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Research Paper

Computer modelling and experimental investigation of building integrated sub-wet bulb temperature evaporative cooling system

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HIGHLIGHTS

- Computer modelling of a sub-wet bulb temperature evaporative cooler.
- Experimental validation of the computer model.
- High measured cooling capacity of 225 W/m^2 of wet surface area.
- High wet bulb effectiveness of 1.02.
- Suitable for building integration.

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ABSTRACT

The paper presents computer modelling and laboratory experiment results of a sub-wet bulb temperature indirect evaporative cooling system for space cooling in buildings. The prototype employs hollow porous ceramic water containers as wet media material for water evaporation. The cooled air is delivered without increasing its moisture content. The performance of the cooler was evaluated using a computer model, and the results of which were validated experimentally. The cooling capacity and effectiveness of the cooler were evaluated at inlet air dry bulb temperature of 30 and 35 °C and relative humidity ranging from 35% to 50%. It was found that the cooler can supply air for space cooling at sub-wet bulb temperature conditions; achieve measured cooling capacity approaching 225 W/m^2 of exposed ceramic material wet surface area and wet bulb effectiveness higher than unity. The high thermal performance of the constructed evaporative cooler indicates the system could be a potential substitute to conventional mechanical air-conditioning systems in buildings in many parts of the world where hot and dry climatic conditions prevail.

1. Introduction

Energy consumption in buildings stands at between 30 and 40% of the total primary energy use globally [1,2]. A major part of this is used to provide comfort conditions for occupants. For example, in regions with cold and temperate climates such as northern Europe, energy for space heating and hot water accounts for over 60% of the total energy use in buildings, whereas in hot climate regions, a similar proportion of energy consumption is required for space air cooling in buildings. The growing demand for air-conditioning systems in the world is mainly driven by the increase in living standards, affordability, population growth and cheap energy in some parts of Middle East. This has led to peak electricity loads increasing sharply in many countries with severe strains on electricity grids, putting pressure on governments to respond with short term measures of building new fossil-fuelled power plants and extending the grid infrastructure, which in turn is costly and impacts negatively on the environment.

Currently, the market for air-conditioning systems is dominated by mechanical vapour compression systems, which are energy-intensive systems and suffer from low performance in hot climates where they are often required. In hot and dry climates such as desert climates, application of low carbon cooling technologies such as evaporative cooling can offer a viable solution for space cooling in buildings. The current focus for many researchers includes methods of integrating evaporative cooling into contemporary architecture and the development of novel wet media materials for efficient evaporation of water. Duan et al. [3]

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Nomenclature

c_{pa}	specific heat capacity of air (J/kg K)
c_{pfw}	specific heat capacity of water (J/kg K)
D	depth of airflow channel (m)
D_{im}	water vapour diffusion coefficient in the wet channel (m^2/s)
dx	control volume step length (m)
g	moisture content of air (kg/kg_d)
g_a	moisture content of air in the wet channel (kg/kg_d)
g_{ao}	outlet air moisture content of wet channel (kg/kg_d)
g_{do}	outlet air moisture content of dry channel (kg/kg_d)
h_c	thickness of ceramic container (m)
g_{fw}	moisture content of air at saturation (kg/kg_d)
h_{fg}	latent heat of vaporisation of water (J/kg)
h_w	thickness of water layer in the ceramic container (m)
h_d	height of dry channel (m)
h_a	height of wet channel (m)
h_c	wall thickness of ceramic panel (m)
K_a	air thermal conductivity (W/m K)
L	length of airflow channel (m)
$\dot{m}$	air mass flow rate in the wet channel (kg/s)
$\dot{m}_d$	air mass flow rate in the dry channel (kg/s)
$\dot{m}_{fw}$	water mass flow rate in the wet channel (kg/s)
N	number of control volumes
Nu	Nusselt number (–)
Pr	Prandtl number (–)
Re	Reynold number (–)
Sc	Sherwood number (–)
Sh	Schmidt number (–)
T	air dry bulb temperature (°C)
t_a	air dry bulb temperature in the wet channel (°C)
t_{ao}	wet channel outlet air dry bulb temperature (°C)
T_d	air dry bulb temperature in the dry channel (°C)
T_{di}	dry channel inlet air dry bulb temperature (°C)
T_{do}	dry channel outlet air dry bulb temperature (°C)
T_{dp}	inlet air dew point temperature in the dry channel (°C)
T_{fw}	air temperature of the water film on the surface of the ceramic panel (°C)
T_{wi}	inlet air wet bulb temperature in the dry channel (°C)
U_d	overall heat transfer coefficient (W/m^2 K)
x	air flow direction coordinate (m)

Greek symbols

α_d	convective heat transfer coefficient in the dry channel (W/m^2 K)
α_a	convective heat transfer coefficient in the wet channel (W/m^2 K)
ε_{dp}	dew point effectiveness (–)
ε_{wb}	wet bulb effectiveness (–)
λ_c	thermal conductivity of dry ceramic material (W/m K)
λ_{csw}	thermal conductivity of water saturated ceramic panel (W/m K)
λ_w	thermal conductivity of water layer in the hollow ceramic panel (W/m K)
μ	air dynamic viscosity (kg/m s)
ϕ	porosity of the dry ceramic material (–)
ρ	density of air (kg/m^3)
σ_a	convective mass transfer coefficient in the wet channel (kg/sm^2)

conducted an extensive review of indirect evaporative cooling technology and pointed out the continuous development of the technology. The authors concluded that indirect evaporative cooling systems have the potential to be a viable alternative to conventional mechanical vapour compression refrigeration systems in air conditioning in buildings.

The use of evaporative cooling for thermal comfort in buildings was practiced by ancient Egyptians and the Romans for hundreds of years by placing a wet mat over a door or window frame in the summer time through which prevailing winds force air into the building living space [4]. Today, this method of space cooling has been refined and adopted for modern buildings in hot and arid areas such as Middle East, South western part of the United States and the Indian subcontinent [5]. For example, in Saudi Arabia, there are over 48,000 rooftop-mounted direct evaporative air coolers installed in tents accommodation, railway stations and public spaces [6]. In such climates, evaporative cooling can be an effective solution in achieving space comfort in buildings for most times of the year. Fig. 1 shows that evaporative cooling systems, when operating at optimum conditions, can meet the comfort requirement in buildings by bringing depressing the ambient air dry bulb temperature and humidity to within the required building comfort zone for air conditioned building [7].

1.1. Arrangements of evaporative cooling technology

Evaporative cooling systems can be classified into two main categories: direct and indirect coolers. Direct evaporative cooling is the process of evaporating liquid water to the surrounding air to cause its dry bulb temperature to decease. This evaporation process is adiabatic in nature as the surrounding air sensible heat decreases as the dry bulb temperature is depressed while its latent heat increases with a rise in moisture content. Modern direct evaporative cooling systems employ sophisticated wet pad materials through which forced air is drawn in by a fan for direct contact between the airstream and water [8].

In contrast, in an indirect evaporative cooler, the supply air is cooled without increasing its moisture content. This is accomplished by using a heat exchanger to separate the dry and hot inlet airflow from the cool and wet outlet airflow in the wet channel [3]. The temperature gradient necessary for heat transfer between the two airflows is influenced by the wet bulb temperature of the airflow in the wet channel where direct evaporation takes place. The cool air in the dry channel is then supplied without increasing its moisture content. However, in such systems, the supply air is at best cooled to within 2–3 °C of the wet bulb temperature. This constitutes a severe thermodynamic limitation, and a disadvantage compared to vapour mechanical air-conditioning systems.

An improvement to the cooling process of indirect evaporative cooling systems has been the focus of many leading researchers with the aim of increasing thermal effectiveness and supplying air temperatures below the ambient air wet bulb temperature. The pioneer work of Maisotsenko led to the development of the M-cycle which for the first time sub-wet bulb temperatures can be achieved by an evaporative cooling process. The M-cycle is a combination of a cross-flow, multi-perforated flat-plate heat exchanger and evaporative cooling, in which; the supply air is cooled in the dry channel at constant moisture content part of which is diverted to wet channel to perform the evaporation process [9]. Thus, the wet channel air temperature is decreased below the bulb temperature, and the lower boundary limit can be extended to the dew-point temperature of the incoming air. This type of evaporative cooling system is also referred to as dew point or sub-wet bulb temperature indirect evaporative cooling.