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Optimization of a heat assisted air-conditioning system comprising membrane and desiccant technologies for applications in tropical climates

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ABSTRACT

Separating dehumidification and cooling loads in air-conditioning systems has been proven to be a potential strategy to reduce electricity consumption if the dehumidification of air is mostly performed by heat-powered system components. Referring to experimental experiences in Singapore, this paper presents a novel electricity-efficient air-conditioning system consisting of a membrane unit, an evaporatively cooled sorptive dehumidification system (called ECOS system) and a high-efficient conventional cooling unit. The dehumidification of air is performed by a combination of the membrane unit and the ECOS system, and the sensible cooling of air is accommodated by a high-efficiency conventional chiller and in part by the membrane device. In order to find an optimized balance of the three air-conditioning components, an optimization-based simulation approach using a genetic algorithm is developed. The optimization is based on a simple objective function that comprises operating and investment costs. The optimization results reveal that an integration of a relatively large membrane unit, a small ECOS unit and a chiller operating at an elevated evaporation temperature is the most cost effective combination meeting comfort criteria. The resulting optimized combination has potential to save more than 50% of the system's lifetime operating cost compared to conventional systems supplying 100% fresh air.

1. Introduction

Air-conditioning systems contribute more than 30% to the total electricity consumption of buildings worldwide and up to 70% in hot and humid regions [1]. Conventional air-conditioning systems based on dew-point technologies have a high demand for electric energy in order to handle both latent and sensible loads of the ambient air in one single thermodynamic process [2]. In such systems, generally the humid ambient air is cooled below a necessary dew-point temperature (6–10 °C) in order to satisfy the dehumidification need.

Membrane-based humidity and heat exchanger units operating between the return and the fresh air stream can reduce the electricity demand of such systems considerably due to the reduction of latent and sensible loads on the chiller system [3]. A further reduction of the electricity demand is possible if the whole latent load of the supply air is covered by a combination of a membrane unit and a desiccant dehumidification system [4]. This combination benefits from a partial dehumidification and cooling in the membrane unit (with only little additional electricity consumption for fans) and the substitution of electric energy by heat energy for the final dehumidification process in the desiccant system [5]. The required heat energy can be supplied e.g. from waste energy sources or via solar energy conversion [6]. After sufficient dehumidification, the sensible cooling of the air can be performed by a highly efficient conventional chiller unit (operating at elevated evaporation temperatures, e.g. in combination with chilled ceilings or chilled beams) [7] or even by novel technologies like indirect evaporative cooling [8].

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Nomenclature and acronyms

a	Height of channels (m), Thickness of adsorption bed (m)
A	Area (m^2)
AC	Air-conditioning system
c	Specific heat capacity ($Jkg^{-1}\ K^{-1}$)
C	Objective function (€)
c_1	Unit electricity cost (€/kWh)
c_2	Unit heat cost (€/kWh)
c_3, c_4	Unit material cost (€/m^2)
c_5, c_6	Unit fabrication cost (€)
COP	Coefficient of performance (−)
D_{eff}	Effective diffusion coefficient of the membrane ($m^2\ s^{-1}$)
E	Electric/heat energy consumed over the system's lifetime (kWh)
$\dot{q}$	Specific heat flux (Wm^{-2})
$\dot{q}_{ads}$	Specific heat flux due to generated adsorption heat (Wm^{-2})
$\dot{q}_{conv}$	Specific heat flux due to convective heat transfer (Wm^{-2})
$\dot{q}_{mass}$	Specific heat flux due to mass transfer (Wm^{-2})
h	Convective heat transfer coefficient ($Wm^{-2}\ K^{-1}$)
H	Enthalpy (J)
J	Specific water vapour transfer rate ($kgm^{-2}\ s^{-1}$)
k	Convective mass transfer coefficient ($kgm^{-2}\ s^{-1}$)
N	Number of pairs of channels (−)
Q_{ads}	Adsorption heat (Jkg^{-1})
t	Time (sec)
T	Temperature (K)
u	Air velocity (ms^{-1})
W_s	Water content in the adsorbent ($kg_w kg_s^{-1}$)

Greek Letters

α	Convective heat transfer coefficient ($Wm^{-2}\ K^{-1}$)
β_{eff}	Effective mass transfer coefficient ($kgm^{-2}\ s^{-1}$)
δ	Thickness of membrane (m)
ε_{lat}	Latent effectiveness
ε_{sen}	Sensible effectiveness
ε	Porosity in the adsorbent bed (−)
ρ	Density (kgm^{-3})
ψ	Dehumidification efficiency
ω	Humidity ratio ($kgkg^{-1}$)

Subscript

a	Air
ads	Adsorption
amb	Ambient air
ave	Average
co	Cooling, Cooling air
e	Electric energy
fab	Fabrication
fan	Fan
h	Heat energy
$invt$	Investment
lat	Latent
m	Membrane
mat	Material
mp	Surface of membrane, primary air side
ms	Surface of membrane, secondary air side
nom	Nominal
opr	Operation
p	Primary air, process air
reg	Regeneration
ret	Return air
s	Secondary air, Solid desiccant material
sen	Sensible
tot	Total
v	Vapour
w	Water

Solid desiccant dehumidification systems are a promising technology offering heat driven dehumidification in an electricity efficient manner [9]. However, most desiccant systems have the drawback that the heat being released during the water adsorption process increases the temperature of the desiccant material (and that of the dehumidified air) and thus decreases the adsorption capacity of the desiccant material [10]. To compensate for this, Ng et al. [11] and Finocchiaro [12] proposed the water cooled solid desiccant dehumidification. The water flow in the tubes handles the released adsorption heat in the desiccant bed. However, the main concern about this kind of device is the required external source of cooling water [13]. An air cooled desiccant dehumidifier unit was proposed by Worek and Lavan [14]. This configuration allows the cooling air flow to remove the released adsorption heat to a certain extent. The present paper reports in particular on the combination of a novel Evaporatively Cooled Sorptive dehumidification system (called ECOS system) with a membrane dehumidification system. The ECOS concept is based on studies by Henning et al. [10]. In the course of the work reported here an ECOS unit has been designed which is suited for applications in tropical climates (see section 2.3). This novel ECOS system is featured by a combination of an adsorption and an evaporative cooling process in a single dehumidification unit.

The present paper proposes a novel "two-stage dehumidification system" comprising membrane and ECOS technologies towards the development of an electricity-efficient air-conditioning system for tropical climates as presented in Fig. 1. In such a system, the application of membrane technologies is more cost effective than the use of desiccant methods – both from the perspective of investment as well as operating cost. On the other hand, the application of the ECOS system is necessary, because a membrane unit alone cannot realize the necessary dehumidification if only the return air from the conditioned space (which has an increased humidity and temperature compared to the inlet air) is applied to drive the membrane dehumidification process. Thus, the question arises: what would be an optimal combination of membrane and desiccant technologies in order to reach minimum operating and investment costs while the comfort criteria are satisfied? In order to answer this question, this study aims at employing a systematic optimization approach in order to find optimal dehumidification configurations. Numerous research works have been published focussing on the optimization of air conditioning systems. However, to the best knowledge of the authors, the optimization of an integrated system consisting of a membrane unit, a desiccant dehumidification system (in particular the novel ECOS system) and an electricity-efficient sensible cooling device has not yet been studied in detail for applications in the tropical climate.

In this paper, a time-resolved mathematical model of the subsystems and the whole system is developed. A simple objective