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THE ROLE OF SURFACE BUILDING MATERIALS IN AIR QUALITY APPLICATIONS

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Abstract: In the general context of air quality modelling, the role of surface building materials is investigated through the analysis of near surface thermal flow characteristics. The consequences for dry deposition on vertical surfaces are analysed using data from a series of controlled releases of fluorescein made in October 2014 at the University of Salento (Lecce, Italy) in an urban-like environment. Data were obtained from a total of 4 one-hour long releases in proximity to a vertical wall on which a panel made of different materials (i.e. glass, marble, ceramic and pietra leccese) was hung while recording. Detailed atmospheric conditions were measured simultaneously and are reported in a companion paper (Conry et al., 2016). Here we focus on the analysis of near-surface thermal flow characteristics and evaluate thermophoretic forces which occur when a strong temperature gradient exists between the surfaces and the environment. Specifically, high-frequency 2D surface temperature data from videos at 10Hz using an infrared thermo-camera were used. Surface temperature data so obtained were combined with air temperature measured by thermocouples positioned close to each material, and one thermo-hygrometer which recorded environmental temperature and humidity conditions, to estimate thermophoretic forces. Computational Fluid Dynamics simulations were used to aid data interpretation.

Key words: *building material, thermographic measurements, thermophoretic velocity, CFD*

INTRODUCTION

Air quality predictions in urban areas are usually done by models which includes the specific modelling of dry deposition via the parameterization of the deposition velocity v_d which in turn depends upon particle physical properties, characteristics of air flow and surface properties (Piskunov, 2009). In the presence of a spatial gradient of particle concentration, Brownian diffusion moves particles from high concentration towards low concentration areas. This mechanism is predominant for particles smaller than $0.2\mu\text{m}$ (Hussein et al., 2012). In addition, the movement of particles from a hot surface to colder air is due to the so-called thermophoretic force, and it occurs in the presence of a spatial temperature gradient (Baron et al., 2011). Several studies have dealt with this phenomenon: Nazaroff and Cos (1987) found that the deposition velocity depends on the combination of drift, thermophoretic and Brownian motion; Tsai et al. (1999) found that even for small temperature gradients thermophoresis plays an important role for particles less than $0.1\mu\text{m}$.

In urban areas significant temperature gradients at surface-air interface are present, mostly due to the presence of different building materials able to store and release the absorbed heat at different time scales. This influences dry deposition on buildings. Detailed surface temperature fields can be obtained via high-frequency thermographic techniques. In this work we describe the methodology for obtaining high frequency temperature data and use them to evaluate thermal-related forces acting relevant for dry deposition on vertical surfaces. Those data were gathered during a field experiment performed in October 2014 at the University of Salento (Lecce, Italy). The experiment consisted in the emission of an aerosol following the ‘fluorescein release technique’ presented in Maro et al. (2014). The experiment was followed by the measurement of concentration data of aerosol deposited on different building materials samples (for more details see Conry et al., 2016). We used thermography to highlight the thermal

behaviour of materials commonly employed in building construction and its effect on aerosol deposition, the latter evaluated via Computational Fluid Dynamics (CFD) simulations.

METHODOLOGY

Experimental set-up

The experiment followed the method by Maro et al. (2014) and was based on the simultaneous emission of an aerosol consisting of fluorescein and Sulphur hexafluoride (SF₆) as tracer gas, used to track the plume in the environment close to the wall. The scheme of instrumentation shown in Figure 1a was employed to acquire data on aerosol concentration, temperature, and wind speed and direction at high frequency (20 Hz).

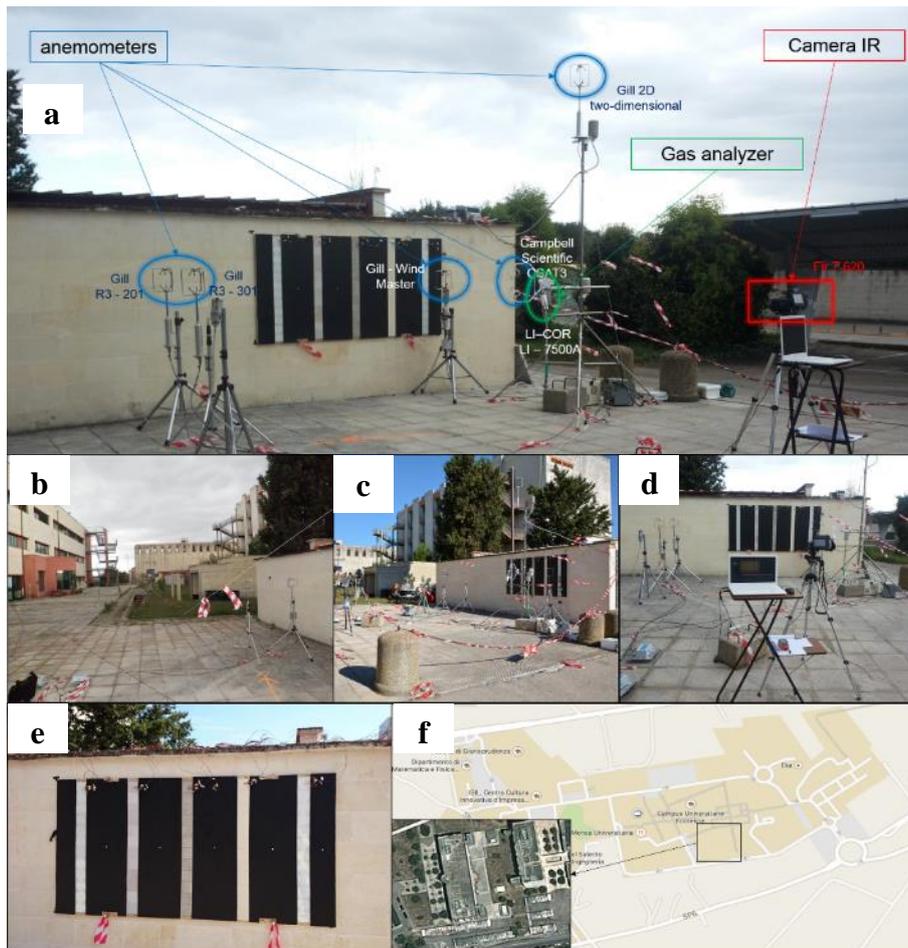


Figure 1. a) Experimental set-up; South (b), South-West (c) and West (d) view; e) panel with material; f) aerial view

A wooden panel (OSB3, sizes: 2.50m x 1.25m) was hung up on the façade of a wall facing west and located between two buildings, which formed a wide “street canyon” in the Ecotekne Campus of the University of Salento (Lecce, Italy) (Figure 1b,c,d). The whole experiment was carried out during three days (25 to 27 October 2014). In total, four 1h Tests (Test 1, Test 2, Test 3 and Test 4 hereinafter) were performed. Samples of five different materials were attached to the panel (Figure 1e): standard glass (SG), auto-cleaning glass (AG), marble (M), ceramic (C) and Lecce stone (L) (from left to right in the figure). Each sample was 10cm x 10cm square, with a thickness ranging from 4mm to 1cm. Insulating material (polystyrene) was used to cover the underlying surface of the panel to make uniform the surface and avoid interspaces that could disturb the flow. Further, the insulating material was painted black to

CFD modelling set-up

3D steady-state CFD simulations were performed by ANSYS Fluent to support field measurements in identifying the influence of near surface temperature gradients on pollutant dispersion and deposition. As a preliminary analysis, we simulated dispersion of a tracer gas (SF6) from a source located at the same position as in the experiment. We considered Test 1 and Test 4 which are characterized by similar meteorological conditions, but different deposition velocities (see Conry et al., 2016). Meteorological conditions used as boundary conditions were those recorded during the experiments (Table 2). Wind velocity was calculated as the mean hourly value, wind direction as the mode of wind direction in the hour. Numerical simulations were performed by employing the standard $k-\varepsilon$ model (Launder and Spalding, 1979), together with the Fourier equation for temperature. The Boussinesq approximation has been assumed (density and other physical parameters do not change, except for the density in the buoyancy forces term), using thermal expansion coefficient $\beta=0.0033\text{K}^{-1}$. The inlet wind velocity, turbulent kinetic energy TKE and dissipation rate ε profiles were specified as follows:

$$U(z) = \frac{u_*}{\kappa} \ln\left(\frac{z+z_0}{z_0}\right) \quad TKE = \frac{u_*^2}{\sqrt{C_\mu}} \left(1 - \frac{z}{\delta}\right) \quad \varepsilon = \frac{u_*^3}{\kappa z} \left(1 - \frac{z}{\delta}\right) \quad (2)$$

where $z_0=0.08\text{m}$ is the roughness length, κ the von Kàrmàn constant (0.40), $\delta=13.5\text{m}$ is the computational domain height and $C_\mu=0.09$. Symmetry boundary condition was specified at the top and lateral sides of the domain. At the boundary downwind of the obstacles a pressure-outlet boundary condition was used. No-slip wall boundary conditions were used at all solid surfaces. The computational domain was built using about one million elements, with a finer resolution close to the panel (smallest dimension of the elements was 0.025m) (Figure 4a).

Table 2. Wind velocity, direction, friction velocity and temperatures of surface used in CFD simulations

Test	Wind velocity at 1.5m (m/s)	Wind Direction	Friction velocity u_* (m/s)	Surface temperature T_{IR} (K)						
				AG	M	C	L	SG	Panel	Wall
1	2.70	330°	0.36	287	287	287	287	287	288	288
4	1.90	330°	0.25	290	291	292	291	292	295	288

The deposition velocity was estimated the model of Lai and Nazaroff (2000) as follows:

$$\frac{v_d}{u_*} = \left[3.64 Sc_p^{2/3} (a-b) + 39\right]^{-1} \quad (3)$$

where a and b are empirical functions of the particle Schmidt number Sc_p and Reynolds number $r+$. This model has been successfully tested in conditions of building interior smooth wall and low friction velocity. The procedure followed here is the same by Maro et al. (2014), using u_* in the range 0.23-0.36 m/s as calculated from numerical simulations at a distance of 0.5m from each sample (corresponding to the distance of LVS1, see Conry et al., 2016).

RESULTS AND DISCUSSION

We considered Test 1 and Test 4 which were characterized by similar meteorological conditions, but different concentration values, i.e. concentrations were much higher in Test 1 (not shown here). We studied the thermal field as lunge to identify its contribution in concentration, by comparing T_{IR} , T_{TC} and T_{AIR} . For T_{IR} and T_{TC} an algorithm was used to remove spikes, and temperature temporal variations were averaged (Figure 2). Averages surface temperature are also summarized in Table 2.

The analysis shows that glasses did not adsorb heat as the ceramic did, while both materials easily lost internal heat. Marble and ceramic were the materials which absorbed and released heat more slowly. As for the different tests, major differences were found between Test 2 and Test 4 which were performed in the morning (Test 1 and Test 3 were instead carried out in the afternoon). The presence of a temperature gradient may have played a dominant role in the different deposition of fluorescein found in Tests 1 and 4. The different thermophoretic force was in fact responsible for moving particles with V_{th} (Figure 3) depending on the temperature gradient and directed opposite to the gradient itself. In particular, V_{th} in Test 1 was constantly negative being the material samples colder (about 2°, see Figure 2) than the air close to the sample and with the surrounding air. In Test 4, the thermophoretic velocity was affected by

fluctuations and in some cases (ceramic) also showed positive values. The material temperature was still lower than air close to the sample as in Test 1, but the difference was smaller (about 1°). More important, the surrounding air was in some cases colder than the sample.

By combining experimental data with CFD results we have attempted to evaluate the effect of surface-air temperature gradients on pollutant dispersion. The concentration pattern indicates that the plume was mostly parallel to the wall along the wind direction (Figure 4b). Table 3 summarizes deposition velocities estimated from equation 3 and those estimated by measurements (see Conry et al., 2016). Similar to the experiments, higher deposition velocities during Test 1 were found, confirmed by an increase of gas concentrations obtained in Test 1 (not shown here) when temperature gradients were the largest. However, calculated velocities, although consistent with results by Maro et al. (2014) using the same deposition model, are about two-three orders of magnitude lower than experiments and, further, the velocity diminishes as the distance of the sample from the source increases, thus not capturing higher concentrations at SG (Conry et al., 2016). Further investigations are ongoing to assess these discrepancies which may be due to limitations of the CFD modelling approach as well as the simplicity of the employed deposition model of equation 3. The latter, in fact, takes into account only turbulent transport through the particle concentration boundary layer near smooth surfaces, neglecting other transport mechanisms, such as thermophoresis which, in our case, has been proven to play an important role on particle deposition (Conry et al., 2016).

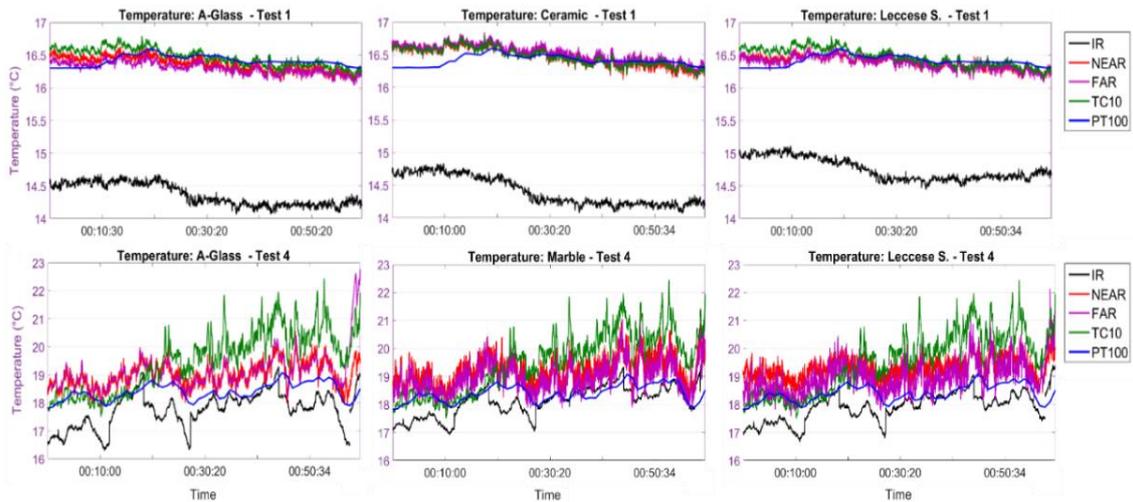


Figure 2. Time series of averages surface temperatures estimated for each material in Tests 1 and 4

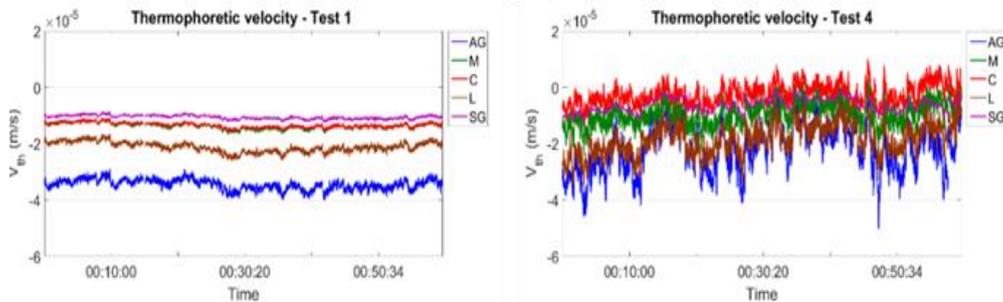


Figure 3. Time series of the thermophoretic velocity estimated in Tests 1 and 4

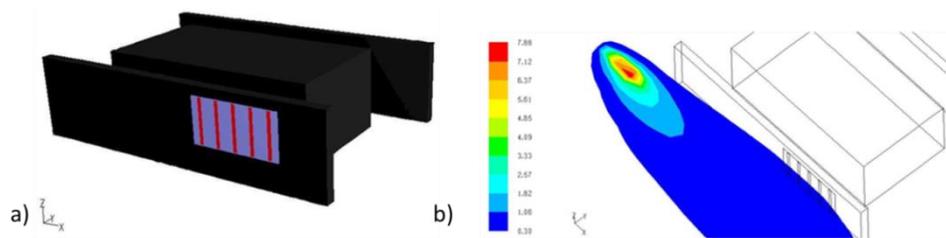


Figure 4. a) Sketch of geometry used in CFD simulations. Violet: panel; red: samples; b) Plume (C^*) at source height in Test 4. $C^* = CH^2 U_{ref}/Q$, where C is the calculated concentration, H the building façade height (2.25m), U_{ref} the reference velocity and Q the emission rate

Table 3. Deposition velocities: model vs. experimental

Test	CFD					Experimental				
	AG	M	C	L	SG	AG	M	C	L	SG
Test 1	1.44×10^{-5}	1.41×10^{-5}	1.39×10^{-5}	1.36×10^{-5}	1.34×10^{-5}	8.17×10^{-3}	1.05×10^{-3}	1.03×10^{-3}	N/A	7.53×10^{-3}
Test 4	1.00×10^{-5}	9.82×10^{-6}	9.64×10^{-6}	9.46×10^{-6}	9.30×10^{-6}	4.16×10^{-4}	2.44×10^{-4}	2.49×10^{-4}	N/A	5.11×10^{-4}

CONCLUSIONS

A field experiment was performed to investigate the dry deposition of aerosols onto building materials. High-frequency thermographic techniques were employed during the experiment to quantify the thermal behaviour of materials commonly employed in building construction and its effect on aerosol deposition. The aerosol deposition via Computational Fluid Dynamics (CFD) simulations was also evaluated. The use thermographic techniques allow the evaluation of temperature differences between different materials at a frequency close to atmospheric turbulence. It is suitable to study the combined effect of near-surface atmospheric turbulence and buoyancy. The analysis showed the presence of a temperature gradient in Test 1 and 4 and thermophoretic velocity suggests that thermophoresis acted in a decisive way in Test 1 by increasing the deposition of fluorescein greatly. This effect was not captured entirely by CFD simulations, highlighting the need for further development of a deposition model and refinement of wall-parameterizations when temperature gradients are present which can be derived from controlled field and laboratory experiments.

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