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Evaluation of a dehumidifier with adsorbent coated heat exchangers for tropical climate operations

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ABSTRACT

This paper presents the evaluation of a solid desiccant dehumidifier equipped with adsorbent powder coated heat exchangers (PCHX). The main component of the solid desiccant dehumidifier includes two heat exchangers that are coated with silica gel RD type powders in order to increase water adsorption uptake by improving its heat and mass transfer. A series of experiment are conducted to evaluate two key performance indices, namely, moisture removal capacity (MRC) and thermal coefficient performance (COP_{th}), under various hot and humid air conditions. Conventional granular adsorbent packed heat exchangers (GPHX) are employed to benchmark the performance of the adsorbent coated heat exchanger (PCHX). Results reveal that the PCHX exhibits higher uptake performance due to better heat and mass transfer. It is found that the moisture removal capacity increases from 7.4 g/kg to 11.0 g/kg with air flow rates of 35 kg/h, resulting in the extended contact time of the water vapor. Experiments also demonstrate that the moisture removal capacity is highly affected by inlet air humidity ratio. In addition, marked improvement in COP_{th} can be achieved by a lowered hot water regeneration temperature.

1. Introduction

A humid tropical climate region is basically defined as a region where its monthly latent cooling load of outdoor air exceeds its monthly sensible cooling load. As a city-state with little land mass, the use of air-conditioning in Singapore has become a norm in its buildings. The electricity demands for cooling in building sectors accounted for 31 ± 2% of total electricity consumption in all sectors in Singapore [1–3].

Conventional mechanical vapor compression cycles (MVC) are widely used in order to overcome sensible loads and latent loads in air-conditioning systems. In a humid region, however, MVC typically operates in a way to lower supply air temperature below the dew-point temperature in order to remove high humidity, which leads to the waste of energy. Moreover, conventional air conditioning system utilizes refrigerants such as CFCs which are harmful to our ozone layer as well as they affect the respiratory systems of humans [4].

Desiccant dehumidification is one possible solution that can minimize the aforementioned problems via a de-coupling cooling concept that separates latent cooling from sensible cooling in the air handling units (AHUs) of buildings. Liquid desiccants have been used in industrial application since 1930s and they are more flexible in their application. They have lower pressure drop and lower regeneration temperature as compared to solid desiccants [5,6]. However, such liquid desiccant dehumidifications are also toxic and corrosive in nature, which renders them unsuitable for air-conditioning application. Liquid desiccants were also found to have carryover effects.

As such, with less energy input, solid desiccants are more compact and less subjected to corrosion and carryover effects A solid desiccant dehumidification system is typically classified into two types by packing method, namely, a fixed bed type and a rotary wheel type that is the most appropriate dehumidification type for air-conditioning application [7–10]. However, the fixed bed design has not been used well for air-conditioning system because it is required to stop the process once the desiccant have reached its saturation state [11]. The rotary wheel design is the most widely used in as HVAC systems.

Some investigations have been carried out on novel hybrid cooling systems that incorporate a heat pump and a membrane

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technologies [12–17]. Chen et al. employed a heat pump as a heat source at 40–50 °C to regenerate a composite desiccant wheel that was placed between an evaporator and a condenser to conduct a second stage of dehumidification [12]. A lower power consumption of 1.86 kW has been achieved with the hybrid configuration as compared to a conventional condensing or desiccant wheel. A heat pump has been also applied to a liquid desiccant dehumidification system by Xie et al. [14]. Authors developed theoretical models of key components and analyzed the system energy performance. They concluded that COP can be increased from 5.1 to 5.5 by adopting a multi-stage heat pump. Das et al. investigated the performance of membrane contractors for liquid desiccant cooling system [16]. Their simulation results showed that the performance of the contactors are significantly affected by the membrane properties such as porosity, pore size and thickness. Zhang et al. applied both a heat pump and a hollow fiber membrane to two-stage liquid desiccant dehumidification system [17]. The proposed system consists of cross-flow hollow fiber membrane modules, which acts as two dehumidifiers and two regenerators, and a compression heat pump system. The authors concluded that the COP can be increased by about 20% under the typical hot and humid conditions.

Recently, many studies have been focused on the development of desiccant materials to improve adsorption capacity and thus the performance of the solid-based desiccant dehumidification system [18–24]. In spite of the advancement of the rotary wheel configuration and the novel composite desiccant material, it was pointed out that the removal of adsorption heat generated during dehumidification was a critical issue to be solved for further improvement of a solid-based desiccant dehumidification [30,31]. The adsorption heat attenuates the adsorption capacity of the system, being away from the ideal isothermal system, which leads to more irreversibility loss, generating high entropy during the operation processes that severely affect the coefficient of performance of the system. Some researchers proposed the concept of adsorbent-coated cross-cooled heat exchanger [32–34]. Prior to this, a finned tube exchanger where the granular adsorbent was packed by a wire mesh was introduced in industrial applications such as adsorption chillers and adsorption desalination systems [35,36]. This granular adsorbent packed heat exchanger was also employed in the dehumidification system [37]. However, it was found that the performance hasn't improved as much as expected due to the poor contact not only between adsorbent and metal fins, but also among adsorbent solids [38], inducing very low heat transfer efficiency. Fig. 1 shows examples of the adsorbent coated heat exchanger with different materials and coating methods.

Many investigation also have been carried out mathmatically and experimentally to study thermal coefficient of performance (COP_{th}), defined in Eq. (3), of various dehumidification systems [39,40]. Typical COP_{th} of solid desiccant dehumidification systems was found to varies from 0.02 to 0.67 depending on the operating conditions and desiccant materials. For a hybrid cooling system where the solid desiccant dehumidifier is incorporated with MVC systems, evaporative cooling systems or thermal driven chiller such as AB and AD chiller, their COP are expected to be above 1.0 [41–43].

The objective of this study is to improve the overall performance of a solid desiccant dehumidifier by incorporating the adsorbent coated heat exchangers. Its performance is judiciously investigated under different operating conditions.

2. Adsorbent powder and sorption characteristics

Silica gel has relatively high moisture adsorption capacity and low regenerative temperature of 50 °C–90 °C. Among various types of silica gel, type 'RD' silica gel, manufactured by Fuji Silysia Chemical Ltd., Japan, was selected as a desiccant for dehumidifying humid air because it exhibited higher uptake capacity under higher relative humidity in the range of 70%–90% when it was mixed with a binder material. Its thermophysical properties are summarized in Table 1 [35]. In the present work, we reproduced powder silica gel of 0.07 mm in diameter by using a grinder and a mesh sieve (no.200) since the manufacturer does not provide a micronized silica gel. The powder adsorbents allows for coating a thin layer onto the metal fins and evenly mixed powder with the binder. It is worth noticing that both the granular silica gel and powder silica gel have the identical thermophysical properties except for apparent diameter.

Fig. 2 shows water equilibrium uptake on the silica gel type RD powder with respect to water vapor pressure and relative humidity in the temperature range of 25–80 °C. The measurements were conducted based on the gravimetric method using the Aquadyne DVS analyzer manufactured by Quantachrome Instruments. It is observed from Fig. 2(a) that the equilibrium uptake is proportional

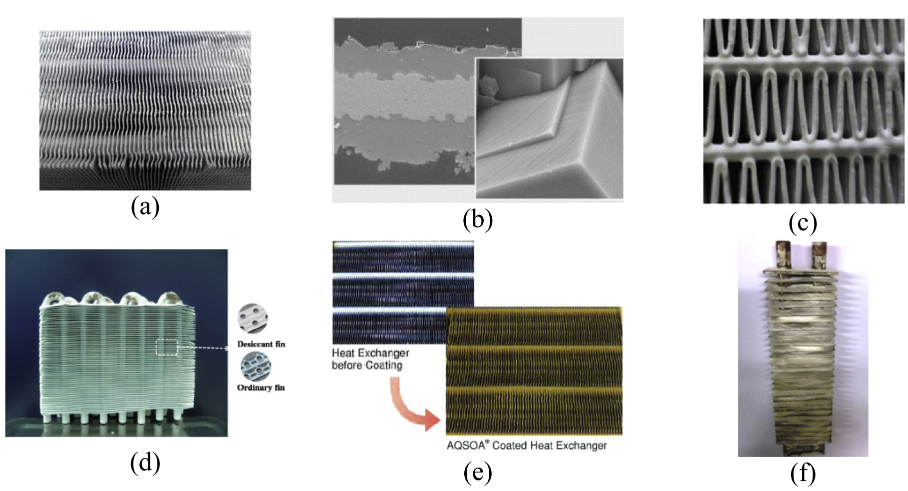

Fig. 1. Examples of the adsorbent coated heat exchanger with different desiccant materials and coating methods: (a) silica-gel coating with binder by dip-coating method [25], (b) in-situ crystallization of SAPO-34 zeolite [25], (c) SPAO-34 zoloite coating with binder by dip-coating method [26], (d) Li-modified desiccant coating by electrostatic spraying method [27] (e) AQSOA Z01 coating with binder by dip-coating method [28], and (f) silica-gel coating with binder by dip-coating method [29].

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