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The hygrothermal performance of residential buildings at urban and rural sites: Sensible and latent energy loads and indoor environmental conditions

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ABSTRACT

Cities often show nighttime air temperatures higher by 3–4 °C than adjacent non-urban areas. This yields to cooling loads in average higher by 13% for urban than rural buildings. Here we assess the hygrothermal performance and the heating and cooling loads of a reference building representative of the Italian stock. We compare its performance calculated with hourly urban weather data (2002–2008) with the performance of the same building using a rural dataset instead. Milan's Urban Heat Island reduces the heating loads by 12% and 16%, for the non-insulated and insulated building, respectively, while the cooling loads are increased by 41% and 39%. The urban building also shows dehumidification loads 74–78% lower than the rural building. Moreover, during the 2003 heat wave, the indoor air temperature is computed to be 1.5 °C–2.2 °C higher in a non-conditioned urban building than in the rural one. This increases the wakefulness, occupants' vulnerability to overheating, and impacts the overall hygrothermal performance. Our findings highlight the need of a different design concept for urban with respect to non-urban buildings, even though they are, by law, in the same climate zone.

1. Introduction

As the growth of world's population mostly concerns urban areas, which are responsible for 71% of global energy-related carbon emissions [1], zero energy and healthy communities are nowadays a key target. Therefore, a robust understanding and description of the microclimates where most of buildings are located is necessary, as demonstrated by the increasing number of studies on Urban Heat Islands (UHIs) and their impacts [2,3].

Urbanization is known to induce local climate change phenomena [4]: urban areas present higher air temperatures than their rural proximities, especially during the night [5], often by 3–4 °C, with higher peak differences, sometimes exceeding 10 °C [3]. For instance, in London, a maximum daytime Urban Heat Island Intensity (UHII) of 8.9 °C was found in a semi-urban area during a partially cloudy period, while a maximum nocturnal UHII of 8.6 °C was found in the urban area in clear sky conditions with wind velocity below 5 m s^{-1} [6,7]. In Athens, UHIIs from 2.7 °C up to 10 °C are reported by studies using data from dedicated meteorological stations [8]. UHIs determine a higher number of extreme hot nights at an urban location than at a rural site, which is expected to be exacerbated by global climate change [4], likely increasing the mortality during heat waves [9].

Metropolitan areas present also lower humidity than non-urban adjacent zones [10], with monthly average differences in relative humidity exceeding 10% [11], although some short duration events of urban moisture excess may occur [12]. Moreover, the wind velocity within the urban canopy is a fraction of that over the rooftops [13], in the range of one fourth to one third [14]. In addition, at 1.5–2 m above the street level the air temperature is about 1–3 °C warmer than over the urban canopy layer [15]. Also rainfalls are affected by the urban texture: precipitations can be increased downwind, slightly increased over the city, and reduced upwind in the rural surroundings [16].

Each city has its specific features which result in different UHIs [2]. An interesting case study is that of Milan, Italy. Its metropolitan

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region is populated by ∼7.4 million people [17], with an average urban population density of ∼7400 people/km^2, and exceeding 15,000 people/km^2 in the semi-central wards of the city [18]. The first study on Milan's UHI is that by Bacci and Maugeri [19], who report a yearly average UHII exceeding 1.2 °C relative to the period 1951–1981, and found a positive correlation between UHII increase and increase in the average radius of the city from 1850 to 1981. Anniballe et al. [20], by means of satellite remote sensing, found an urban-rural surface temperature difference of 9–10 °C during daytime and about 50% less during nighttime within Milan's urban fabric.

Despite the vast literature on the topic, as yet, building energy simulations (BES) are often performed with old weather datasets, mainly collected by weather stations located at the airports. With urban weather data instead of a rural reference, the cooling loads are in average 13% higher, and for each 1 °C of UHII the cooling load is increased by 20% [3]. For a tertiary building in Modena, Italy, Magli et al. computed higher heating primary energy needs outside the city by 19–20%, lower cooling primary energy needs by 8–10%, and lower CO_2 equivalent emissions by 5–7% [21]. Considering instead the overheating risk, although dwelling features and users' behavior are the determinant factors in the exposure to the heat risk, the UHI draws the spatial variation [22]. While the general trend for typical buildings in a given region can fairly estimate the exposure to overheating, modeling specific dwellings remains challenging. A comparison between EnergyPlus simulations and measurements in 823 dwellings in the UK has shown an average RMSE of 2.7 °C for the indoor maximum daily temperature [23].

In this paper we show the analysis of hourly weather data series (2002–2008) collected at an urban station in Milan, and at a rural one. With these, we computed the heating, cooling, humidification and dehumidification loads, as well as the overheating and over-drying risk (i.e., too low humidity) for a representative residential building. Moreover, we considered the conditions that induce wakefulness and reduce sleep efficiency, the transmission of bacteria, viruses, and respiratory infections, as well as the proliferation of house mites. We gave special attention to the indoor conditions during the heat wave of 2003, when in Milan the mortality increased by 23% over the 1995–2002 average, corresponding to 559 deaths in excess [24].

2. Method

2.1. Simulation model

We computed the whole building (3-D) dynamic heat and moisture balance using the software model WUFI Plus 3.0.3 [25]. It resolves the enthalpy balance with the finite control volumes method, coupling heat transfer with liquid and vapor moisture transport in porous media, accounting for latent heat transformations as well as for temperature and moisture dependent thermal and moisture transport properties [26]. Wind driven rain is also considered. WUFI Plus was validated within the context of IEA Annex 41 [27], and tested with measurements in the laboratory and experimental buildings [28–30]. For a residential building in Quebec City (Canada) and Phoenix (AZ, USA), Ge and Baba found a difference within 2.7% between the heating and cooling loads computed with WUFI or EnergyPlus [31].

2.2. Case study

As a case study, we selected a typical residential building, based on a survey of Milan's building stock [32]. It is a stand-alone ten-story tower building, representative of the 1961–1975 housing stock [33]. Being an isolated building, thus not surrounded by urban canyons, there are no significant obstructions around it that may influence the radiative and convective exchanges. The dimensions of the selected building equal to 20.3 m × 20.3 m × 30 m with the façades facing the cardinal directions. The net floor area is of 3307 m^2, and windows of 1.6 m × 1.7 m are on each façade, sized according to local regulations. The same building is simulated in a non-insulated and in a retrofitted condition (Table 1). The non-insulated case presents a building envelope technology representative of multi-story residential buildings in Italy. The refurbished case, instead, complies with the new energy regulation [34], with external wall insulation (ETICS) and an insulated cool roof. The shading coefficient was adjusted to achieve a reduc-

Table 1
Building envelope characteristics and surface areas used for the simulations.

Building components	Orientation and area (m^2)	Case 1: No insulation	Case 2: Insulated building
Wall	Tot. 2014 N: 503.5 E: 503.5 S: 503.5 W: 503.5	U = 0.49 W m^{-2} K^{-1} 0.015 m Cement lime plaster, Double hollow-brick masonry with air gap (0.08 m − 0.05 m − 0.12 m), 0.015 m cement plaster and finish coat. ρ_s = 0.50; ε = 0.90	U = 0.22 W m^{-2} K^{-1} 0.015 m Cement lime plaster, Double hollow-brick masonry with air gap (0.08 m − 0.05 m − 0.12 m), ETICS with 0.1 m EPS insulation. ρ_s = 0.50; ε = 0.90
Roof	412	U = 0.56 W m^{-2} K^{-1} 0.015 m Cement lime plaster, 0.25 m precast reinforced concrete slab, 0.08 m slope screed, 0.05 m concrete screed and modified bitumen roofing felt. ρ_s = 0.25; ε = 0.90	U = 0.23 W m^{-2} K^{-1} 0.015 m Cement lime plaster, 0.25 m precast reinforced concrete slab, 0.08 m slope screed, 0.05 m concrete screed, 0.1 m EPS insulated panel, cool PVC roof membrane (ρ_s = 0.56; ε = 0.90)
Floor	412/ Tot. 3709	U = 0.51 W m^{-2} K^{-1} 0.015 m Cement lime plaster, 0.25 m precast reinforced concrete slab, 0.05 m concrete screed and 0.008 m granite finishing	U = 0.51 W m^{-2} K^{-1} 0.015 m Cement lime plaster, 0.25 m precast reinforced concrete slab, 0.05 m concrete screed and 0.008 m granite finishing
Floor over cellar	412	U = 0.52 W m^{-2} K^{-1} 0.25 m precast reinforced concrete slab, 0.05 m concrete screed and 0.008 m granite finishing	U = 0.29 W m^{-2} K^{-1} 0.015 m Cement plaster, 0.06 m EPS insulated panel, 0.25 m precast reinforced concrete slab, 0.05 m concrete screed and 0.008 m granite finishing.
Window	Tot. 418.5 N: 108.8 E: 106 S: 97.92 E: 106	U = 2.85 W m^{-2} K^{-1} Frame factor = 0.8 g-value = 0.75 Standard double glazing unit + external venetian blinds	U = 1.4 W m^{-2} K^{-1} Frame factor = 0.8 g-value = 0.57 Double glazing unit with low emissivity coating + external venetian blinds

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