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Effect of dynamic characteristics of building envelope on thermal-energy performance in winter conditions: In field experiment

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ABSTRACT

Research about building strategies for energy saving is taking a growing interest worldwide. New solutions for building envelopes require increasingly sophisticated investigation to analyze the thermal-energy in-field dynamic response of constructions. Moreover, in-lab experiments are difficultly able to represent real environment boundary conditions. In this paper, effect of dynamic properties of building opaque envelope is investigated in winter conditions through an extensive continuous monitoring campaign of a dedicated experimental field. The field consists of: two full-scale buildings, an outdoor weather station, and two indoor microclimate stations. The two buildings were designed with the same stationary envelope characteristics, but different envelope technologies, materials and, therefore, different dynamic properties. Nevertheless, following Italian regulations about building energy performance in winter, they should behave the same. With the purpose to verify this hypothesis, a continuous long-term comparative monitoring is developed. The results only partly confirm that simplified hypothesis. In fact, in winter, while the two buildings exhibit equivalent long-term energy behavior, a weak difference is registered in terms of air temperature in free-floating, transient, and operative HVAC systems' regime. Additionally, non-negligible discrepancies are registered in terms of mean radiant temperature, indoor humidity and internal–external envelope surface temperature, given the different transpiration rate of the two envelope systems and different solar reflectance values of the roofs.

1. Introduction

The research interest focused on buildings' energy efficiency, passive solar architecture, innovative optimization strategies and retrofit interventions has received a growing interest in last decades [1], given the acknowledged key role of constructions to reduce global environment impact in terms of fossil fuels' depletion and carbon emissions [2]. In particular, many research efforts focused on elaborating integrated multicriteria tools aimed at optimizing the overall buildings' energy performance through: (i) envelopes' improvement, (ii) reduction of heating and cooling requirement, and (iii) innovative control strategies [3]. In order to improve the overall thermal-energy performance of opaque and transparent components of buildings' envelope, several scientific contributions focused on indoor thermal-energy monitoring of specific case studies with the purpose to quantify benefits and possible penalties of tested retrofit solutions when exposed to different climate conditions [4]. For instance, a wide investigation concerned the implementation of innovative envelope materials and coatings on case study buildings, after an in-lab analysis and optimization of the tested solutions [5]. Particular attention was paid to the effect of cool roofs and cool coatings to reduce building energy requirement for cooling in different climatological contexts, through experimental monitoring and calibrated-validated dynamic simulation [6,7]. In particular, Kolokotsa et al. in [7] elaborated a numerical and experimental analysis of a cool roof application on a research office building in Crete, Greece. The analysis was carried out through continuous indoor–outdoor environmental monitoring and validated dynamic simulation, in order to extend the experimental results to a number of variations in boundary conditions and for longer periods than the experiment duration. The need for dynamic simulation modeling was also to analyze the influence of several innovative passive techniques [8] impacting the indoor thermal performance of the monitored areas, e.g. occupants-based strategies [9].

In order to develop rigorous thermal-energy continuous monitoring, important researches during last decades also focused on the performance analysis of dedicated full-scale test-buildings, which allowed higher dynamic parameters' control than existing occupied buildings. In particular, a key research contribution was

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Nomenclature

r	Pearson correlation coefficient, –
RH	relative humidity, %
T	temperature, K
T_{air}	indoor air temperature, °C
T_{mr}	indoor mean radiant temperature, °C
T_{op}	indoor operative temperature, °C
TR	Test-Room, monitored prototype building
TR-1 and TR-2	Test-Room 1 and 2, respectively
VC	coefficient of variation, –
σ	standard deviation

produced by the development of PASSYS research project, where several important papers were published in the field of experimental analysis of thermal properties through outdoor test cell facilities [10] since 1993. Then, the necessity to discuss further around dynamic thermal behavior of buildings, and building components in particular, was focused by the PASLINK network [11]. They provided significant improvements in the field of both testing and analysis techniques, also guiding other researchers in creating new test facilities, such as the research field presented in this work [12]. In particular, Strachan and Vandeele in [12] presented a series of case studies concerning specific building components, in order to analyze and to better model their dynamic field behavior through sophisticated computer modeling techniques. Additionally, they showed that laboratory conditions could produce lower uncertainties, but the only outdoor continuous monitoring facilities allow the investigation of real wide operational ranges of dynamic conditions' variability. In this view, Baker and van DijK in [13] reviewed both stationary and dynamic methodology for assessing building thermal performance. In particular, they applied parameter identification in order to investigate dynamic effects imputable to heat accumulation. The transient mathematical model led to the development of new softwares for parameter identifications, which implementation could be useful in order to compare the research of this paper with respect to other key contributions by PASLINK network [12,13], as future development of this work. Additionally, Jiménez and Madsen, starting from the results of outdoor testing, presented an overview of models aimed at predicting thermal characteristics of buildings and building components [14]. In particular, they outlined the main differences between linear, non-linear, and time-invariant approaches. Therefore, they applied some of the presented models to the case study of the PASLINK experimental field, with the purpose to estimate the thermal transmission coefficient and the solar transmittance of the tested wall (the periodically modifiable part of the opaque envelope) in the cell. This series of contributions shows how such outdoor test facility could also be useful for identifying, and therefore optimizing, the performance of each building component, such as the experimental wall of [10–15], that was also used to present the procedure for using IDENT in MATLAB [15]. Additionally, the necessity of an up-to-date research network sharing the same purpose demonstrated the scientific need of this kind of sophisticated multivariable experiments [16]. In this view, the purpose of these full scale buildings (i.e. the Test-Room experiment presented in this work) mainly consists of the thermal-energy and humidity analysis of the behavior of real buildings, i.e. with common envelope multilayer structure and HVAC systems. In this view, this paper in particular concerns this experimental investigation with varying winter conditions, showing the importance of dynamically variable boundaries in determining building indoor environmental quality.

Starting from these key research contributions [10–16], other interesting applications of small-scale buildings were carried out in order to simulate and investigate the role of buildings' envelope on the thermal behavior of the urban canopy [17] and local climate phenomena such as urban heat island effect and its huge impact on buildings' energy performance [18]. Thanks to the implementation of such a sophisticated experimental setup, important enhancements were carried out to investigate building envelope properties and to optimize innovative materials for energy saving. In particular, the role of reflective coatings for both interior and exterior cladding of building envelope was investigated by Joudi et al. in [19]. In this study, three monitored steel clad test-cabins were used to investigate the role of infrared-reflective coatings under various conditions, which results were also used to evaluate the year-round energy use of the same cabins. A detailed analysis concerning several innovative roof technologies was carried out by D'Orazio et al. in [4], where the experimental setup consisted of a test building equipped with six roof modules. Each module represented a different technology, i.e. green roof, traditional clay tile roof, etc. and the overall setup was monitored in terms of roof thermal behavior and outdoor weather conditions.

Notable enhancements in the field of house-sized dedicated building monitoring were carried out in order to study the dynamic thermal performance of buildings' envelopes such as the thermal inertia characteristic. In particular, the investigation of PCMs' (Phase Change Materials) effect produced important results thanks to the continuous monitoring of small house-sized cubicles carried out in [20]. Castellón et al. in [20] presented the experimental setup consisting of nine small house-size cubicles made with brick or concrete, where PCM applications were tested through continuous monitoring of free-floating conditions and operative HVAC system conditions. The monitoring equipment consisted of indoor and surface temperature sensors in each test-cell, while the weather data were available from an autonomous station located nearby. The internal dimensions of the prototypes (2.4 m × 2.4 m × 2.4 m) were established in order to be big enough to be representative, but small enough to be economically feasible, and the mutual position of the test-cells was established in order to avoid inter-building effects affecting the measurements [21]. The same PCM applications were studied by Bontemps et al. in [22] which purpose was to evaluate the role of PCM inclusion into a wall in terms of indoor temperature and thermal flux through the same wall. To this aim an outdoor test cell was constructed and it consisted of two juxtaposed rooms separated by glass bricks with or without PCMs' inclusion. The experimental setup was monitored through fluxmeters and thermocouples which data were used to calibrate and validate one-dimensional numerical model with the final purpose to characterize several PCMs' implementations.

The growing interest in evaluating new high performance envelope technologies and materials guided through the elaboration of the experimental campaign presented in this paper. The concept of the two full-scale test-buildings, designed in order to represent typical Italian construction practice in terms of materials, geometry and technical properties of the envelope and of the HVAC technologies [23], was carried out by following the recent regulation about energy efficiency in buildings. The Test-Rooms were designed and built in 2012. Each Test-Room was equipped with a complete indoor monitoring station connected to a dedicated outdoor weather station. Differently with respect to the previous experimental campaigns described before, these buildings were constructed with traditional materials and complete envelope solutions, such as real doors and windows, structural systems, and multilayer walls-roof-ceiling. The coupled parallel analysis concerning indoor–outdoor environment of both the Test-Rooms was mainly conceived to investigate the comparative hygrothermal and energy behavior of such cabins in winter conditions. Therefore, the role of important dynamic features, usually neglected in Italian regulation for building design in winter conditions, e.g. the active