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Experimental assessment and model validation of a vertical cooling panel

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ABSTRACT

The energy used for cooling has increased in recent decades and the predicted future rise in consumption is driving a pressing need for more efficient technologies. Some technologies use environmental sinks as heat dissipation alternatives. This paper presents a model validation with experimental data from a passive vertical cooling panel. The novelty of the solution lies in two main characteristics. The first is that the panel is in a vertical position, and thus the heat sink is the ambient temperature and surrounding instead of the sky temperature. The second is that the panel is north-oriented. Avoiding the sun lengthens the operating time to the entire day, while most studies explore options that are limited to night radiation. The aim is to include this element as a heat exchanger before water moves into the cooling tower from the condenser stage in cooling systems. The results have shown that the model approaches significantly the experimental data with an average error of 1.5% in the dissipated heat. Besides, the cooling capacity of the panel varies from 107 to 230 W/m^2 depending on the inlet temperature and fluid flow conditions, confirming the viability of the integration in buildings.

1. Introduction

The demand for cooling has increased over recent years, and it is expected that this demand will increase in the future [1]. This has led to a considerable growth in electricity consumption, mostly in warm climates during summer periods. The performance and efficiency of cooling systems is a current challenge, one which has been mostly tackled with combined active and passive techniques that decrease the amount of energy required. Passive cooling systems are those techniques that use natural driving forces to circulate fluid, while active systems require external mechanical power to operate. Hybrid systems are the combination of both, the use of natural driving forces and the need of mechanical power [2]. The system presented in this paper is included within hybrid cooling system solutions. In this article, a novel use of a passive vertical cooling panel is analysed and its model is validated with experimental data.

This solution arises from applying biomimetic concepts for cooling purposes in buildings [3]. The project, entitled 'Redesign of the Integration of building energy from Metabolisms of Animals' (RiMA), sought animal thermoregulation strategies predisposed to implement in the design of HVAC&R systems [4]. From this experience, several natural-inspired solutions were developed, such as to thermoelectric façade optimization based on beehives strategies [5], office buildings thermal performance improvements inspired by tunas thermal regulation [6] or heat recovery ventilator cores simulation in cascade connection based on tunas heat management strategies [7].

All these solutions can be the result of applying two different approaches; the solution-based approach, where a solution is found in nature and is transferred to the technological domain, or, on the contrary, the problem-based approach, where a problem is defined in the technological field and possible solutions are sought in nature. In this case, the initial aim was to find an alternative which would minimise the drawbacks carried using systems that include evaporative cooling (problem-based approach). Among those drawbacks there are the high water consumption, the risk of legionella outbreaks, high operation and maintenance costs, and noise and vibrations. In this context, different forms of heat dissipation in animals that avoid evaporative cooling were sought. In fact, dry heat dissipation techniques used by certain animals, based on the use of dry body surfaces instead of sweating, are extrapolated to buildings as mean of cooling. One of the examples of dry heat dissipation is the elephant, which dissipates excess heat through its pinnae [8]. Hence, the main question to be answered was, what would be the performance and applicability of a cooling system

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Nomenclature

α_a	thermal diffusivity
α_s	solar absorptivity
A	surface area (m^2)
c_e	specific heat (kJ/kg K)
C_s	thermal conductivity of the bond (W/m K)
d_t	distance between tubes (mm)
d	index of agreement
D	diameter (mm)
ρ	density (kg/m^3)
σ	Stefan–Boltzmann's constant ($W/m^2 K^4$)
ε	emissivity
f	friction factor
F'	panel efficiency factor
F_R	heat removal factor
g	gravity
h	heat transfer coefficient ($W/m^2 K$)
k	thermal conductivity (W/m K)
L	height
$\dot{m}$	mass flow rate (kg/s)
n	number of pipes
η_f	fin efficiency factor
Nu	Nusselt number
Pr	Prandtl number
q	volumetric flow rate (l/min)
$\dot{Q}$	total heat transfer (W)
$\dot{Q}/A$	total heat transfer per unit area (W/m^2)
Ra	Rayleigh number
Re	Reynolds number
$\dot{S}$	solar radiation (W/m^2)
U_L	overall thermal losses coefficient ($W/m^2 K$)
T	temperature (°C)
t	thickness (m)
μ	dynamic viscosity (kg/m s)
v	wind velocity (m/s)

Subscripts

a	air
amb	ambient
conv	convective
exp	experimental
ext	external
f	film
in	inlet
int	internal
mod	model
out	outlet
p	panel
rad	radiative

based on the use of heat dissipation surfaces? Integrating this solution in building facades would eliminate or reduce most of the drawbacks associated with evaporative cooling and will improve the performance of a cooling system.

Cooling by heat dissipation is based on transferring excess heat from a building to a sink at a lower temperature, such as ambient air, the water, the ground or the sky [9]. The same study shows that the main processes of heat dissipation are usually divided into one of four types: ground cooling, evaporative cooling, convective (or ventilation cooling), and radiative cooling.

The studies related to radiative heat dissipation usually adopt the sky temperature as heat sink. For this reason, the studies are focused on night cooling and employ flat plate solar collectors. The study by Erell [10] was one of the first models for calculating night radiative cooling, where the model for solar collectors was adapted to night heat dissipation. More recent studies have used similar models for radiative and convective dissipation, as in the case of [11], where the maximum error achieved of the dissipated heat was 5% for three different panel configurations. Through this technique, the cooling capacity of flat plate collectors has been demonstrated. In similar cases, up to 10% of the power consumption for cooling purposes is saved [12]. Moreover, even a constant cooling capacity through the night has been demonstrated [13]. Other study has also analysed the cooling capacity of a radiative panel depending on the tilted angle, where the cooling potential decreases considerably in a vertical position [14]. The rise of interest and investigation the last years on phase change materials has also affect the radiative cooling, where Zang et al studied the performance of a hybrid system involving night radiative cooling with microencapsulated phase change material storage. They conclude that the system has weaker effect in hot and humid climates than dry climates with low ambient temperature at night [15]. In fact, passive cooling systems are dynamic systems and their performance varies with time of day, seasons [16] and location.

In all the above studies, the system configuration consists in the connection of the radiative panel to a storage tank, being the panels roof elements and the sky temperature the heat sink [17]. Therefore, the working temperatures are lower than the temperatures considered in this paper and so are the cooling capacity rates. However, the solution presented in this paper is a vertical panel. Regarding vertical cooling systems, the most expanded solutions are based on exterior cooling walls using evaporative cooling [18,19]. Yong et al. [20] analysed the performance of a solar heating and cooling panel in vertical position. In a further study, they assess the effects of radiation and convection on a cooling panel at different tilt angles. Part of the analysis includes the relation between ambient temperature and radiation performance, where it is concluded that increasing the temperature difference between the ambient air and the panel will increase the radiation cooling capacity [14].

There are two primary differences between this study and the studies summarised above. The first is the use of a vertical panel for heat dissipation during 24 h rather than only night cooling. The second is that heat dissipation is assumed to occur with the ambient temperature and the surroundings, instead of sky temperature. In addition, this proposal offers numerous design possibilities regarding architectural integration. In principle, it requires large vertical surfaces to dissipate heat. The larger the surface the higher the heat dissipation rate and so the cooling potential. Thus, the final solution will be directly related with the design of the façades and the integration of the cooling panel as an external layer of those surfaces. To that end, an experiment was carried out during the entire day on a cooling panel placed next to a building facade. The objectives of the paper are:

- To analyse the effects of the ambient temperature on the performance of the cooling panel.
- To model the panel to obtain theoretical values for the outlet temperature and validate it with the experimental data.
- To assess the panel's cooling potential and applicability in buildings.

The panel used in this study is north oriented and it is monitored 24 h a day. Given the verticality of the panel and the orientation, the heat is transferred to the ambient temperature instead of the sky temperature. The performance of the panel is based on the dissipation of heat by means of natural convection and radiation to the ambient air and the surroundings. To the best of our knowledge, to date no work has been conducted to evaluate the cooling perfor-