Wall System with Dynamic Thermal Insulation

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Dynamic thermal insulation systems (DTISs) can adapt to external environment conditions and help to reduce energy consumption and increase occupants' thermal comfort, contributing towards the mitigation of overheating. DTISs adjust their configuration to optimize heat transfer through the façade.

Keywords: adaptive façade ; dynamic thermal insulation system ; thermal comfort

1. Overheating Problem and Mitigation Measures

The building construction sector plays an essential role in energy consumption. In fact, in 2021, the use of fossil fuels in buildings accounted for approximately 8% of global energy-related and process-related CO_2 emissions, with another 19% resulting from the generation of electricity and heat used in buildings, and an additional 6% resulting from the manufacture of cement, steel, and aluminum used in building construction. As a result, the building sector is responsible for about a third of the total global final energy consumed and process-related CO_2 emissions [1].

With climate change, the Earth's average temperature has increased and will continue rising if no action is taken [2]. Moreover, the increased frequency of extreme meteorological events also has important consequences. Extremely high air temperatures contribute to cardiovascular and respiratory disease deaths, particularly in older people. Despite evidence of the effect of the environment and climate on health, more political actions and investments are needed [3].

According to the six leading international datasets consolidated by the World Meteorological Organization (WMO), the last seven years (2015–2021) have been the warmest ever, and 2021, in particular, was one of the hottest. In addition, climate change is causing increasingly frequent heat waves and extreme weather events. In June and early July of 2022, record-breaking temperatures were registered in Europe, North Africa, the Middle East, and Asia. An increase in tropical nights and extremely hot days is expected in the future. These conditions will intensify in cities due to the heat island effect.

In the housing sector, the overheating phenomenon is enhanced by extreme heat events, causing thermal discomfort to users. Adequate housing conditions are acknowledged in several international documents and thermal comfort is pointed out as a key factor for the occupants' wellbeing [4]. Thermal comfort is typically assessed by air temperature and humidity-related parameters, and several models are available in the literature to quantify it [5][6]. Concerning this topic, certain authors have discussed the most adequate model for a specific climate [7] and others their impact on the energy demand [8].

In addition to the external stimulus, overheating depends on the characteristics of the building and the behavior of the occupants [9][10]. The simplest model to assess overheating is based on a limit value for air temperature above which the building will be in discomfort. A common limit value is 25 °C. On the other hand, some adaptive models propose an operative temperature comfort range dependent on an indicator of the exterior climate [11]. In this way, these models take into account not only the possibility of occupants interacting with the building to improve their thermal sensation but also their ability to adapt depending on previous experiences, namely the outdoor environment. The mitigation measures to tackle overheating can be classified into passive and active. Active solutions employ cooling techniques through mechanical means and require energy consumption, while passive solutions use constructive techniques and properties of materials and components to reduce overheating [12][13].

According to the IEA (International Energy Agency), air-conditioning and electric fans (active means) are responsible for almost 20% of the total electricity used in buildings worldwide. Since 1990, the energy demand for space cooling has more than quadrupled at an average pace of 4% per year since 2000 [14]. In the next three decades, the use of air-conditioning is expected to increase, becoming one of the main drivers of global electricity demand [15].

Thus, in order to tackle overheating, minimize the amount of energy required for space cooling, and prepare buildings for future climate scenarios, it is crucial to value passive design strategies to optimize heat transfer towards the indoor environment, which includes adopting measures such as shading, building components with heavy thermal mass, and enabling natural ventilation or night-time cooling whenever the outdoor temperature is lower than the indoor temperature and the humidity conditions are favorable [16][17].

Green façades and roofs are also possible solutions, as they restrict heat flow to the interior environment by 70% to 90% in summer [18]. Several authors also refer to the use of special glass, such as double or triple glazing or a low-E glass coating to control solar heat gains [16][19]. Cool roofs are also pointed out as a possible passive design strategy that minimizes solar heat gains [20].

Even if passive measures to mitigate overheating are not enough to achieve comfort conditions, their use must be considered for the positive impact on reducing energy demand.

2. Adaptive Façades

The façade is the part of the building envelope that most conditions the heat exchange between the internal and external environments. Thus, it greatly impacts the building's thermal behavior and is critical for guaranteeing a comfortable indoor temperature. While heat exchanges in winter must be prevented by assuming low values of the heat transfer coefficient, in summer, these exchanges may be desirable, and having high U-values can benefit thermal comfort, contributing to the mitigation of the overheating phenomenon [21].

Façades are subjected to random meteorological variations throughout the year, such as solar radiation, precipitation, wind, and extreme temperatures, which have a relevant impact on interior comfort and energy consumption [22]. Furthermore, façades must respond to different functional scenarios that may contradict one another: shade vs. artificial lighting, views vs. privacy, solar gain vs. overheating, and daylight vs. glare [23]. Therefore, several parameters must be considered and reconciled during the design stage.

These particularities have instigated the research and development of different adaptive façades (AFs) concepts. Generally, these elements are defined as multi-parameter high-performance building envelopes that can change their behavior, mechanically or chemically, in real-time, according to external climate stimulus, through materials, components, or systems, to meet occupant needs [24][25]. Thus, it is possible to satisfy and optimize several functional requirements regarding heat transfer, air and water vapor flow, rain penetration, solar radiation, noise, fire, strength, stability, and aesthetics [26].

However, assessing the performance of AFs is difficult as no standardized evaluation procedures are defined, primarily because of their complexity and singularity. In addition, the existing building energy standards and rules that are being used to assess AFs have limited relevance for these systems, leading to less reliable results. Attia et al. [25] state that it is necessary to produce specific experimental protocols, datasets, and performance-monitoring methodologies and to adapt numerical simulation tools to guarantee an accurate comparison with traditional façades. Indeed, the accurate and reliable performance evaluation of a building with an AF is the first barrier to hinder the use of these systems in the market. The second barrier is the multiple stages that adaptive façades must pass before they can be used [25].

Indeed, according to Attia et al. [25], static performance measures (e.g., U-value, g-value, etc.) cannot adequately define the performance of AFs. Testing, inspecting, and assessing the operation performance of these systems in terms of thermal comfort and energy savings is very important. The results of long-term monitoring are also crucial. However, available results are scarce, and, for these reasons, very little is known about their actual behavior. Another critical factor restraining its full implementation in the market is the lack of awareness about using or interacting with an adaptive façade, which continues to be a barrier to occupant satisfaction and comfort.

Nowadays, the increasingly strict demands for building thermal insulation are reflected in EU member regulations. It is well-proven that thermal insulation is an effective way to reduce the heating energy consumption of a building while providing indoor thermal comfort. Yet its effects on the cooling season are somewhat disputed, as, in some conditions, it can worsen the overheating phenomena. However, this issue loses its relevance if the façade can react and adjust to the prevailing environmental conditions. Thus, the concept of the dynamic thermal insulation system (DTIS) was developed as a technology that counterbalances the few disadvantages of intense thermal insulation, by allowing buildings to adapt to varying seasonal climate conditions, changing from an insulation state to a conductive state [26]. Due to their capacity to vary their thermal resistance based on the surrounding conditions, DTISs are included in the adaptable façades category, modifying the heat flux between the internal and external environments.

DTISs are divided into four categories: passive systems that only use natural power sources to operate; hybrid systems that use a simple or complex automation system to operate; active systems that depend on a constant power supply to operate and maintain their performance; and systems not specified. Most of the studies on dynamic insulation systems focus on active technologies (60%) and are simulation-based (53%) [26].

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