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Investigation on the effect of innovative cool tiles on local indoor thermal conditions: Finite element modeling and continuous monitoring

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ABSTRACT

The achievement of building indoor thermal comfort conditions with the minimum energy need represents a challenge for both designers and researchers. To this aim, the development of passive strategies, e.g. cool roofs, for reducing the thermal gain entering building envelopes has spread in the scientific community. In this view, Computational Fluid Dynamic method is applied in this research in order to quantify the effect of a cool roof solution within the indoor environment of the thermal zone adjacent to the roof, by analyzing the attic local conditions. The case study is represented by an attic room of a continuously monitored residential building located in central Italy. A two-dimensional finite element analysis is carried out to investigate the indoor air temperature and air velocity field inside the attic. The available experimental data are used for validation. Therefore, the thermal profiles generated by (i) the roof with traditional brown-colored brick tiles and (ii) the same roof with innovative cool clay tiles are investigated. The final purpose is to compare the indoor thermal comfort conditions generated within the vertical cross section of the attic, in order to study the cool roof effect at different height of occupants' body. The main results show up to 2.79 K and 1.54 K air temperature difference between the cool and traditional roof configurations, in summer and winter conditions, respectively. A thermal stratification is detected during summer inside the attic, leading to strongly non homogeneous comfort conditions, particularly marked in the "hot" tiles scenario, demonstrating the usefulness of this contribution.

1. Research background

In a modern, energy-conscious society, the reduction of buildings energy consumption and the improvement of indoor thermal comfort conditions are considered the most important goals to be achieved. In fact, the building sector accounts for over 40% of the overall energy used in the European continent [1], and has been working on the implementation of ever more efficient ways to save energy both at urban and building scale, given the huge threaten of global warming and urban heat island phenomena. At urban scale, Synnefa A. *et al.* [2] and Salata F. *et al.* [3] investigated the possibility to improve the local microclimate conditions by means of high albedo surfaces such as cool colored thin layer asphalt and vegetation. The impact of environmental and human factors on microclimate variability and urban heat was also studied [4], together with the effect of urban neighborhoods on the performance of building cooling systems [5]. At building scale, both passive and active strategies for the enhancement of the building envelope thermal performance have been implemented and evaluated [6]. In this scenario, "cool" solutions and more in particular highly reflective envelope surfaces *i.e.* roofs, walls, and pavements, have been acknowledged to be the most effective and sustainable way to reduce building energy consumption and improve indoor thermal comfort conditions [7]. In fact, the use of cool materials can reduce up to 8 °C the building envelopes' surface temperature at ground level in urban environments [8]. In particular, cool materials are able to minimize the building roofs' heat stress given that the median sensible heat flux is negative while the maximum value is of the order of a few W/m^2 [9]. Cool roofs represent therefore one of the main mitigation strategy against urban heat island at urban scale, given their capability to guarantee a mean decrease of 0.3 K of

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the average ambient temperature per 0.1 rise of albedo [10]. Additionally, the use of cool roofs can lead to significant cooling energy saving and indoor thermal benefits at building level. An annual electricity savings up to 125 kWh per year was detected for instance in Ref. [11]. Moreover, Santamouris *et al.* [12]. measured that cool roofs can lead to a 1.2–3.3 °C reduction of the peak temperatures in non-air-conditioned residential buildings in various climate conditions, with a 9–100% decrease of the discomfort hours and a combined 18–93% reduction of the cooling loads. Furthermore, high albedo roofs were demonstrated to lead to seasonal energy savings up to 80% for monitored in Sacramento, CA, with negligible energy penalties [13]. Finally, cool roofs were demonstrated to be effective as cooling strategy also in cold climates, *i.e.* Canada, as reductions of the peak electricity demand up to 5.4 W/m2 were detected [14].

In recent years, however, such evaluations about the thermal benefits and energy savings of cool technologies and passive building envelope solutions in general have been increasingly supplemented by Computational Fluid Dynamics (CFD) tools [15–18]. These simulations represent powerful tools to investigate, for instance, a large number of different scenarios aimed at reaching a proper thermal performance of the building envelope. Taminaga *et al.* [19] used them to investigate the air-flow around isolated gable roof buildings with different roof pitches, by means of a steady-RANS model, and to investigate the flow field around a high rise building, by means of an unsteady-RANS model [20]. García-Sánchez *et al.* performed a numerical study aimed at characterizing the uncertainty related to the variability in the inflow boundary conditions for RANS simulations, on the prediction of flow in a real building canopy [21]. CFD simulations were also used by Yang *et al.* [22] to investigate the indoor temperature and air age of a bedroom with wall hanging air conditioning in summer, and by Risberg *et al.* [23] to study the indoor climate in a low-energy building in northern Sweden.

In the last three decades, many research activities have been devoted to the investigation of natural convection heat transfer [24,25] and, more in particular, natural convection phenomena inside enclosures [26] and attic spaces. The main purpose of these studies is to provide thermal comfort to the occupants in attic-shaped buildings and to minimize the energy costs associated with heating and air-conditioning. Generally, the investigated model is simplified to a representative cross-section of the attic, thus considering a two-dimensional isosceles or right-triangular geometry.

The most studied boundary conditions are represented by (i) enclosure heated from below (winter condition) and (ii) enclosure heated from both top sides and cooled from the bottom (summer condition). Both experimental and numerical analyses are usually carried out, and in both scenarios the most critical issues are represented by (i) the validity of the symmetry assumption and (ii) the treatment of the corners. Additionally, most of the attic CFD analyses and research studies available in literature are associated to the definition of the effects of changes of (i) the roof pitch angle and (ii) the Rayleigh number on the flow and thermal field inside the enclosure, for both laminar and low turbulence regimes.

In this context, Saha *et al.* [27] modeled natural convection in an attic space subjected to periodic thermal forcing. Moreover, Ridouane *et al.* [28,29] addressed laminar and turbulent natural convection to an isosceles triangular cavity representative of conventional attic spaces, and Basak *et al.* [30] analyzed the temperature and flow field for low-Rayleigh number natural convection in triangular enclosures. Furthermore, the influence of the height/base ratio of a pitched roof triangular cross-section on the temperature and flow field for a two-dimensional natural convection model was investigated by Asan and Namli [31]. It is noteworthy that, in most of the turbulence studies until now performed, the maximum considered value for Ra was as high as 10^4–10^5. Hasani and Chung [32] remarked that this was too low for an attic, and suggested values of Ra up to 10^6, while Kamiyo *et al.* [33,34] and Talabi *et al.* [35] numerically investigated enclosure configurations in both bottom and upper heating conditions for $10^9 \leq \mathrm{Ra} \leq 10^{11}$, by using differential Reynolds stress turbulence model. Kamiyo *et al.* also wrote a comprehensive review of natural convection in triangular enclosures [36,37], which makes clear that, despite the large literature available about the study of heat transfer in triangular enclosures, only a little part of it is truly representative of a realistic attic configuration, and even less is supported by significant experimental feedbacks.

2. Motivation

Moving forward from previous research studies about cool roofs focused on material optimization and thermal zone temperature reduction [38,39] or energy saving for cooling, this work focuses on a more local perspective, by highlighting the very punctual effect of cool roof tiles in order to be focused on the occupant perception of such techniques with varying indoor height and position within the monitored thermal zone. To this aim, the investigation is carried out on the local indoor environment of a non-controlled (free floating conditions) attic room selected as case study. The main purpose is to define the thermal profile generated by more innovative cool tiles inside the attic room compared to traditional brown-colored brick tiles, in order to determine at which height inside the room the cool roof effect disappears or can be negligible for human perception. The final objective is to evaluate and compare the indoor thermal comfort conditions generated inside the attic by the application of cool tiles rather than traditional brick tiles. To this aim, CFD numerical simulations of two different configurations are performed: (i) roof covered by brown-colored brick tiles and (ii) roof covered by innovative cool tiles [39].

The numerical analysis is carried out by using the experimental data available from the continuous monitoring performed in the period 2011–2015 (still on-going) both inside and outside the case study attic space. In particular, roof and pavement surface temperatures are used as input boundary conditions for the two-dimensional CFD model of the attic vertical section. Additionally, the experimentally measured indoor air temperatures are used for the validation of the CFD model.

3. Materials and method

The methodology applied in this research work consists of the following main steps:

-selection of the proper case study, *i.e.* non-conditioned (free floating) attic room of a residential building;
-continuous monitoring of the indoor microclimate parameters, *i.e.* surface temperature and indoor air temperature [39];
-CFD simulation of the indoor thermal profile and velocity field generated inside the attic room by the application of (i) traditional brick tiles and (ii) innovative cool tiles;
-validation of the model by means of the experimental continuously monitored data;
-post-processing and discussion of the achieved results.

In particular, two main scenarios are here assessed:

- *Scenario_0*: roof covered by traditional brown-colored "hot" brick tiles;