Renewable and Sustainable Energy Reviews 82 (2018) 545–575

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Review of indirect and direct solar thermal regeneration for liquid desiccant systems

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ARTICLE INFO

Keywords:
Liquid desiccant
Indirect solar regenerator
Solar collector/regenerator
Water desorption rate
Dehumidification capacity
Performance comparison

ABSTRACT

The large electricity consumption due to the extensive use of vapour compression machines in the air conditioning and industrial sectors dramatically increases the emissions of greenhouse gases. Besides, the synthetic halocarbon refrigerants used in said machines are responsible for ozone depletion. These environmental concerns give an opportunity to solar thermally-driven liquid sorption systems, whose energy consumption primarily lies on the regeneration heat of liquid sorbents. This paper surveys both theoretical and experimental studies on solar thermal regeneration methods of the hygroscopic solutions used in liquid sorption systems. A brief review of some conventional and alternative liquid desiccants utilised in said systems is firstly presented. Furthermore, information about several configurations of regenerators and their performance is covered in detail, putting special emphasis on solar collector/regenerators, which use directly solar energy to reconcentrate the weak desiccant solution. A comparative assessment of relevant thermophysical properties of some hygroscopic liquids is realised in order to determine their suitability for use in sorption systems. The results show that the aqueous solutions of potassium formate and ionic liquids are very promising desiccants due to their low vapour pressures, specific heat capacities and dynamic viscosities, as well as their non-corrosiveness. A performance comparison between typical regeneration units and solar collector/regenerators is also carried out. It could be shown that solar collector/regenerators have a high potential for enhancing the water desorption rate from a diluted desiccant solution and, consequently, the capacity of the air dehumidification process within the absorber.

1. Introduction

Since the beginning of mankind, the energy has been the motor of social, economic and technological development of the society. The world's energy consumption, which still depends greatly on fossil fuels, is continuously augmenting due to the industrialisation and the increase in population, thus worsening the global warming caused by greenhouse gases.

Among the primary energy consumer sectors stands out the building sector, which accounts for 40% of the world's primary energy consumption and is responsible for about one third of global CO2 emissions [1]. In Germany about 80% of the energy consumed in buildings is used to support the indoor human thermal comfort requirements, generally by means of electrical vapour compression systems [2], which deal simultaneously with both sensible and latent loads by cooling the process air below its dew point. However, this approach is energy inefficient since the air should be reheated to the desired temperature. Additionally, the refrigerants used in said systems (CFCs, HCFCs, freons, halons) deplete the ozone layer.

On the other hand, the drying process, in which water or another solvent is removed from a solid, semi-solid or liquid, consumes about 12% of the total energy used worldwide in industrial sectors like the pharmaceutical, fine chemical and food industries [3]. The most common drying method is thermal drying, which involves simultaneously the convective heat transfer from hot air to the product and the subsequent evaporation of its water content to the air. Since drying is a highly energy-intensive process due to the required latent heat of evaporation, it is important to improve its energy efficiency. At high temperatures, conventional convective dryers exhibit high thermal efficiencies, but at the expense of product quality [4]. Heat pump convective dryers possess good potentials to dry efficiently at low temperatures but they depend heavily on electricity to drive their compressors [5]. Non-convective drying methods for high quality product drying like freeze drying and microwave drying are not yet widely utilised in industry due to a variety of reasons. Freeze drying for instance is very expensive, and its application is consequently limited to high-value products [4]. Microwave drying requires high grade and more expensive electrical energy and also faces some technological

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http://dx.doi.org/10.1016/j.rser.2017.09.053
Received 5 August 2016; Received in revised form 16 June 2017; Accepted 14 September 2017
1364-0321/

Nomenclature

A	Surface area [m^2]
$a_{a\text{-}s}$	Specific interfacial surface area of the air/solution contactor [m^2/m^3]
C_{gap}	Air channel gap [m]
c_p	Isobaric specific heat capacity [J/(kg K)]
d	Diameter [m]
D_{AB}	Diffusion coefficient [m^2/s]
D_p	Opening of air control dampers [%]
F_w	Wetting factor [m^2/m^2]
g	Gravitational acceleration [m^2/s]
$G_{g,c}$	Global solar radiation on the tilted surface [W/m^2]
Gr	Grashof number [dimensionless]
H	Height [m]
H	Specific enthalpy [J/kg]
h_c	Convective heat transfer coefficient [$W/(m^2$ K)]
h_m	Convective mass transfer coefficient [$kg/(m^2$ s)]
$h_{w,fg}$	Latent heat of water condensation/vaporisation [J/kg]
I	Tilt angle [°]
K	Thermal conductivity [W/(m K)]
L	Length [m]
Le	Lewis number [dimensionless]
$\dot{m}$	Mass flow rate [kg/s]
N	Ratio of mass to heat transfer Grashof numbers [-]
Nu	Nusselt number [dimensionless]
P	Partial pressure [Pa]
Pr	Prandtl number [dimensionless]
Q	Heat flux [W/m^2]
Ra	Rayleigh number [dimensionless]
Re	Reynolds number [dimensionless]
Sc	Schmidt number [dimensionless]
Sh	Sherwood number [dimensionless]
T	Temperature [K]
U	Heat loss coefficient [W/(m^2 K)]
V	Velocity [m/s]
Y	Molar absolute humidity [kmol/kmol]
Z	Scaling factor [dimensionless]

Greek symbols

A	Solar absorptance [dimensionless]
β	Mass transfer coefficient based on gas-phase concentration [m/s]
γ	Surface tension [N/m]
$\Delta\chi_{abs/reg}$	Dehumidification/humidification capacity [kg/kg]
Δh_d	Differential enthalpy of dilution [J/kg]
$\Delta\dot{m}_{w,abs/reg}$	Water absorption/desorption rate [kg/s]
Δp	Pressure drop [Pa]
Δs	Thickness [m]
ε	Void fraction [m^3/m^3] or thermal emittance [dimensionless]
$\varepsilon_{h,abs/reg}$	Enthalpy effectiveness [dimensionless]
$\varepsilon_{s,reg}$	Liquid-side regeneration effectiveness [dimensionless]
$\varepsilon_{T,abs/reg}$	Temperature difference ratio [dimensionless]
$\varepsilon_{\chi,abs/reg}$	Air side humidity effectiveness [dimensionless]
η	Efficiency [dimensionless]
M	Dynamic viscosity [Pa s]
ν	Kinematic viscosity [m^2/s]
ξ	Mass fraction of desiccant solution [kg/kg]
P	Density [kg/m^3]
Σ	Stefan-Boltzmann constant [5.67×10^{-8} W/(m^2 K^4)]
τ	Transmittance [dimensionless]
Φ	Relative humidity [%] or view factor [dimensionless]
X	Absolute humidity [kg/kg]

Subscripts

a	Process air
abs	Absorption process
amb	Ambient
c	Column or collector
cs	Cross-section
cold	Cold fluid
cond	Conduction
conv	Convection
db	Dry bulb
dp	Dew point
equ	Equilibrium
f	Heat transfer medium
gr	Ground
h	Hydraulic or collector housing
hot	Hot fluid
in	Inlet flow
ins	Thermal insulation
lam	Laminar flow
m	Mass transfer property
out	Outlet flow
p	Packing material or absorber plate
rad	Radiation
reg	Regeneration process
s	Desiccant solution
sky	Sky
tran	Transitional flow
turb	Turbulent flow
w	Water vapour or water
wb	Wet bulb
x	Local quantity scaled to the lengthwise distance from leading edge

Superscripts

*	Based on Uniform Heat/Mass Flux (UH/MF) boundary conditions

issues like uneven heating, textural damage and limited penetration of microwave radiation within the product [6].

In order to achieve reductions in energy consumption, peak electricity demand and energy costs in the air conditioning and drying sectors without damaging the environment and lowering the desired comfort conditions and product quality standards, the development of cost-effective solar thermally-driven liquid sorption systems is required. Said systems rely on the capacity of eco-friendly hygroscopic solutions in removing the air moisture content by an absorption process [7] and on solar heat for the solution regeneration with temperatures ranging from 40 to 70 °C [8]. The concentrated solution is then stored without thermal losses to be used for the air conditioning and drying processes during periods when solar radiation is not available.

Indirect solar regenerated systems consist of the main components absorber and regenerator. In the absorber, the moisture of the inlet process air is removed by bringing it into contact with sprinkled desiccant solution, which then becomes diluted gradually over time. In the regenerator, the water content of the weak solution is reduced by increasing its temperature (and consequently, its vapour pressure), and by removing the produced water vapour through a scavenging air stream. The heat required for the regeneration process can be supplied by either air-led [9] or water-based solar collectors [10]. More recently,