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Roof cooling by direct evaporation from a porous layer

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ABSTRACT

As the world continues to urbanise, significant challenges are arising to environment, energy and water sustainability in cities. One of the most challenging consequences of increased urbanisation is increased energy consumption adversely affecting the quality of life, environment and public health. This motivated many researchers to find innovative methods to reduce energy consumption in buildings for cooling practices. In this paper, a series of experiments was conducted to investigate the performance of an evaporative layer of porous media and the effects of its particle size on reducing the roof surface temperature. To do so, customized rectangular Plexiglas columns were packed with three types of sand with well-defined particle size distribution saturated with water with all boundaries closed except the top, which was exposed to air for evaporation. The obtained results revealed the great potential of drying porous media to reduce the heat flux through roof via utilizing a part of the energy for liquid vaporization. As particle size decreased the temperature of roof remained lower than the bare roof for a longer time as a result of the presence of more liquid pathways connecting the receding drying front to the evaporation surface, which kept the surface wet for a longer time. Our results present new insights about the physical mechanisms controlling the performance of drying porous media to regulate roof surface temperature.

1. Introduction

Increasing energy efficiency is an immediate priority to cut carbon emissions, secure energy as well as save on energy bills. Over the past few decades, the improvement of living standards and the affordability of air conditioning have led to a considerable increase in the energy consumption related to space cooling. Additionally, the so-called urban heat island effect, resulting from increased urbanisation, contributes to making cities several degrees hotter than their rural surroundings [1–3]. This increases energy consumption for cooling of residential and commercial buildings. Therefore, developing novel approaches to improve cooling energy efficiency of buildings is essential to meet our low carbon economy targets. This will become even more important in the near future with the increase in climate change, not only in hot, but also in temperate climates such as in the UK [4,5].

Traditionally, roofs in some mid and high latitude locations consist of envelope materials (such as clay and asphalt) with a relatively high absorption coefficient, transferring large amounts of heat to the building. This leads to warmer indoor spaces in the summer and as a result higher demands for air conditioning. Roofs can represent up to 32% of the horizontal surface of built-up areas [6] and are important determinants of energy flux and heat transfer through the building envelopes. The roof offers the greatest opportunities for improving the cooling of buildings. It is the building element that is most exposed to the sky. Therefore, significant efforts have been made to reduce this heat load by improving roof design [7,8]. As a result of such efforts, several methods have been proposed. The so-called 'green roof' is an example of such a design [9,10]. A green roof is a roof that contains a soil (growing media) and vegetation layer as its outermost surface, allowing better regulation of building temperatures [9]. Although use of green roofs provides significant benefits, not only in energy consumption but also in urban microclimatological and environmental terms [11], some disadvantages have been noted as well. Installation cost is elevated and maintenance of the green roof system, i.e. watering and replacing the old plants, is required regularly at additional cost. Besides, in terms of building structure, enhanced structural support is required to accommodate green roof systems to ensure sufficient capacity to resist weight load under the soil and vegetation and avoid collapse [12], further adding to the cost.

Other examples of alternative roofs include roof ponds and evaporation-based roof cooling systems [7,13]. While no porous

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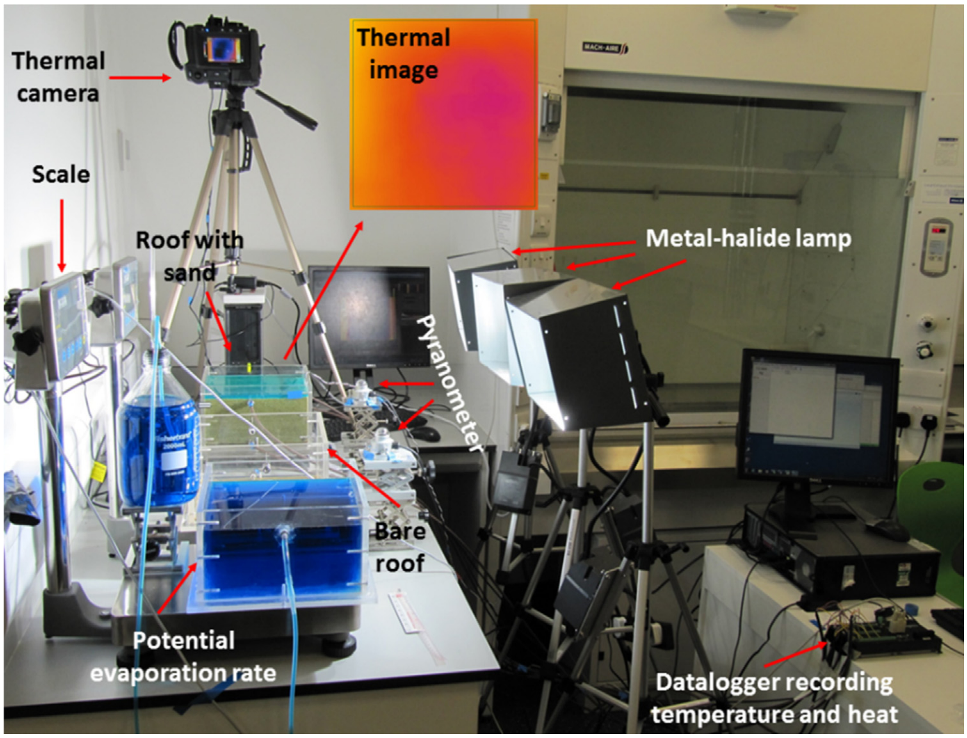

Fig. 1. Experimental setup. The container filled with dyed water was used to measure the potential evaporation rate. The container packed with sand particles (labelled as "Roof with sand") was used to investigate the performance of drying porous media in reducing the surface temperature compared to the bare roof (the middle column). A thermal camera was fixed on top of the roof covered with drying porous media. Metal halide lamps were used to heat the containers. Two pyranometers were used to measure the radiation flux (they were positioned parallel to the roofing surfaces to capture the flux normal to these surfaces). The column packed with sand grains was equipped with thermocouples at the surface and bottom of the column. Additionally, a heat flux sensor was buried in the middle of the sand column. The data measured by the thermocouples, heat flux sensors and the pyranometers were recorded using a datalogger connected to a PC.

medium is used in these evaporative roof systems, latent heat of evaporation remains the main mechanism used to cool the building roof [14], as with green roofs. Crawford and da Silva [13], among many others, studied the capability of a roof-based evaporative pumping system to lower thermal loadings imposed on the interior of a building to reduce energy consumption as a result of air conditioning. Jain [15] presented thermal models to evaluate the performance of various passive cooling roof systems including bare roof, wetted roof surface, and evaporative cooling using water pond with movable insulation and concluded that a roof pond with movable insulation offers an efficient method for roof cooling.

There are many papers that investigated evaporation-based (green or otherwise) roof cooling systems and a comprehensive review is beyond the scope of the present paper. But in general, the effectiveness and viability of these types of roofs depend very strongly on the local settings such as local climate, native vegetation, and water availability [1,16,17]. It should be also noted that the very concepts of these types of roofs are designed for regions with abundant rainfall and water resources, and with native vegetation species that produce high cooling by evapotranspiration (in the case of green roofs). Considering the rising temperature trends even in temperate cities (e.g. London), it is important to develop innovative, sustainable and cost-effective approaches capable of cooling buildings under a variety of conditions.

Recently, there have been some efforts to evaluate the performance of porous materials to be used on roofs (without vegetation) to create an effective system for reducing heat flux through buildings by utilizing their moisture absorption and evaporation capabilities [12]. A robust explanation and quantitative tool to predict the performance of a given drying porous media on reducing the heat flux through buildings are still missing due to a lack of deep physical understanding of how the thermal performance of drying porous media is affected by their transport properties, the properties of the evaporating fluid, and the external boundary conditions [18–22].

Typically the evaporation rate from initially saturated porous media is relatively high and is controlled by the atmospheric condition, the so-called stage-1 evaporation. During this period, liquid water is transported toward the evaporation surface via the capillary induced liquid flow connecting a receding drying front, marking the interface between the saturated and unsaturated zone [23], to the evaporation surface where liquid vaporization takes place supporting the evaporative demand. At a certain drying front depth or surface water content, the liquid continuity between the drying front and the evaporation surface is ruptured as a result of the interplay among the upward capillary force and the downward gravity and viscosity forces. Consequently the liquid meniscus recedes from the surface to a level below the surface forming an overlying thin dry layer. This marks the end of stage-1 evaporation [24]. When all liquid meniscuses are disrupted, a new vaporization plane forms very close to the surface which marks the onset of the so-called stage-2 evaporation. During this period, liquid is transported from the saturated zone to the new vaporization plane formed inside the porous medium followed by liquid vaporization at that level and vapour diffusion through the overlying dry layer [25]. Stage-1 and stage-2 evaporation are limited by the atmospheric conditions and the transport properties of porous media, respectively [26–28].

In the present paper, a novel approach was proposed to reduce the energy consumed for cooling buildings by utilizing drying porous materials (with no vegetation) on roofs. By consuming a part of the radiative energy received at the roof surface for liquid vaporization, the evaporative porous layer reduces the heat flux through the roof, as well as the convective heating of the outdoor