate and thermal losses with drag coefficient, e.g., with decreasing plan area density. The correlation is represented by a power law function and the rate of increase is progressively higher in relation to growing wind velocities.

$TUF_{nv(H)}$ values are fairly small, even for a relatively high leakage parameter as the one on which data shown in Table 1 are based. However, the seasonal thermal losses due to infiltration could become significantly high, even in moderately cold winter zones with yearly heating degree-hours around 60,000 as in Turin. In such zones, as can be derived from Table 1, overall theoretical, i.e., referred to a constant wind velocity along the entire period, winter thermal losses might range from 0.9 kWh/m², in high-density urban areas with low wind velocity (0.5 m/s), to 39.36 kWh/m², in isolated building with moderately high wind speed (3 m/s). Furthermore, thermal simulation included calculation of the shading effect due to the obstruction factor; which was found to be increasingly influential for value of pad ≥ 25.

As far as airflow rates were concerned, data show that only in practically isolated buildings and at v ≥ 3 m/sec, the minimum air change per hour for residential indoor air quality (ACH = 0.5) could be reached (Table 1).

Table 1. Heating Thermal Urban Factor and Air Changes per Hour for various wind velocities, PAD, and Cd (location-averaged values); U value = 0,76 W/m²K; 3 mm crack thickness as air leakage parameter.

Pad	Drag Coefficient	TUF NV(H) [W/dh m2]				ACH [V/h]			
		Wind velocity (m/sec)							
		0.5	1	2	3	0.5	1	2	3
0	1.125	0.072	0.170	0.398	0.656	0.064	0.151	0.351	0.577
2.8	0.901	0.063	0.150	0.348	0.573	0.059	0.132	0.309	0.503
4	0.811	0.059	0.139	0.325	0.537	0.052	0.117	0.291	0.474
6.25	0.658	0.055	0.124	0.288	0.472	0.047	0.109	0.254	0.415
11.2	0.398	0.038	0.091	0.210	0.345	0.033	0.079	0.187	0.308
16	0.241	0.030	0.065	0.155	0.251	0.026	0.056	0.137	0.225
25	0.122	0.023	0.045	0.103	0.165	0.019	0.039	0.090	0.143
30	0.102	0.022	0.040	0.093	0.152	0.018	0.036	0.082	0.132
35	0.082	0.019	0.036	0.081	0.132	0.014	0.032	0.072	0.117
40	0.044	0.015	0.024	0.055	0.090	0.012	0.021	0.049	0.079

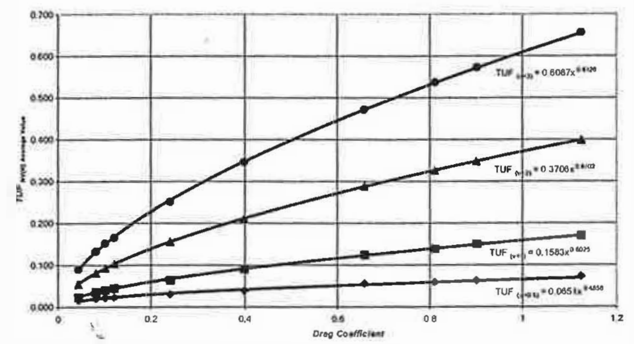

Figure 2a. Fitting curves of location-averaged TUFnv(H) as a function of Cd, for various wind velocities .

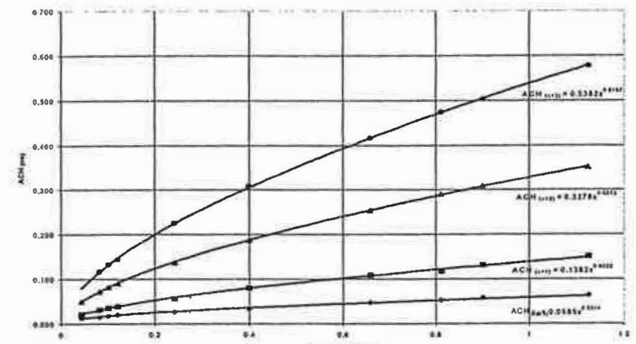

Figure 2b. Fitting curves of location-averaged winter ACH (closed windows) as a function of Cd, for various wind velocities.

With regard to *summer conditions,* thermal simulations (no internal gains) were analysed for three locations (Turin, Catania, Athens). Both reference cooling load (Cl_{ref}, windows closed all hours of the hottest day) and $TUF_{nv(C)}$ – normalised, respectively, to the cooling degree-hours and the cooling degree-hours corrected (see eq. 2) – for the considered locations were averaged, being of the same order of magnitude (Table 2). Given the negligible influence of infiltration and convective wall exchange on the overall cooling loads, Cl_{ref} values were averaged amid all wind velocities as well.

For the same reason, as Table 2 shows, the variation of C_d does not affect Cl_{ref}, which, instead, decreases slightly in relation to the effect of shading for C_d < 0.25 (PAD > 16%).

$TUF_{nv(C)}$ values increase with decreasing C_d, e.g., increasing PAD, following an exponential fitting trend which is dependent on wind velocity. As Fig. 3a shows, this trend, strongly apparent at $v = 0.5$ m/s, declines progressively with increasing wind velocity and almost disappears at $v = 2$ m/s, while is even reversed at $v =$ 3 m/s meaning that the shading effect over-compensates the decreased airflow rate. Hence, $v = 2$ m/s can be considered a threshold wind velocity above which the effect of *urban drag*, i.e., of urban form, becomes non-influential on potential cooling energy savings due to ventilation.

Table 2. Cooling Thermal Urban Factor and Air Changes per Hour for various wind velocities, PAD, and Cd (location-averaged values); U value = 0,76 W/m²K; 3 mm crack thickness as air leakage parameter

Pad	Drag Coefficient	Cl_{ref} [W/dh m²]	$TUF_{NV(C)}$ [W/dh m²]				ACH [V/h]			
			Wind velocity (m/sec)							
			0.5	1	2	3	0.5	1	2	3
0	1.125	23.853	5.575	5.059	4.617	4.418	16.422	31.704	65.462	98.270
2.8	0.901	23.853	5.738	5.178	4.617	4.418	14.657	28.375	58.520	87.882
4	0.811	23.853	5.738	5.178	4.617	4.418	13.892	27.064	55.550	83.372
6.25	0.658	23.853	5.857	5.135	4.617	4.418	12.498	24.240	51.067	75.098
11.2	0.398	23.853	6.099	5.298	4.736	4.375	9.732	19.448	40.095	58.361
16	0.241	23.853	6.424	5.460	4.816	4.495	7.559	14.228	30.234	45.435
25	0.122	22.877	6.584	5.415	4.772	4.411	5.348	10.441	21.538	32.306
30	0.102	22.504	6.663	5.415	4.729	4.368	4.911	9.546	19.687	29.538
35	0.082	22.179	6.706	5.454	4.689	4.368	4.401	8.565	17.664	26.481
40	0.044	21.891	7.107	5.557	4.772	4.368	3.225	6.265	12.937	19.398

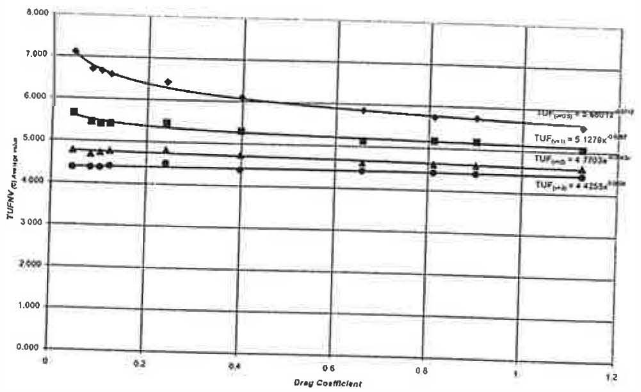

Figure 3a. Fitting curves of locations-averaged TUFnv(C) as a function of Cd, for various wind velocities .

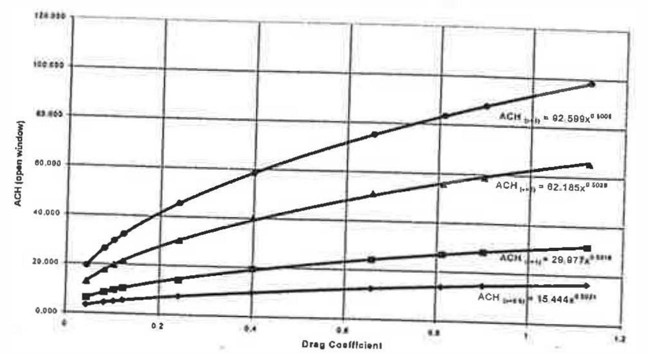

Figure 3b. Fitting curves of location-averaged summer ACH (open windows) as a function of Cd, for various wind velocities.

Comparison between Cl_{ref} and $TUF_{nv(C)}$ allows for deriving the cooling energy savings corresponding to different C_d values.

Similarly to winter infiltration, but, obviously, with much higher absolute values, airflow rates through open windows increase progressively with urban drag and wind velocity (Fig. 3b).

VENUS PROCEDURE

The proposed *VenUS* procedure is aimed at assigning a score related to wind driven natural ventilation potential, to the form configuration of an existing or planned urban area.

A two-step sequence is foreseen:

- calculation of the *Theoretical Annual Energy Saving Potential ($TAESP_{nv}$)* due to wind driven natural ventilation for a considered area;
- assignment of a Ventilation Urban Score (*VenUS*) on the basis of a classification of $TAESP_{nv}$ values.

The $TAESP_{nv}$ of a given urban form represent the annual net energy savings, i.e., cooling savings balanced with heating losses, based on hourly temperature reference data (hottest and coldest days of a typical year) and averaged annual wind velocity of the considered location.

$TAESP_{nv}$ is a wind drag related factor based on the analysis above described and can be calculated by the following expression:

$$TAESP_{nv} = \left[(CL_{ref} \times Dh_{(C)}) - (TUF_{nv(C)} \times Dh^*_{(C)})\right] - \left[TUF_{nv(H)} \times Dh_{(H)}\right] \quad (3)$$

Where $CL_{(C)}$ = the cooling load at closed window [W/(dh•m²)];
TUF = thermal urban factor as above defined ;
$Dh_{(H)}$= annual heating degree hours of the considered location;
$Dh_{(C)}$ = annual cooling degree hours of the considered location
$Dh^*_{(C)}$ =annual cooling degree hours corrected in order to take the amount of ventilation hours into account , eq. (2).

The assignment of *VenUS* is done according to a classification of energy saving values ranging within a span derived from the above-described regression analysis.

CONCLUSIONS

The proposed procedure can be seen as a tool aimed at helping urban designers and municipalities technicians in evaluating the environmental impact –namely, the effect on wind driven natural ventilation- of alternative urban form configurations. It is part of the set of models and tools developed within the PRECis Project. An existing application of this procedure needs to be carried out on various urban configurations in order to evaluate the effectiveness of this environmental aid tool.

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