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Numerical investigation of the energy performance of a guideless irregular heat and mass exchanger with corrugated heat transfer surface for dew point cooling

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ABSTRACT

The paper presents an investigation into the energy performance of a novel irregular heat and mass exchanger for dew point cooling which, compared to the existing flat-plate heat exchangers, removed the use of the channel supporting guides and implemented the corrugated heat transfer surface, thus expecting to achieve the reduced air flow resistance, increased heat transfer area, and improved energy efficiency (i.e. Coefficient of Performance (COP)) of the air cooling process. CFD simulation was carried out to determine the flow resistance (K) factors of various elements within the dry and wet channels of the exchanger, while the 'finite-element' based 'Newton-iteration' numerical simulation was undertaken to investigate its cooling capacity, cooling effectiveness and COP at various geometrical and operational conditions. Compared to the existing flat-plate heat and mass exchangers with the same geometrical dimensions and operational conditions, the new irregular exchanger could achieve 32.9%–37% higher cooling capacity, dew-point and wet-bulb effectiveness, 29.7%–33.3% higher COP, and 55.8%–56.2% lower pressure drop. While undertaking dew point air cooling, the irregular heat and mass exchanger had the optimum air velocity of 1 m/s within the flow channels and working-to-intake air ratio of 0.3, which allowed the highest cooling capacity and COP to be achieved. In terms of the exchanger dimensions, the optimum height of the channel was 5 mm while its length was in the range 1–2 m. Overall, the proposed irregular heat and mass exchanger could lead to significant enhanced energy performance compared to the existing flat-plate dew point cooling heat exchanger of the same geometrical dimensions. To achieve the same amount cooling output, the irregular heat and mass exchanger had the reduced size and cost against the flat-plate ones.

1. Introduction

Conventional mechanical vapour compression air conditioning systems consume high power, create high carbon emission and cause severe environmental impact. Several alternative cooling systems, e.g. adsorption, absorption, desiccant and ejector cooling, are less efficient in terms of energy utilisation and practicality [1]. Evaporative cooling, by using water evaporation to absorb heat, is an extremely low energy and environmentally friendly cooling principle. However, owing to the theoretical constraint of the air wet-bulb temperature, this system has very limited temperature reduction potential which has restricted its wider application [2–5]. Dew point cooling, being a new form of Indirect Evaporative Cooling (IEC), can break up this limit, thereby achieving higher cooling efficiency than conventional IEC. This technology is established on a M-cycle heat and mass exchanger which basically has the cross- or counter-flow types [6–10].

Researches on the M-cycle cross- and counter-flow heat and mass exchangers for dew point evaporative cooling are numerous. These included the experiment-based, simulation-based and combined experiment and simulation works. In terms of the experiment, Bruno F. [8] constructed a flat-plate cross-flow heat and mass exchanger which used a special medium with high water retention and wickability characteristics as the wet channel, and a

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Nomenclature

a	side length of computational element, m
A	heat and mass transfer area of computational element, m^2
COP	Coefficient of Performance
C_P	specific heat capacity, kJ/kg °C
De	equivalent diameter, m
Dh	hydraulic diameter, m
en	latent heat, kJ/kg
g	gravity acceleration, m/s^2
h	convection coefficient, $W/(m^2\ °C)$
h_m	mass transfer coefficient, m/s
H	height, m
hum	humidity ratio, kg/kg
i	enthalpy, kJ/kg
l	length, m
l_0	thermal entry length, m
Le	Lewis number
Nu	Nusselt number
n	number
P	pressure, Pa
$\triangle P$	pressure drop, Pa
$\triangle Pf$	frictional pressure loss, Pa
$\triangle Plocal$	local pressure loss, Pa
$Qcooling$	cooling capacity, kW
Qm	mass flow rate, kg/s
Pr	Prandtl number
Re	Reynolds number
s	area, m^2
T	temperature, °C
Tf	air temperature, °C
u	air velocity, m/s
W	electric power, kW
x	distance, m

Subscripts

air	air
air, wet	wet air
dp	dew point
dry	dry channel
dry, in	inlet of dry channel
dry, out	outlet of dry channel
f	airflow
fan	fan
in	inlet
out	outlet
steam	water steam
pump	pump
vap	evaporated water
w	channel wall
water	water
wb	wet-bulb
wet	wet channel
wet,in	inlet of wet channel
wet, out	outlet of wet channel

Greek

λ	conduction coefficient, kW/m °C
α	thermal diffusivity, m^2/s
λf	coefficient of friction resistance
ζ	coefficient of local resistance
σ	surface wettability factor
$\triangle$	difference between two states
μ	dynamic viscosity, kg/(m s)
ρ	density, kg/m^3
φ	working air fraction over inlet air
ε	effectiveness
η	efficiency

moisture-impervious membrane as a dry channel. The tests indicated that the exchanger had a dew point effectiveness of 75%, which was relatively lower under the given operational condition. Coolerado (USA) developed a cross-flow heat exchanger with perforated holes on the flow paths. A test indicated that this type of exchanger could obtain the wet bulb and dew point effectivenesses of around 80% and 50% under the specified operational condition [11], which is around 20% higher than that of the conventional IEC heat exchangers. Velasco G. at al [12] carried out an experiment study into a polycarbonate-made IEC heat exchanger. The results indicated the IEC heat exchanger could obtain higher cooling capacity and also increased cooling effectiveness when spraying water against the cooling air. Higher outdoor air temperature or air flow rate helped obtain enhanced cooling performance of the system. Riangvilaikul et al. [13] carried out an experimental investigation into a novel dew point evaporative cooling system, indicating that the wet-bulb and dew point effectivenesses were in the range 92%–114% and 58%–84%, under the pre-set operational condition.

In terms of the computer simulation and combined modelling and experiment, J. Lin et al. [10] presented a numerical study of a dew point evaporative cooling system with counter-flow configuration. The study found the saturation point of working air occurring at a fixed point regardless of the inlet air conditions, minimum intensity point of water evaporation of 0.2–0.3 m from the entrance and overall heat transfer coefficient above 100 $w/(m^2\ K)$ in wet channel of the unit. Tuisidasani et al. [14] studied the relation between the Coefficient of Performance and air velocity for a tube type IEC heat and mass exchanger using both modelling and experimental methods, indicating that the maximum COP of the IEC unit was 22 at the primary air velocity of 3.5 m/s and the secondary air velocity of 3 m/s, leading to 10.4 °C of primary air temperature drop. Riangvilaikul and Kumar [15] presented a numerical study of a counter-flow heat exchanger, which involved the numerical simulation of the heat and mass transfer processes within the flow channels, and experimental validation [13]. Reasonable agreement was achieved between the numerical and experimental results, giving 5–10% of deviation in terms of the outlet air temperature and effectiveness, respectively. The dew point effectiveness of the unit was in the range 58%–84%, higher than cross-flow exchanger. Zhao et al. [16] conducted a numerical study into a novel counter-flow flat-plate heat and mass exchanger for dew point cooling, indicating that cooling effectiveness and energy efficiency of the exchanger were largely dependent on the dimensions of the air flow passages, air velocity and working-to-intake air ratio, and less dependent on the temperature of the feed water. Zhan et al. [6] carried out a comparative study into the M-cycle counter-flow and cross-flow flat-plate heat exchangers for indirect evaporative coolers (IEC), indicating that the counter-flow exchanger offered greater (around 20% higher) cooling capacity,