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Recent developments in solid desiccant coated heat exchangers – A review

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HIGHLIGHTS

- One-stop archive for developments in solid desiccant coated heat exchangers (DCHEs).
- Comprehensive study on the selection of desiccants and binders.
- Thorough analysis on the effect of operating parameters on dynamic performance.
- Detailed review of advances in mathematical modeling of DCHEs.
- Discussion on the potential system-level applications of DCHEs.

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ABSTRACT

Rapid urbanization and higher thermal comfort requirements have sharply increased buildings' energy demands. In tropical countries, for achieving energy efficient air-conditioning, desiccant dehumidifiers, which decouple sensible and latent load, are essential. While fixed-bed and rotary wheel desiccant dehumidifiers suffer from reduced adsorption capacity and lowered heat transfer efficiencies, desiccant coated heat exchanger (DCHE) system is a promising technology that can improve the energy efficiency of the standard vapor-compression air conditioners. Moreover, DCHEs also have prospective benefits in heat pump, adsorption chiller, and atmospheric water harvesting applications.

In this paper, the advantages of DCHEs over other dehumidifiers are established, and a comprehensive review of various desiccant materials and binders used in DCHEs is carried out. The possibilities of using advanced materials to achieve superior energy efficiencies are also underlined. Different methods of coating the desiccant on heat exchangers are described, and quantitative parameters required to analyze the performance of the system are presented. Operating parameters affecting the dehumidification and thermal performance are identified, and the effect of their variation on the dynamic behavior of DCHEs is elaborately studied. The significance of using mathematical models as design tools is recognized, and the underlying assumptions, applicability, and limitations of the models for simulating the complex heat and mass transfer phenomenon are highlighted. The possibility of integrating an additional heat transfer equipment such as sensible heat exchangers, heat recovery devices, solar evacuated tube collectors, cooling towers, and evaporative coolers with DCHE is also presented. Finally, the potential system-level applications of DCHEs as heat pumps, adsorption chillers, water harvesters, and standalone air-conditioners are assessed.

This review paper provides an update on recent developments in desiccant dehumidification and is intended to be a "one-stop" archive of known practical solutions that DCHEs can offer.

1. Introduction

In developed nations, the energy contribution from buildings towards total energy consumption has increased from 20% to 40% in the past decade [1]. Due to the rise in population and extensive economic growth witnessed in developing nations, the primary energy requirement of the whole world is expected to grow by 48% from 2012 to 2040 [2]. Increasing energy demand in buildings for better thermal comfort levels implies that the energy consumption in the indoor environment would also rise in the future by 34%. Precisely, in tropical climates, the air-conditioning process constitutes about 50% of the total building energy consumption [3]. The total cooling load comprises up to 70% latent component and 30% sensible component. For realizing comfortable living conditions, excess temperature and humidity in the air must

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be reduced to acceptable levels.

Hitherto vapour-compression air-conditioning system has been widely adopted for fulfilling the air-conditioning requirement. In this system, there is a strong coupling between temperature and humidity. Outdoor air is supplied to a cooling coil, which is maintained at a temperature much lower than the dew point temperature of the air. In most cases, an additional reheating process is essential to circulate the air under acceptable thermal comfort conditions [4]. The process efficiency is low because the cooling coil has to simultaneously reduce both latent and cooling load [5]. Hence, decoupling the latent load has the potential to significantly increase the energy efficiency of the conventional air-conditioning system [6]. Furthermore, the vapor compression air-conditioning system employs mechanical compressors which require high-grade electrical energy as an input source. Goetzler et al. [7] highlight as many as twenty alternatives to the conventional air-conditioning systems and comprehensively classify them into three categories: electrically activated solid-state technologies, electro-mechanical systems, and thermal driven systems. Solid-state systems such as magnetocaloric and thermoelectric technologies and electro-mechanical technologies such as thermoelastic and membrane heat pumps demonstrate promising energy-saving potential. However, these novel substitutes are either in their infancy stages of research and development or involve higher cost and complexities for practical applications. High carbon emission levels associated with electricity generation and widespread awareness towards sustainable living have led to the development of efficient alternatives that use clean energy for air-conditioning purpose [8].

A purely thermal alternative for reducing the latent load is achieved by compressing the air. When the moist air gets compressed, its dew point temperature increases and the water molecules get condensed. However, an enormous amount of cooling water is required to cool the air to a desired temperature, thereby making this technique infeasible [9]. This difficulty of reducing air humidity is currently addressed by the use of desiccant dehumidifiers in the air-conditioning process. Apart from the conventional air conditioners, desiccant dehumidifiers can also be used in thermally-driven adsorption chilling systems. Adsorption chillers could be an alternative to the vapor compression air-conditioning system because of high durability of adsorbent materials, low heat source temperature, and maintenance free operations. Several systems have been developed in Europe and Japan to study the performance of adsorption cooling systems. The fundamental drawbacks of the adsorption air-conditioning systems are due to its bulkiness [10], more extended pay-back periods, lower adsorption efficiency, and higher irreversibility [11]. With the recent developments in desiccant dehumidifiers, the potential challenges of adsorption air-conditioning technology can be addressed.

In the desiccant dehumidification process, moist air is dehumidified by the principle of adsorption. There is a direct contact between the humid air and the dry desiccant. The desiccant adsorbs moisture on its surface and reduces the latent load in the air. The adsorption capacity of the desiccant is a direct function of relative humidity (RH). Any condition such as an increase or decrease in temperature or humidity ratio that causes a change in RH affects its adsorption capacity. The desiccant cannot adsorb moisture indefinitely because of its limited adsorption capacity. In order to realize continuous operation, the adsorbed water molecules have to be removed from the desiccant. This process of regeneration of desiccants is carried out by adopting low grade and clean sources of energy, namely, industrial waste heat or solar energy [12]. Since the driving force for moisture adsorption is the change in RH, desiccants can be regenerated even at lower temperatures.

Desiccant dehumidification is classified into two types based on the type of desiccants used: liquid desiccants and solid desiccants. A comprehensive review of liquid desiccants including mathematical modeling and economic evaluations can be found in the literature [13]. Despite their extensive use, the most prominent drawback associated with liquid desiccants is that they are capable of chemically reacting with moist air and show possibilities of harming people who would breathe the air. On the other hand, solid desiccants are highly durable, environmentally friendly, and inexpensive when compared to liquid desiccants. These advantages have placed solid desiccant dehumidification systems as the potential successors of vapor-compression systems. Solid desiccant dehumidification systems are classified into three types: fixed-bed; rotary wheel; and desiccant coated heat exchangers (DCHEs).

1.1. Fixed bed systems

In fixed bed systems, desiccant matrix is packed on a stationary bed, and moist air (also known as process air) flows through the bed. The process air and the regeneration air flow alternately to achieve dehumidification and regeneration. In the dehumidification process, the desiccant adsorbs moisture and produces dry air. During the regeneration process, the hot air is passed through the desiccant matrix to reactivate it for the next cycle of dehumidification. Since the adsorption process is not continuous, many beds are installed to achieve continuous dehumidification. Consequently, large surface area per cooling capacity is required. Although the fixed bed systems are easy to fabricate, the overall heat transfer coefficient is low due to poor contact between the bed and the desiccant matrix. The reduced heat transfer efficiency affects the adsorption capacity and the cooling performance of the fixed bed dehumidifiers [14].

1.2. Rotary desiccant systems

In rotary desiccant systems or desiccant wheels, desiccant is impregnated on a wheel. In one portion of the wheel, moist air gets dehumidified, while in the other portion, hot air is supplied for regeneration. The wheel rotates at a constant speed making the dehumidification process continuous [15]. Impregnating the desiccant on a wheel improves the contact between the air molecules and the desiccant matrix due to which higher utilization of the desiccant for dehumidification process is observed.

In both fixed-bed and rotary type desiccant dehumidifiers, the adsorption capacity is reduced because of heat released during adsorption process. The adsorbed gaseous molecules release their kinetic energy into the desiccants in the form of heat of adsorption and increase its temperature. As a result, RH decreases and the adsorption capacity of the desiccant is reduced [16,17]. Since the adsorption process is exothermic, appropriate simultaneous cooling techniques need to be employed to achieve an improved adsorption capacity [18,19]. Additionally, the total cooling load remains unchanged as the heat released during the adsorption process results in higher air temperatures at the outlet. In other words, the desiccant adsorbs moisture from the air and turns the latent heat in the air into sensible heat. Therefore, after-coolers are installed to reduce the temperature of hot air released from these systems. An extensive review of the fixed bed systems has been carried out by Ramzy et al. [20], and the possibility of using industrial waste heat has been extensively discussed by Fathalah et al. [21]. Similarly, La et al. [22] have reviewed the working principle of rotary bed based desiccant dehumidifiers. White et al. [23] studied alternative desiccant materials for desiccant wheels, and Ge et al. [24] reviewed the applicability of using solar energy.

1.3. Desiccant coated heat exchangers (DCHEs)

DCHEs were developed to address the drawbacks of fixed-bed and rotary desiccant systems. In DCHEs, desiccants are coated on the fins, and the process air flows over the fin side of the heat exchanger. To increase the desiccant's adsorption capacity and remove adsorption heat, a cooling fluid is passed through the tubes during dehumidification. As the cooling fluid removes the sorption heat, a significant