Applied Thermal Engineering 107 (2016) 888–897

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Air dehumidification by cooled adsorption in silica gel grains. Part I: Experimental development of a prototype

Lorenzo Pistocchini *, Silvia Garone, Mario Motta

Department of Energy, Politecnico di Milano, via Lambruschini 4, 20156 Milan, Italy

HIGHLIGHTS

- Development and testing of a fixed bed adsorption dehumidifier.
- Adsorption beds made by finned tube heat exchangers packed by silica-gel grains.
- Cooled adsorption allows reducing the regeneration temperature below 55 °C.
- Optimized geometry of packed beds entails low pressure losses in the air side.
- Low cost dehumidifier provides promising thermal and electric performances.

ARTICLE INFO

Article history:
Received 3 March 2016
Revised 26 May 2016
Accepted 16 June 2016
Available online 30 June 2016

Keywords:
Adsorption dehumidification
Fixed-bed
Silica gel
Isothermal adsorption
Experimental

ABSTRACT

This work deals with the development and testing of a fixed-bed adsorption dehumidifier, designed to manage the latent load in air conditioning. The system is based on the batch operation of two finned tube heat exchangers, where silica gel grains are packed between the fins. The water flow in the tubes provides the required heat supply and rejection, allowing a quasi-isothermal operation. As a result, the heat supply temperature can be reduced below 55 °C, fostering the use of waste heat and solar thermal collectors. Moreover, the inversion of the air flow direction between the operating stages is not needed to achieve suitable levels of dehumidification, enabling a design simplification. The test campaign has shown that the electric and thermal performances of the low-cost prototype highly depend on the operating conditions, but both reach very promising values under the worst environmental conditions, when the energy consumption is higher.

1. Introduction

We here report the development, features and energy performances of a thermally driven air dehumidifier for the conditioning of ventilation air. The temperature of the required heat supply is lowered thanks to the quasi-isothermal operation, making it suitable for waste heat recovery and solar cooling applications.

This feature is particularly relevant in the present context of developed countries, where the enhancement of heat recovery is considered both strategic and more feasible compared to the past.

The potential is that of contributing to the reduction of consumptions and GHG emission, so much so that it has become a constant topic of national and international research programmes [1]. On the other hand, such a potential is also becoming increasingly accessible compared to the past: the different sectors, like transport, electricity, heating and cooling are becoming more and more interconnected. Hence, low and middle temperature heat will be more easily collected by distributed heat storages, which act as an energy buffer of intermittent sources of heat and electricity, like renewables.

If heat is more easily and constantly available, the focus is shifted on running processes at low temperature and exploit the greatest fraction of the recovered heat.

In the field of heat driven cooling systems, those based on the physical adsorption of fluids on microporous materials are good candidates to run on low-grade heat sources [2]. They exploit the fact that, at constant vapour pressure, the uptake of vapour in the micropores is inversely related to the temperature. A thermal swing therefore allows changing the humidity content of desiccants. Adsorption chillers indirectly use this feature to produce cooling power [3], while desiccants can be exploited in air conditioning to directly dehumidify the air and manage the latent load [4]. Such application is gaining growing importance, since air

* Corresponding author.
E-mail address: lorenzo.pistocchini@polimi.it (L. Pistocchini).

http://dx.doi.org/10.1016/j.applthermaleng.2016.06.103
1359-4311/

Nomenclature

COP	Coefficient Of Performance
d	diameter of silica gel grain (m)
Dp1, Dp2	respectively, pressure drop across HX_1 and HX_2 (Pa)
EER	Energy Efficiency Ratio
HX_1	adsorption heat exchanger 1
HX_2	adsorption heat exchanger 2
$\dot{m}$	mass flow rate of air (kg/s)
$\dot{m}_w$	mass flow rate of water (kg/s)
p	distance between the fins (m)
Q_c	cooling energy provided to the conditioned air flow in one operating cycle (kWh)
Q_s	heating energy provided to the conditioned air flow in one operating cycle (kWh)
SCP	Specific Cooling Power, per unit mass of dry adsorbent (W/kg)
T	temperature of inlet air (°C)
T1, T2, T3, T4, T5	air temperature in different points of testing loop (°C)
Tc	inlet temperature of cooling water (°C)
Tc1	temperature of cooling water upstream the mixing valve (°C)
Tc2	outlet temperature of cooling water (°C)
Th	inlet temperature of heating water (°C)
Th1	temperature of heating water upstream the mixing valve (°C)
Th2	outlet temperature of heating water (°C)
u	moisture content mass by mass (water uptake) in silica gel (kg/kg)
$\dot{V}1, \dot{V}2$	volumetric flow rate of air in different points of testing loop (m^3/h)
$\dot{V}c, \dot{V}h$	respectively, volumetric flow rate of cooling and heating water (m^3/h)
W_{el}	electricity consumption of fans and pumps in one operating cycle (kWh)
x	humidity by mass of the inlet air (kg/kg)
x1, x2, x3, x4, x5	humidity by mass of air in different points of testing loop (kg/kg)
$\overline{\Delta x}$	average specific dehumidification rate: difference of humidity by mass between inlet and outlet of the adsorption bed, averaged over the duration of the dehumidifying stage (kg/kg)

Greek characters

τ	stage duration of dehumidification or regeneration (min)

Subscripts

min	minimum
max	maximum
l	related to latent heat of water evaporation/condensation
s	related to sensible heat, due to the change of air temperature
lost	related to heat losses
out	at the heat exchanger outlet

renewal and humidity control are essential to guarantee air purification and thermal comfort [5–7], especially in energy efficient buildings with no air leakage. Moreover, desiccant systems are a suitable alternative to the conventional but inefficient process of dehumidification by condensation of water vapour, which occurs at low temperatures and needs a post-heating of the air flow.

To enhance the potential of low grade waste heat exploitation, cooled adsorption has been pursued as a way to reach lower regeneration temperatures.

1.1. Isothermal adsorption

In fact, water adsorption is a highly exothermic reaction, and raises the temperature of the microporous material during the vapour uptake. As a consequence, the temperature at which the material can release the adsorbed vapour increases too. This happens for instance in the wheels used by Desiccant and Evaporative Cooling (DEC) systems, where the adsorption process is almost adiabatic [8]. To minimize such a regeneration temperature, which in turn determines the temperature of the heat supplied to the cyclic process, the adsorption heat must be removed during vapour uptake, and supplied during vapour release. For this purpose, two-stage rotary desiccant cooling systems have been developed [9,10], where a double adiabatic dehumidification stage, implemented by desiccant wheels, is split by an intercooler. Such costly solutions, although keeping the benefits of rotary systems, cannot actually approach isothermal adsorption and desorption processes. As a more effective alternative, the desiccant material can be coated on (or inserted in) a heat exchanger, where heat removal and supply is provided by either an air or a water flow, as proved by different technical solutions in the recent years [11–13]. Due to the batch operation of such systems, we consider the water flow as the more effective and compact way to implement the sequence of the stages in the fixed bed, as done by Finocchiaro et al. to realize their cooled packed bed [14].

Much research work has been done in order to maximize the heat conduction in the coating: zeolite can be directly synthesized or deposited on conductive supports [15,16], however it has a high affinity for water vapour. So it provides a deep dehumidification level but needs a high regeneration temperature, which is not a good feature for the scope of the present work. New adsorption materials have been developed, characterized by a shifted S-shaped isotherm like aluminophosphates and metal-organic frameworks [17,18], which allow to reduce the regeneration temperature. So far, either their cost or reliability makes them unsuitable for a widespread commercial deployment. Silica gel is well suited to dehumidification in air conditioning, thanks to the low cost, low regeneration temperature and high adsorption capacity. Anyway it is poorly suited to coated solutions, as it needs a polymeric substrate (which entails a further thermal resistance) to be coated on a heat exchanger [19,20].

2. Design of the dehumidifier

Up to now technical and economic obstacles, like the investment cost and the complexity of the systems, have severely limited the diffusion of adsorption cooling and dehumidification. We present a cost effective system, which can be installed within a conventional air handling unit. It is a fixed bed adsorption system, based on the batch operation of two finned tube heat exchangers, where silica gel grains are packed between the fins, as depicted in Fig. 1. By the water flow through the tubes, sorption heat is properly supplied and rejected during all the stages of the working cycle.