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Steady-state investigation of water vapor adsorption for thermally driven adsorption based greenhouse air-conditioning system

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ABSTRACT

In the present study, water vapor adsorption onto silica-gel, activated carbon powder (ACP) and activated carbon fiber (ACF) has been experimentally measured at 20, 30 and 50 °C using a volumetric method based adsorption measurement apparatus for greenhouse air-conditioning (AC). The Guggenheim–Anderson–De Boer and Dubinin–Astakhov adsorption models are used to fit the adsorption data of silica-gel and ACP/ACF, respectively. The isosteric heat of adsorption is determined by Clausius–Clapeyron relationship. The adsorbents are evaluated for low-temperature regeneration with aim to develop solar operated AC system for greenhouses. Ideal growth zone for agricultural products is determined by which the steady-state desiccant AC cycle is evaluated on the psychometric chart and adsorption isobars.

Steady-state moisture cycled (MC_{SS}) by each adsorbent is determined for demand category-I, II and III which are based on 60%, 40% and 20% relative humidity of dehumidified air, respectively. In case of demand category-I, the ACP enables maximum MC_{SS} at all regeneration temperatures (T_{reg}), ideally sitting at 47 °C. The ACF enables double MC_{SS} as compared to silica-gel during demand category-II at T_{reg} ≥59 °C. However, the silica-gel is found the only applicable adsorbent for the demand category-III.

1. Introduction

1.1. Background of the greenhouse air-conditioning

The absolute humidity in the agricultural greenhouses used to increase continuously due to the photosynthesis and evapo-transpiration processes by which plants remain in danger of insects/pests/fungus attack and condensation/dripping of water vapors. Generally photosynthesis occurs during daytime whereas evapo-transpiration continues throughout the day and night times. Photosynthesis is the most important process in plants by which the plant makes carbohydrate using the carbon dioxide in the presence of light energy. During this process, the plant releases half of the water vapors into the air which was sucked from the plant roots as expressed by Eq. (1). Furthermore, the greenhouse temperature tends to increases continuously because of the presence of sunlight.

$$2nCO_2 + 4n(H_2O)\ \text{from roots} \xrightarrow{\text{Photons}} 2(CH_2O)_n + 2nO_2 + 2n(H_2O)\ \text{into air} \tag{1}$$

Evapo-transpiration is the summation of evaporation from the soil and transpiration from plant. Hagishima et al. [1] reported the average transpiration rate of 150–456 g/day for three plants having leaf area of 0.99–1.47 m^2. Thus it can be concluded that the greenhouse humidity increases day and night times. The plant's growth and/or flowering are highly influenced by the relative humidity (RH) as well as CO_2 level in the greenhouse [2,3]. In greenhouses, sufficient amount of CO_2 is always required for effective photosynthesis which also limits the applicability of return air utilization for any kind of greenhouse air-conditioning (AC) system. The required relative humidity for a plant depends on its ideal vapor pressure deficit (VPD) that may vary depending upon the plant growth stage, maturity stage, danger of insect/pest/fungus

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Nomenclature

A	adsorption potential [kJ/kg]
BDDT	Brunauer, Deming, Deming, Teller
C, C_o	GAB model constant related to heat [–]
DEC	direct evaporative cooling
E	adsorption characteristic parameter [kJ/kg]
Є	effectiveness of cooling device [–]
HX	sensible heat exchanger
ΔH_c, ΔH_k	functions related to water sorption heat [kJ/kg]
IEC	indirect evaporative cooling
IUPAC	Int. Union of Pure and Applied Chemistry
K, K_o	GAB model constant related to heat [–]
M	equilibrium adsorption uptake [kg/kg]
MC_{SS}	steady-state moisture cycled [kgH$_2$O/kgads]
M-Cycle	Maisotsenko cooling cycle
MF_{A-A}	adsorbent to air mass fraction [gads/kgDA]
M_m	monolayer adsorption uptake [kg/kg]
M_o	maximum adsorption capacity [kg/kg]
M_{mo}	GAB model adjustable monolayer uptake for temperature effect
n	fitting constant for D–A equation [–]
P	pressure [kPa]
P_o	saturation pressure [kPa]
P/P_o	relative pressure [–]
Q	heat energy [kW]
q_m	GAB model constant for temperature effect
Q_{st}	isosteric heat of sorption [kJ/kg]
R	specific gas constant for water [kJ/kg-K]
RH	relative humidity [–]
T	temperature [°C or K]
VPD	vapor pressure deficit [kPa]
W	steady-state adsorption uptake [kgH$_2$O/kgads]
X	humidity ratio [gH$_2$O/kgDA]

Subscript

ads	adsorption/adsorber
db	dry bulb
dew	dew point
eva	evaporator
reg	regeneration
wb	wet bulb

attack, extreme weather conditions, and water stresses etc. [4]. For example, Short et al. [5] found the different ideal VPDs for five growth stages of greenhouse tomatoes including germination, seedling, vegetative, early and mature fruiting. The optimizations of air humidity ratio, intake solar radiation intensity, CO_2 enriched outdoor air, and rated crop water requirement for effective photosynthesis and evapo-transpiration bring the temporal variability in the sensible and latent load of AC.

1.2. Motivation of the study

The greenhouse environment involves in higher relative humidity AC as compared to AC for human's thermal comfort as shown in Fig. 1 [4,6–8]. Desiccant AC systems are getting lots of attention in order to control the humidity in various air-conditioning applications e.g. greenhouses [9,10,4]; buildings [11,12]; automobiles [13]; wet markets [14]; marine ships [15,16]; museums [17,18]; hospitals, product storage and preservation etc. [19]. Being free from refrigerants, it enables zero ozone depletion and global warming potential. In addition to higher air quality it can be operated on low grade waste heat or renewable thermal energy sources. Fig. 2 shows that the desiccant AC in comparison with the conventional vapor compression AC has the ability to achieve the sensible and latent load of AC distinctly, which gives the opportunity to fulfil above mentioned greenhouses AC demands. Desiccant AC combines the desiccant dehumidification (1→D) and low-cost evaporative cooling (D→2) [19]. On the other hand conventional VAC cools the air below the dew point (1→V1:V2) so the heating is required from (V2→2) in order to obtain the desired conditions of temperature and humidity [14,20–22]. It can be noticed from Fig. 2 that it is unnecessary to over cool the air below the dew point in case of desiccant AC which results in energy saving. According to a feasibility study [23], the electricity saving of 24% is obtained by

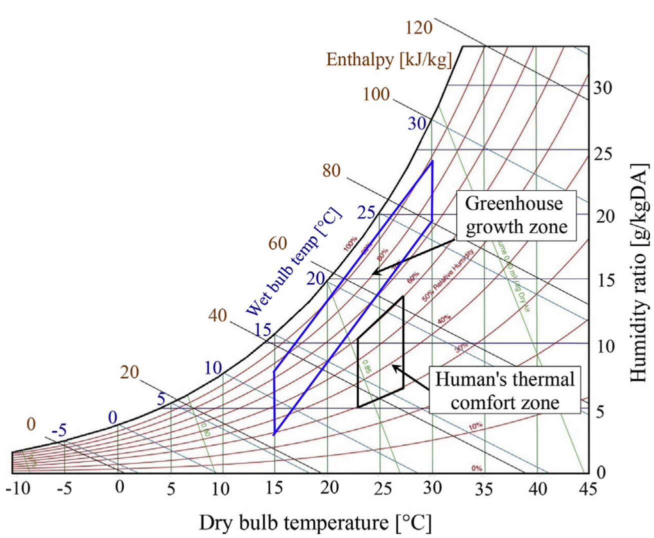

Fig. 1. General comparison between air-conditioning zones for agricultural greenhouse and human's thermal comfort.

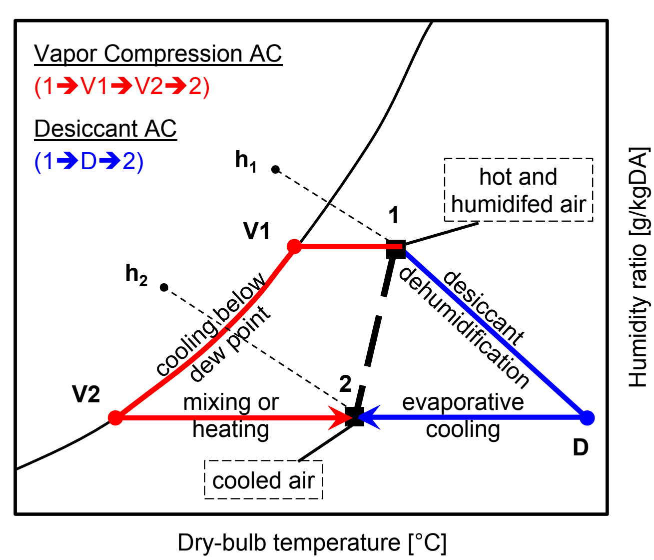

Fig. 2. Psychrometric comparison between conventional vapor compression and desiccant air-conditioning.