

Application of Nanofluids in Buildings

Laura Cirrincione ^a, Gianluca Scaccianoe ^a, Marco Vocciante ^{b,*}

^aDipartimento di Ingegneria, Università degli Studi di Palermo, Viale delle Scienze Bld. 9, 90128, Palermo, Italy

^bDipartimento di Chimica e Chimica Industriale, Università degli Studi di Genova, via Dodecaneso 31, 16146, Genova, Italy
marco.vocciante@unige.it

This work reviews and discusses experimental and simulative studies related to nanofluid applications in buildings energy systems and envelope components, including photovoltaic thermal systems, Heating, Ventilation and Air Conditioning (HVAC) systems, thermal energy storage systems and windows. An overall review of the current studies available in the literature has been conducted, providing an overview of the potential benefits of using the main nanofluid-based techniques in the building sector, with reference to both energy and environmental considerations. The results show promising prospects for future developments, proposing the use of nanofluids for applications in buildings as a viable and effective sustainable solution, in line with what is included in the most relevant energy and environmental initiatives, such as the Sustainable Development Goals (SDGs) and EU Green Deal.

1. Introduction

Optimizing energy management and decarbonizing urban settlements represent two of the main goals of the International, European and National energy and environmental policies. Evidence of this are some relevant actions, such as the United Nations (UN) Sustainable Development Goals – SDGs (particularly Goals 11 and 12 concerning “responsible consumption and production” to “make cities and human settlements inclusive, safe, resilient and sustainable” (UN, 2024), the European (EU) environmental long-term strategies (EC, 2018) and frameworks on climate and energy (EC, 2014), GreenDeal (EC, 2019), and NextGenerationEU (EC, 2020); this last policy was subsequently imported nationally by most countries, as the Italian National Recovery and Resilience Plan – PNRR (MIMIT, 2021).

To this aim, it is important to improve the energy and environmental performance of buildings, since as well know, they constitute the predominant part of the urban fabric and are responsible for a large portion of energy consumption and related pollutant emissions (about 40% globally (IEA, 2019)). Among the various consumption items, those related to space conditioning (both heating and cooling) account for the largest share (UNEP, 2020).

In this framework, an effective strategy to enhance buildings resilience to climate change impacts consist in fostering the use of sustainable technologies, also from a circular economy perspective, in order to promote the energy equity and accessibility and move towards the conditions of Nearly Zero Energy Buildings – NZEB (EC, 2010) and Positive Energy Districts – PEDs (Cirrincione et al., 2023), as recommended by several European and National Directives (González-Prieto et al., 2023). Energy-efficient, smart and flexible energy storage and energy exchange are, in fact, crucial elements for a sustainable management of energy supply and consumption from a district energy system standpoint, of which buildings represent the main users (Cirrincione et al., 2022). For this reason, it is necessary to find innovative solutions to take care of building energy needs by increasing the energy efficiency of the processes involved while maintaining optimal comfort conditions for occupants, also in light of the climate peculiarities of the site (Du et al., 2023).

As a result, it can be seen that the recent years have seen the spread of systems that aim to couple the use of renewable energy sources (to reduce the reliance on fossil energy sources and related pollutant emissions), such as PVT systems (Cirrincione et al., 2020), with low-impact storage systems (Cao et al., 2023), such as those based on the use of hydrogen (Saeedmanesh et al., 2018) or PCM materials (Utpol et al., 2024).

At the same time, emphasis has been placed on the search for more effective working fluids that can improve the energy efficiency and thus the environmental and economic sustainability of heat transfer systems. In this regard, nanofluids (NFs) (Choi and Eastman, 1995), which are conductive fluids obtained by dispersing nanoparticles (NPs) of different types (metals, non-metallic elements, oxides, etc.) in conventional fluids (such as water, oil, glycols, etc.), have attracted much attention in the last decade (Bahiraee et al., 2018). Indeed, the use of NFs as working fluids represents a promising passive enhancement method, as the thermal conductivity of the continuous phase can be improved by adding NPs synthesized from materials having a higher thermal conductivity than commonly used fluids. This is also evidenced by many review studies on NFs applicable for heat transfer purposes, supporting their promising use in heat exchangers (HEs), microelectronics, household refrigerators, fuel cells, etc. (Sajid and Ali, 2019), especially when combined with the use of more efficient equipment to further improve savings (Vocciante and Kenig, 2021).

Based on the above considerations, the application of nanofluids for the energy processes concerning buildings seems to have promising prospects and indeed it has begun to be explored in recent times (Sathishkumar et al., 2024). In fact, in a broader view, this would also go a long way toward improving the resilience of buildings to climate change, a much-debated topic on which there has been increasing interest in recent years as mentioned earlier (Peri et al. 2024).

1.1 Aim of the work and adopted methodology approach

Within the above described context, given the novelty of this research topic, the purpose of this paper is to carry out an initial brief literature search on the use and performance of nanofluids for buildings in order to shed some light (and possibly highlight the pros and cons so far encountered) with respect primarily to the type of application and/or the building intended use, as reported in the following sections (Figure 1), also taking into account energy, environmental and economic aspects.

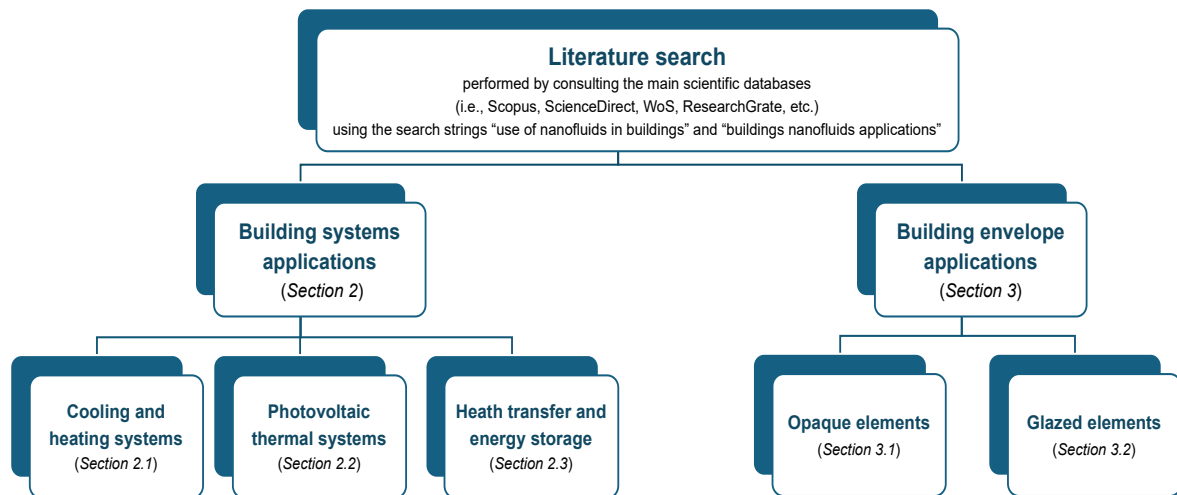


Figure 1: Main applications of nanofluids in the building sector

2. Buildings systems applications

2.1 Cooling and heating systems

Investigations on the application of nanofluids in the cooling and heating systems of buildings, have demonstrated that nanofluids containing suspended metallic nanoparticles (NPs) allow for the increase of thermal conductivity of the base fluids by a substantial amount (Colangelo et al., 2021). Using nanofluids in heating, ventilation and air conditioning (HVAC) systems could reduce volumetric and mass flow rates, and result in an overall enhancement of their performances in terms of coefficient of performance (COP) (Milanese et al., 2022). In fact, nanofluids necessitate smaller heating systems, which can deliver the same amount of thermal energy as larger heating systems using base fluids, but are less expensive, also enabling pumping power savings. This will additionally reduce environmental pollutants because smaller heating units use less power, and the heat transfer unit has less liquid and material waste to discard at the end of its life cycle (Kulkarni et al., 2009). On purpose, as previously mentioned, several studies analyzing various aspects can be found in the recent research literature, of which some of the most relevant ones are summarized below.

The incorporation of nanofluids in domestic absorption cooling systems has been examined to assess the thermal performance of diverse nanofluids typologies and concentration rates to determine an optimal configuration able to improve the cooling performance, hence allowing for a better energy efficiency, while at the same time lowering the running costs. The results confirm the feasibility of applying a self-absorption cooling system in the considered scenario, with nanofluid integrating traditional thermal insulation, proving to be indeed effective (Benazzouz et al., 2025).

Investigations on the performance of an innovative thermoelectric air conditioner powered by photovoltaic systems installed in a residential building using nanofluid as a coolant (as a Freon-free alternative to traditional air conditioning systems), showed an energy saving of 67 % and CO₂ emission mitigation of 76 % when compared with a conventional split air conditioner, while maintaining optimal indoor thermal conditions (Bakthavatchalam et al., 2022).

Another study on the potential use of single and hybrid nanomaterials (TiO₂, MgO and TiO₂/MgO) in split air conditioning device for cooling mode with an evaporative cooling unit has examined the performance of the system (in terms of energy savings), showing the economic viability of such a solution (Elsaid et al., 2025).

A simulative study concerning the use of a CuO nanofluid based solar absorption refrigeration cycle to improve summer cooling of residential buildings highlighted the good potentiality of such approach; showing that it would be possible to achieve a reduction in maximum and minimum indoor temperatures of 2 °C and 3 °C, respectively (compared to the traditional configuration), with an overall annual energy efficiency of over 40 % (Rahmani et al., 2022).

Desiccant-coated heat exchangers are one of the common solutions to lower energy usage and the related pollutant emissions for buildings cooling. An experimental study on the use of cerium oxide nanofluid as cooling fluid in such a system, has demonstrated how the addition and increase in nanoparticle concentration could allow for a moisture removal rate and dehumidification efficiency enhancement comprised between 3 % and 6 %, compared to a standard system (Kumar et al., 2023).

2.2 Photovoltaic thermal systems

Remaining in the field of thermal/energy applications, many researchers have investigated the use of nanofluids in photovoltaic thermal (PV/T) systems, specifically to collect thermal energy and cool the PV panels in order to generate more electricity, with the aim of selecting the optimal nanofluid to employ in this kind of equipment (Bandaru et al., 2021). Although numerous nanofluids have been examined, also mixed with water as primary liquid to form diverse coolants (including SiC, ZnO, TiO₂, CuO and Al₂O₃ particles, or Single / Multi-Walled Carbon Nanotubes), the issue still has several aspects to be explored and deepened, providing interesting insights for future research developments (Chaichan et al., 2025).

2.3 Heat transfer and energy storage

The synergetic effect of nanofluid and phase change materials (PCMs) on the heat transfer performance of a ground heat exchangers (GHEs) has also been explored, showing good potential (Liu et al., 2025).

Nanofluids are good candidates as working fluids, not only for solar harvesting (Alam et al., 2021) and energy storage related to buildings energy usage (Liu et al., 2023), but also for domestic hot water (DHW) systems (Khetib et al., 2021).

3. Building envelope applications

3.1 Opaque elements

Another field of application that is beginning to be explored is that concerning the building envelope. In this regard, the employment of water-based graphene nanofluid additives in cement-based materials has been proven capable of enhancing structural durability and performance of the structure (Wei et al., 2024). While other studies have investigated the use of nanoparticles to modify the thermal response of PCMs used in envelope components as an effective thermal insulation solution to reduce the energy exchange of buildings with their surroundings (Alqaed et al., 2022).

3.2 Glazed elements

Other interesting applications in the building sector concern the integration of the lighting and thermal aspects. On this aspect, a relevant application worth mentioning regards the use of nanofluids for the implementation of smart windows. Windows are indeed essential to maintain adequate indoor comfort conditions, not only in terms of lighting, but also for what concerns both cooling and heating needs (Zhang et al., 2023). With respect to this, the use of oxide-based nanofluids with near-infrared (NIR) selective absorption has been proposed to implement smart windows able to create dynamic light and thermal environments, showing a promising potential in the enhancement of indoor environmental control to manage both lighting and thermal conditions, especially during

summer (Wang et al., 2024). The use of NIR absorbing oxide-based nanofluids (i.e., antimony tin oxide – ATO) has also been investigated in relation to their use in photovoltaic windows (defined as PV-ATO windows), proving to be a viable solution for what concerns both energy savings and color rendering performance; in particular, on this last aspect, PV-ATO windows can actually outperform traditional windows (Shi et al., 2024). With a view to achieve carbon neutral and net-zero-energy buildings, nanofluid-based liquid filled windows represent another recently conceived solution for solar energy harvesting, other than effective indoor lighting and thermal regulation (Abd El-Samie et al., 2024). In fact, it has been proven that such window typology can allow to capture solar energy for domestic water heating with higher efficiency compared to the more-known water flow window, having better bandwidth absorption capacities; hence, representing a feasible and applicable solution especially for buildings located in hot regions (Pu et al., 2023).

Further significant employment in the building sector concerns the integration of the lighting/heating performance of nanofluids-based tubular daylighting devices (TDDs) (Liu et al., 2024). In fact, given that adequate lighting is essential in indoor environments, it often represents one of the major items in terms of energy consumption (Wu et al., 2024). In this regard, and in certain settings, TDDs have been demonstrated to be a good alternative to provide daylighting benefits (up to 50 % more solar radiation harnessed) while improving buildings energy savings and sustainability, even more considering that nanofluids can be integrated in the system to absorb the extra heat produced by TDDs to supply DHW systems (leading to overall savings comprised between 10 % and 20 %) (Liu et al., 2022).

4. Conclusions

The updated literature review showed that the application of nanofluids in the building sector is a new field of research that has attracted increasing interest, especially in the past five years, mainly with regard to thermal aspects. Indeed, the increased demand for energy consumption for air conditioning, due to rising temperatures, has created challenges related to thermal comfort inside buildings and the related environmental aspects in terms of pollutant emissions. It was also possible to observe how, when it comes to storage and exchange systems, especially in the building sector, two conflicting needs arise with respect to thermal conductivity/conductivity and specific heat capacity, namely, that of having a fluid that can store as much heat/energy as possible with high efficiency, while at the same time being able to set processes in motion quickly and with as little loss of charge/energy as possible. In addition, another important aspect to focus on is whether the technology employed is capable of consuming as little energy as possible to transport the storage/exchange fluid. Concerning the aforementioned aspects, the outcomes of the performed literature review has put in evidence that the use of nanofluids for buildings applications actually represents an innovative and effective solution, although it is still at an early stage, showing promising future developments, also with regard to the envelope applications, particularly regarding the lighting aspects.

The results of the conducted analysis will serve as a basis for the purpose of future modeling and experimental application developments of the research, actually under examination by the authors, concerning (i) the type of application best suited to the building type, in terms of building intended use (residential, industrial, commercial, etc.) and (ii) the scale of application, i.e., assessing whether it would make sense to expand the use of nanofluids to the scale of building clusters (e.g., as a district heating/cooling). Such future advancements, both based on considerations regarding energy, environmental and economic aspects, can be useful tools to support stakeholders and policy makers in establishing methods and strategies for sustainable buildings implementation and/or retrofit, in line with the latest energy and environmental policies issued at international, European and national levels.

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