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CHARACTERIZATION OF TURBULENCE SPECTRUM OF INDOOR AND OUTDOOR WIND COMPONENTS

Pelliccioni A[1,2], Gariazzo [1]

[1]Inail-Dimeila, Via Fontana Candida 1, 00040 Monteporzio Catone, Roma, Italy
[2]Isac-CNR, Via Piero Gobetti 101, 40129 Bologna, Italy

Abstract: In outdoor measurements, the wind velocity spectrum is dominated by the Kolmogorov exponent calculated by wavelenght. In indoor environment this exponent may be linked with air change rates. To obtain turbulence data, one field campaign has been conducted inside and outside a laboratory located at the INAIL research center of Monteporzio Catone, Italy, using two triaxial sonic anemometers. The observed indoor and outdoor power spectrums are quite different in their behaviours in the frequency domain. Indoor ventilation systems are found to have a strong effect on wind and its power spectrum. While outdoor spectrum decreases continuosly with the frequency, indoor spectrums show a reduced decreasing rate between 0.001Hz and 0.01Hz, possible ascribed to turbulence production. Differences were also observed for frequencies higher than 1 Hz.

Key words: *wind, indoor, turbulence, power spectrum, ventilation system*

1. INTRODUCTION

It is well known that dispersion of pollutants depends on the characterstics of air turbulence. The spectrum of turbulence is relevant for air pollution dispersion particularly for outdoor in complex areas, such as in the urban cases (Amicarelli et al., 2011; Cantelli et al, 2015; Di Bernardino et al., 2015). In outdoor, the maximum vertical extension of urban plume is usually equal to the vertical extension of planetary bounday layer height during daily conditions (about 800-1200 m) and with the height of stable layer at night (Britter and Hanna, 2003). In the indoor environment turbulence fluctations are strictly linked with the air change rate (AER) (Haghighat et al., 1991) that is directly connected with the relationships between outdoor air pollution and indoor concentrations (Sajani et al., 2015). In literaure, some tracer field experiments have been conducted to investigate pollutant dispersion around buildings (Oikawa and Meng, 1997; Jones and Griffiths, 1984) and through urban areas (Allwine et al., 2002) underlying the relevance between the different turbulence interaction at different scales in order to estimate the indoor pollutant.

By above considerations, indoor air and turbulence are two factors intrinsically interconnected and the knoweledge of one has a direct effect on the others. For outdoor measurements, the velocity spectrum is dominated by the Kolmogorov exponent calculated by wavelenght (Wilczek and Narita, 2012) by the equation 1:

$$E(k) = C_k \cdot \varepsilon^{-2/3} \cdot k^{-p} \qquad (1)$$

where ε is the energy dissipation rate and C_k is the Kolmogorov constant and p=5/3 is the Kolmogorov exponent. By this equation is possible to derive the equation in the frequency domain:

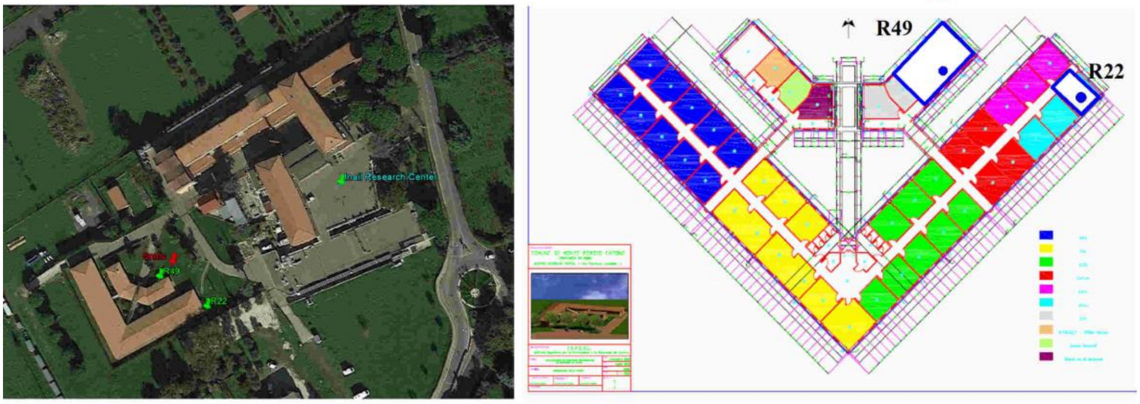
$$E(w) = C(U,V) \cdot C_k \cdot \varepsilon^{-2/3} \cdot |w|^{-p} \qquad (2)$$

where the Kolmogorov exponent p is identical to that one derived by spectrum calculated by wavelength. In indoor environment this exponent may be also linked with air change rates (Hanzawa, et al., 1987; Chow et al., 1994) and the difference between outdoor and indoor p values can be significance of the influence of turbulence penetration in the indoor environment. The influence of outdoor turbulence on indoor environment migh be affected by different indoor ventilation systems. Natural ventilation by leakages and opening of windows and internal doors, as well as mechanical ventilation by HVAC in different operating conditions, affect indoor turbulence both internally produced and penetrated from outdoor. Pressure and thermal gradients are the main driver phenomena of indoor produced and dissipated turbulence. All the above aspects need to be investigated to assess the driver mechanisms of pollution penetration in indoor environment.

In the following a brief description of field campaigns is given, and the comparison between p- in different ventilation conditions.

2. EXPERIMENTAL SETUP AND CHARACTERIZATION OF INDOOR SITE

The Inail is interested in health of worker and within this subject a project for the evaluation of indoor air quality in sponsored project VIEPI (*Valutazione Integrata dell'Esposizione al Particolato Indoor*).
The project has many goals. One of these is the evaluation of infiltraction factors of pollutants and how they depend on the turbulence conditions inside and outside the investigated room. The interest is focused mainly with exposure of worker at research laboratory and at universitry places.



a) b)

Figure 1. Wiew of Inail Research Laboratory at Monteporzio Catone (a). Building layout with locations of outdoor (red dot) and indoor (blu dot) measuraments sitesfor turbulence investigation(b).

To obtain turbulence data, a field campaign has been conducted inside and outside a laboratory located at the INAIL research center of Monteporzio Catone, Italy (Figure 1a). As indoor environment, a meeting room has been selected, named R49 (Figure1b). The characteristic of rooms are shown in Table 1. The room is connected with the main building by a glass panel connection, eventually thermoregulated by fans. The room has a local HVAC system for ventilation and thermoregulation. The outdoor sonic anemometer is located closely to the R49 about 3.5m far from the wall (red dot in Figure 1b). The indoor anemometer is located at 1m from indoor wall of room R49 at height z=1.6m from floor (blue dot in figure 1b).
Five different indoor ventilation regimes were investigated, better described below:

- Windows and door closed **(RoomClsd):** All windows and the entrance door are closed with air exchanged driven by building leakages.
- Windows closed and door opened **(RoomOpn):** Windows are closed and the entrance door of room 49 is open with air exchanged driven by both building leakages and the main building ventilation system
- Two windows opened and door closed **(2WinOpn):** Entrance door closed and two windows opened at opposite position with respect to the location of indoor anemometer; air exchanged driven by direct penetration of outdoor air.
- Windows and door closed, local HVAC on with cooling off **(HVAC-NotCool)**: windows and entrance door are closed with the local HVAC system (four fans for a total of 1700 m^3/h of supply air and one fan with 1000 m^3/h of return air) switched on without air cooling.
- Windows and door closed, local HVAC on with cooling on **(HVAC-Cool)**: windows and entrance door are closed with the local HVAC system switched on with air cooling at 22°C.

Table 1. Characteristic of indoor environment

Room	Dimension (m x m)	Building Height (m)	Volume (m^3)	Number of windows/doors
R49	6x8	2.80	134.4	6/1

Turbulence and sonic temperature measurements were carried out both at indoor and outdoor by means of triaxial sonic anemometers sampling at 32 Hz during a summer field campaign as reported in table 2.

Table 2. Turbulence field campaign characteristics,

TEST date	TEST ID	Indoor	Outdoor
28/7/2017	RoomClsd	R49	besides R49
5/8/2017	RoomOpn	R49	besides R49
29/7/2017	2WinOpn	R49	besides R49
1/8/2017	HVAC-NotCool	R49	besides R49
2/8/2017	HVAC-Cool	R49	besides R49

Each test period represents a steady state condition and starts at 11.00am to end at 16.00pm.

3. SPECTRAL ANALYSIS FOR INDOOR AND OUTDOOR U-COMPONENT

3.1 Main characteristic of observations

Table 3 shows a descriptive statistics of observed wind and temperature parameters in different ventilation conditions. It is worth to note the effect on indoor wind components produced by the ventilation systems. As far as the horizontal wind components are concerned, one or two orders of magnituted higher are observed between natural (RoomClsd) and mechanical ventilation (HVAC-Cool and HVAC-NotCool) systems. The same effect is detected for the standard deviation of the vertical wind component.

Table 3. Mean values and standard deviations of indoor and outdoor cartesian wind components (m/s) in different indoor ventilation regimes. The calculated horizontal mean wind speeds (m/s) is also shown as well as mean indoor and outdoor sonic temperatures (°C).

	Indoor				Outdoor			
TEST ID	**U (Std)**	**V (Std)**	**W (Std)**	**Tsonic (Std)**	**U (Std)**	**V (Std)**	**W (Std)**	**Tsonic (Std)**
RoomClsd	-0.002 (0.009)	-0.091 (0.016)	0.031 (0.008)	31.671 (0.645)	0.492 (1.241)	-1.539 (1.402)	-0.175 (0.628)	31.697 (1.077)
RoomOpn	0.024 (0.027)	-0.080 (0.021)	0.017 (0.017)	33.217 (0.922)	0.341 (1.162)	-1.258 (1.369)	-0.143 (0.557)	42.606 (0.893)
2WinOpn	0.018 (0.037)	-0.087 (0.027)	0.032 (0.022)	32.367 (1.310)	-0.021 (1.012)	-1.389 (1.527)	-0.087 (0.555)	34.914 (1.016)
HVAC-NotCool	0.169 (0.086)	-0.197 (0.089)	0.019 (0.090)	37.814 (1.342)	-0.076 (0.866)	-1.300 (1.181)	-0.053 (0.490)	41.979 (1.402)
HVAC-Cool	0.170 (0.111)	-0.195 (0.119)	-0.045 (0.112)	22.432 (1.029)	-0.020 (0.897)	-1.089 (1.125)	-0.061 (0.464)	43.119 (1.407)

Starting from the collected wind data, the Kolmogorov exponent and the turbulence kinectic energy (TKE) was calculated for each ventilation regime by means of eq. (2). Table 4 shows the results. The normalized relative error (NRE) of estimated p values and its theoretical outdoor value was calculated using equation 3.

$$p_{NRE} = \frac{p_{obs} - p_{Kolm}}{p_{Kolm}} \cdot 100 \qquad (3)$$

It can be seen a substantial agreement between the Kolmogorov exponent calculated for the outdoor data and its theoretical value of 5/3 (average $p_{NRE} \approx -2.4\%$). Conversely, for indoor data the same exponent shows different values depending on the ventilation regimes (average $p_{NRE} \approx -8.1\%$). The lowest p value is estimated when the testing room is not linked with both outdoor and the main building (RoomClsd ventilation) with an error of -66.2%. The p value increases (p=1.46) when the entrance door is opened connecting the room with the main building (p_{NRE}= -12.2%). Opening of windows or switching on the local HVAC system drastrically increase the Kolmogorov exponent with values higher than the theoretical outdoor one. The best p indoor value is reproduced in the 2WinOpn ventilation regime when error is -1.1% and the indoor is totally connected with outdoor by open windows. The indoor TKE values exhibit a behaviour dependent on the ventilation system with increasing values from the isolated room (RoomClsd) to mechanical ventilated room (HVAC-NotCool or HVAV-Cool).

Table 4. Values of the indoor and outdoor Kolmogorov exponent (p), turbulence kinetic energy (m^2/s^2) and p errors for different indoor ventilation regimes.

	Indoor		Outdoor		pNRE (%)	
TEST ID	**p-Kolmogorov**	**TKE**	**p-Kolmogorov**	**TKE**	**Indoor**	**Outdoor**
RoomClsd	0.56	0.0002	1.61	1.95	-66.2	-3.3
RoomOpn	1.46	0.0007	1.62	1.77	-12.2	-2.9
2WinOpn	1.65	0.0013	1.59	1.83	-1.1	-4.5
HVAC-NotCool	2.03	0.0118	1.65	1.19	21.9	-0.8
HVAC-Cool	1.95	0.0196	1.66	1.14	17.2	-0.5

3.2 Spectral Analysis

In figure 2 the power spectrum in different ventilation regimes are shown. The observed indoor and outdoor spectrums are quite different both qualitatively and quantitative.

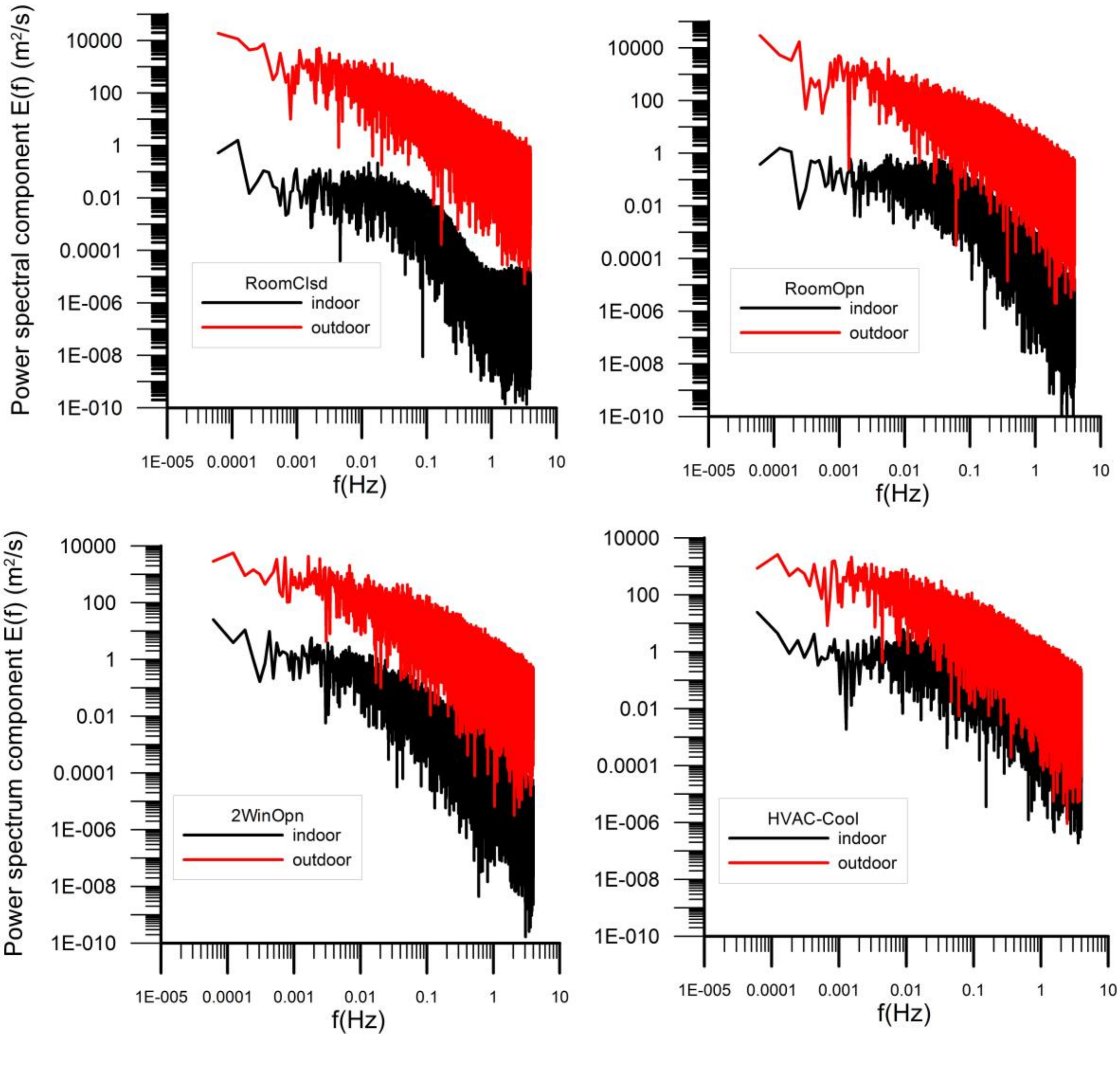


Figure 2. Power spectrum component for different indoor ventilation regimes.

The outdoor spectrum decreases continuosly with frequency, which is coherent with the processes of dissipation in atmosphere. The indoor spectrum shows two different behaviours.

Firstly, in indoor, the decreasing rate of power spectra with frequency between 0.001Hz and 0.01Hz is reduced with respect to outdoor. A light turbulence production is probably the reason of this behaviour. This effect is particular evident in the power spectrum during HVAC-Cool conditions. This anomalous turbulence production can be probably explained by the limitation of room volume. Futhermore, the indoor power spectrum at the higher frequencies (f>1Hz) is more relevant with respect the outdoor spectrum if a normalisation criterion is used to compare data (Ouyang, et al., 2006).

4. Conclusions

We have calculated the power spectrum of U-component in indoor and outdoor sites for different ventilation regimes. The more relevant result concerns the values of the p-Kolmogorov exponent which was found strictly linked with the indoor ventilation conditions, with respect to the typical values of -5/3 observed in outdoor. The power spectrum at frequencies higher than 1Hz implies a slower dissipation of turbulence in indoor environment with respect to the outdoor one. The above results could indicate possible linkages between indoor and outdoor ventilations which should be better investigated.

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