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Effects of Façade and Rooftop Greening on the Surface Pressure Distribution of an isolated cubic Building with vertical Apertures.

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SUMMARY
The present study deals with the effects of façade and rooftop greening on the external surface pressures of an isolated cubic building through reduced-scale wind tunnel experiments. The greening was represented by a layer of open-cell foam attached to the building surface. The model building had openings on both side faces and was exposed to 0° wind. For the vegetation modeling, the pressure drop past four types of polyurethane open-cell foams at two different foam sample thicknesses, was measured in a separate testing procedure and pressure loss coefficients were calculated. A comparison with pressure loss coefficients λ (m^{-1}) and/or leaf area density ($m^2\ m^{-3}$) LAD of real vegetation served to characterize the foam samples in terms of typical façade and roof greening e.g ivy. When vegetation is present, especially at the windward façade, the mean (Cp_{mean}) and particularly the standard deviation (Cp_{stdev}) pressure coefficients demonstrate significant local reductions of up to 15% and 35% respectively, on the roof and on the side walls, compared to without vegetation. The reduction in fluctuating pressure is attributed to the low frequency range. This outcome provides insight into the understanding of the interaction between surface vegetation, approach wind and building-induced flow structures, with implications on air exchange rates through the openings.

Keywords: urban greening, wind tunnel experiments, vegetation modeling, building surface pressure.

1. INTRODUCTION

Green roofs and façade greening are widespread concepts for urban buildings, both in the Mediterranean area and in Central Europe. However, studies focusing on their effect on flow and transport processes in the built environment and the advantages or disadvantages they bring, are lacking. Although external surface pressure measurements have been performed in the past for a bare building (without vegetation) (Karava et al.,2011; Manolesos et al.2018; Jiang et al.2022), incorporating vegetation and determining its aerodynamic effect on the natural ventilation potential of a generic building has yet to be investigated. In this study, focus is on the built environment and the case where wind flows through vegetation, present on building surfaces. Open-cell polyurethane foam material is adopted to model shrub and ivy greening, as it has been successfully applied in the past (Gromke and Ruck, 2009; Gromke, 2018) for trees and forests in reduced-scale wind tunnel studies. Vegetation is applied either on the rooftop or on the windward façade of an isolated model building, which has vertical openings on its lateral sides (Figure 1a) and is exposed to a simulated atmospheric boundary layer, in a wind tunnel.

2. EXPERIMENTAL SET-UP

2.1. Porous medium pressure drop measurements and porosity measurements.

Pressure drop measurements were performed in an open-loop wind tunnel at the National Technical University of Athens (NTUA) to characterize the aerodynamic performance of four types of open-cell polyurethane porous materials: PPI60, PPI30, PPI20, and PPI10, where PPI stands for pores per linear inch. Two layer thicknesses, 5 mm (T_L) and 10 mm (T_{2L}) were studied and the pressure drop was measured, for a velocity range between (0-12) m/s with an increment of 0.5 m/s. The measurements were repeated three times for each sample and the average of the three runs is reported (Figure 1d). The pressure loss coefficient λ is calculated as the second order coefficient determined from the Darcy-Forchheimer relation for the total velocity range (Dukhan and Patel, 2011) and is divided by 2, to be compatible with the definition of λ (Gromke and Ruck, 2009). λ values are presented in Table 1. Porosity measurements were conducted, using a portable digital optical microscope and digital images acquired were processed with a digital imaging processing software (Karoglou et al., 2013). Porosity determination was also performed through apparent and real density measurements of the foams. The measured porosity values (ε) of each porous foam are also presented in Table 1.

2.2. Cubic building pressure measurements

The measurements were performed in an atmospheric boundary layer wind tunnel at the Laboratory of Building and Environmental Aerodynamics, at Karlsruhe Institute of Technology (KIT). Extended details of the boundary layer characteristics and the Reynolds number independency can be found in Pappa et al. (2023).

The cubic model building has two vertical slit-shaped openings (Figure 1a). Each opening (90mm×6 mm) is located at the center of the lateral vertical walls and corresponds to 4.5% of the wall area. The windward and leeward walls did not have openings. The experimental investigation includes measurements for three building configurations (Figure 1a,b,c): i) bare ii) roof fully covered by vegetation and iii) windward façade fully covered by vegetation, differing in layer thickness and porosity (total cases: 15). Measurements of surface pressures were performed with two miniature pressure scanners (type ESP-32HD, PSI Pressure Systems), providing a total of 64 silicon piezo-resistive differential pressure transducers. The sampling frequency was f_s = 1000 Hz, and the acquisition time t_{ac} = 120 s. A transfer function (Bergh and Tijdeman, 1965) was applied to correct for frequency-dependent amplitude damping and phase shift distortions.

3. RESULTS

3.1 Characterization of porous medium as vegetation

Reduced and corresponding full-scale pressure loss coefficients, λ_{rs} and λ_{fs}, are shown in Table 1. λ_{fs} are calculated based on a scale factor of M=1:300 (Pappa et al., 2023;Gromke and Ruck, 2009). Also, the full-scale LAD_{fs} (leaf area density, m^2 m^{-3}) values are presented in Table 1, which characterize typical vegetation. Extended details of the modeling of vegetation and similarity considerations can be found in Pappa et al. (2023). Typical λ_{fs} values are in the range of λ_{fs} = 2.2 - 8.9 m^{-1} for the foliated state and λ_{fs} = 0.5 - 0.6 m^{-1} for the leafless state (Grunert et al.,1984), while typical LAD_{ivy} façade greening values are between 3 - 10 m^2 m^{-3}. From Table 1, this is in agreement with the values calculated from measurements for foams PPI10, PPI20, and PPI30 with layer thicknesses of 5 mm and 10 mm.

Table 1. Vegetation parameters for investigated cases: foam layer thickness T (mm), porosity (ε%), pressure loss-coefficient at reduced-scale λ_{rs} (m^{-1}) and full-scale λ_{fs} (m-^{1}) and leaf area density LAD_{fs} (m^2 m^{-3}).

Foams (pores per inch)	Porosity, ε	Thickness, T(mm)	λ_{rs} (m^{-1})	λ_{fs} (m^{-1})	LAD_{fs} (m^2 m^{-3})
PPI60	96.58±0.11	10 (T_{2L})	2346	7.82	26.10
PPI30	97.15±0.10*	10 (T_{2L})	1000	3.33	11.10
PPI20	97.30±0.12*	10 (T_{2L})	500	1.67	5.60
PPI10	97.55±0.15*	10 (T_{2L})	250	0.83	2.80
PPI30	97.15±0.10	5 (T_L)	913	3.04	10.10
PPI20	97.30±0.12	5 (T_L)	468	1.56	5.20
PPI10	97.55±0.15	5 (T_L)	194	0.65	2.20

*indicates values measured for same material at different thickness

3.2 Pressure measurement results

The analysis of the distribution of mean pressure coefficient, Cp_{mean} and standard deviation pressure coefficient Cp_{stdev} reveals that the vegetation has an influence on the pressure field, especially in the case of the façade greening configuration. In the case of the Cp_{mean} distribution (Figure 2a), this effect is weaker, with the Cp_{mean} values in the order of -15% lower compared to the scenario without greening, near the upstream corner and just before the lateral opening, up to s/H=1.3. Downstream of the opening (s/H>1.5) and towards the trailing edge and along the downstream face, the relative differences are positive and their values are up to +65%, depending on vegetation thickness and λ values. Thicker vegetation layers with lower λ values lead to higher relative differences. On the other hand, the standard deviation pressure coefficients Cp_{stdev} are strongly affected by the presence of vegetation and a clear trend can be seen. A significant reduction in the pressure fluctuations is evident near the upstream edge of the side wall (Figure 2b), in the flow separation zone and on the roof (not shown here). It is clear that the presence of thicker vegetation increases the damping of the pressure fluctuations, reaching relative differences in Cp_{stdev} up to -36%. The effect on the leeward wall follows the same trend for the Cp_{mean} and Cp_{stdev} values, but they differ quantitatively. Here, the thinner the vegetation layer with lower λ values, the greater the relative differences, with changes in Cp_{mean} values below s/H=2.5 up to +54% and in Cp_{stdev} up to +13%.

4. CONCLUSIONS

A wind tunnel study was conducted on the effect of vegetation on the pressure distribution on exterior building surfaces. The scaled pressure drop measurements of selected foam samples employed to represent vegetation, reveal agreement of their aerodynamic behaviour with full-scale vegetation. Although post processing of the pressure measurements is still in progress, the initial results reveal a reduction effect of the façade greening on the fluctuating surface pressure coefficients of an isolated cubic building. Effects on the natural ventilation of the building are expected and are the subject of ongoing research.

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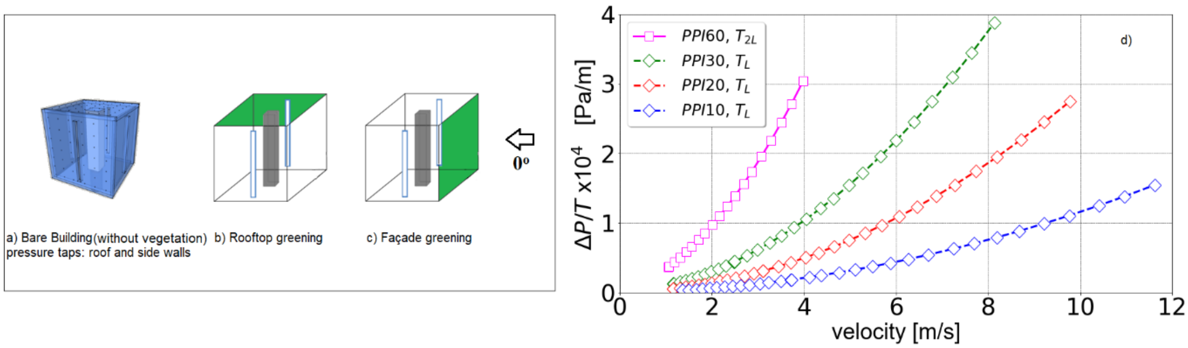

Figure 1. a) Plexiglass cube with slot openings and pressure tap positions, b) Rooftop greening configuration, c) Façade greening configuration, d) ΔP/T vs velocity for PPI60(T_{2L}) and PPI30, PPI20, PPI10 of T_L thickness.

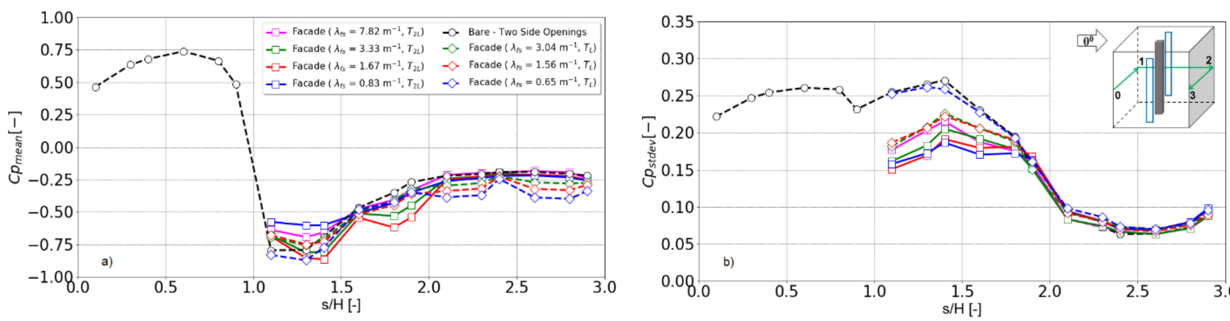

Figure 2. a) Mean pressure coefficients Cp_{mean} and b) standard deviation pressure coefficients Cp_{stdev} of façade greening configuration, along the horizontal line, at mid-height.

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