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Enhancing automotive heat pump efficiency via directly coated desiccant evaporator and condenser

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Abstract

This study aims to enhance automotive air-conditioning performance using a desiccant-based system that overcomes the weight and complexity of traditional desiccant-coated heat exchangers (DCHEs). A compact desiccant-coated heat pump (DCHP) is proposed, where desiccant materials are directly applied to the evaporator and condenser surfaces, eliminating the need for separate desiccant components. Numerical simulations were performed to assess system performance using silica gel and four MOF desiccants—CPO-27(Ni), aluminum fumarate, MIL-100(Fe), and MIL-101(Cr). Among these, MIL-101(Cr) exhibited the best performance, achieving a COP slightly above 8.0 and an 80% improvement over a conventional system, with a moisture removal capacity (MRC) exceeding 8 g/kg, about 30% higher than that of silica gel. The DCHP also maintained supply air within ASHRAE comfort limits without reheating.

Keywords: Desiccant-coated heat pump; Adsorption; Air conditioning, Metal organic frameworks

1. Introduction

Currently, about 55% of the global population resides in urban areas, and this figure is projected to reach 68% by 2050 [1]. The rapid pace of urbanization continues to drive up energy demand, especially for personal and commercial transportation. However, this growing demand coincides with rising fossil fuel prices and highlights the unsustainability of dependence on conventional energy sources. At the same time, energy shortages and escalating fossil fuel costs are becoming increasingly evident worldwide [2]. The International Energy Agency (IEA) [3], reports that vehicle air-conditioning (AC) systems account for over 1.5% of global oil consumption, with about 6% of a vehicle's total energy use devoted to cooling. Without effective intervention, this energy demand is expected to increase fourfold, intensifying both environmental and economic pressures.

Traditionally, vapor compression refrigeration (VCR) has been the standard technology for vehicle AC systems. However, it remains highly energy-intensive and a major contributor to CO_2 emissions [4]. To mitigate these drawbacks, efforts have focused on improving the energy efficiency of VCR-based systems through technological advancements and system optimization [5].

Desiccant-coated heat exchanger (DCHE) has shown great potential for improving energy efficiency in building and industrial applications by using low-grade heat to manage humidity and air quality [6–9]. However, their need for multiple heat exchangers limits continuous operation and increases system weight, which is undesirable for vehicles [10,11]. To overcome this, the desiccant-coated heat pump (DCHP) was developed, where desiccants are applied directly to the condenser and evaporator surfaces, enhancing efficiency and dehumidification [12]. Hua et al. [12,13] demonstrated DCHP systems achieving COPs above seven and efficiently delivering cool, dry air. Despite their success in buildings, DCHP systems for automotive use remain largely unexplored.

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This study aims to enhance automotive AC performance using a desiccant-based system that overcomes the weight and complexity of traditional DCHEs. The proposed DCHP applies silica gel and MOFs directly onto the evaporator and condenser surfaces, eliminating separate desiccant units and improving compactness and efficiency.

2. System description

Fig. 1 shows the DCHP schematic with four air streams—supplied air (SA), outside air (OA), returned air (RA), and exhausted air (EA)—and two DCHEs, a compressor, an expansion valve, and a four-way valve. During cooling, the lower heat exchanger acts as the evaporator, where the refrigerant cools the desiccant to adsorb moisture from OA, producing cool, dry SA for the cabin. Meanwhile, the condenser handles RA, releasing the adsorbed moisture as EA to regenerate the desiccant. The four-way valve then reverses the heat exchangers' roles for continuous operation. Since the heat exchanger's position is fixed, a control system and additional ductwork are required to redirect the airflow. Currently, this configuration can be used for buses with sufficient rooftop space and existing ducts for airflow management. However, smaller vehicles face challenges with this setup, which should be explored in future research.

This study assumes that all heat exchangers are the same size. The cycle time for the adsorbent is defined as the duration it takes to reach maximum adsorption capacity. These cycle times are 180, 180, 550, 400, 740, and 600 seconds for Silica gel, Aluminum fumarate, MIL-100 (Fe), MIL-101 (Cr), and CPO-27 (Ni), respectively.

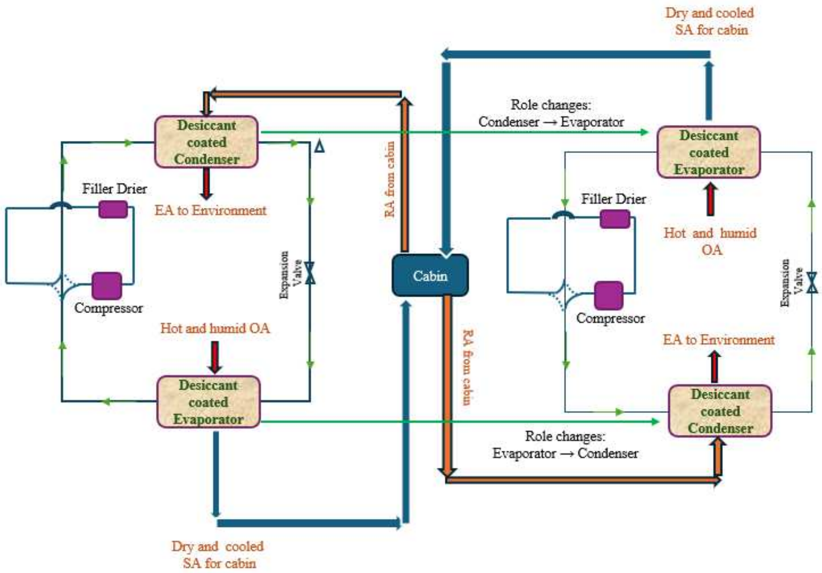


Figure 1. DCHP system schematic.

3. CFD analysis

3.1. Geometry

This study evaluated the DCHP performance using a single fin-tube path to simplify the model and minimize computational cost. The configuration consists of a porous desiccant layer, a fin-tube, a refrigerant passage, and an air region. As shown in Fig. 2, air flows along the X-axis and refrigerant along the Z-axis in a cross-flow setup. Owing to symmetry, only half of the domain was simulated to improve efficiency without losing accuracy. Ansys Fluent is used to perform computational analysis within the domain.

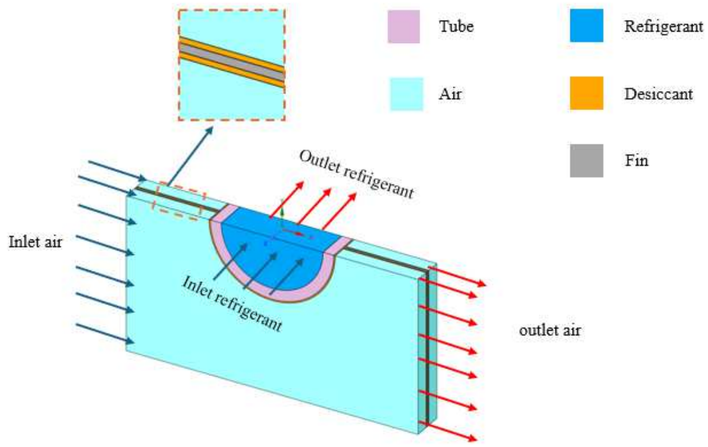


Figure 2. Geometry of DCHP.

3.2. Governing equations

The Linear Driving Force model (Eq. 1) was employed to simulate the adsorption–desorption kinetics between the desiccant and the adsorbate. Energy, momentum, and species conservation in the whole domain are described in our earlier work [10]. A mass flux at the air–desiccant interface (Eq. 2) represented moisture transfer, with δ_d as the desiccant thickness. (Eq. 3) is used to calculate the system's COP. In this equation, $h_{a,in}$ represents the inlet air enthalpy, $h_{a,out}$ is the outlet air enthalpy, m_a is the air mass flow rate, and W_{comp} is the compressor work. The detailed equations, boundary conditions, and thermophysical properties are provided in the reference [10]. It is worth noting that the average COP values are reported in this manuscript. The refrigerant R-1234yf was selected as a suitable choice for automobile applications.

$$\frac{dw}{dt} = k(w^* - w) \tag{1}$$

$$\phi m = \rho_d \delta_d \frac{\partial w}{\partial t} \tag{2}$$

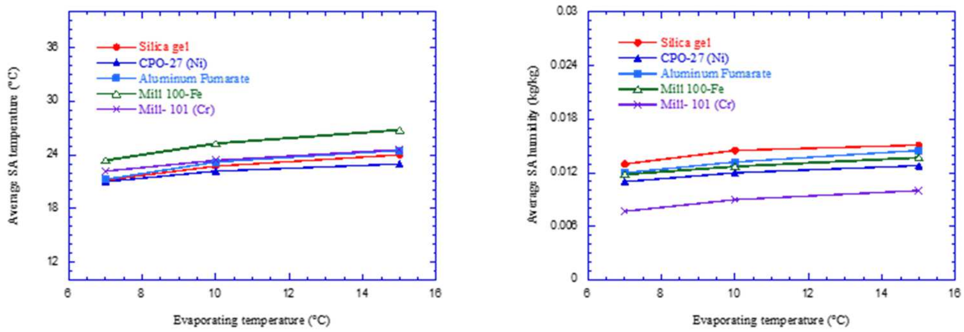
$$\text{COP} = \frac{m_a(h_{a,in} - h_{a,out})}{W_{comp}} \tag{3}$$

4. Results and discussion

This study considers thermal comfort acceptable within a temperature range of 20°C to 27°C. It also specifies a preferred humidity level between $0.003 < w < 0.005$ and a maximum humidity level between $0.014 < w < 0.015$. It is essential to note that all operating conditions in the DCHP system are identical to those in a conventional system, except for the evaporating temperature, which is maintained at 0°C in the conventional system. Our previous study [11] showed that traditional HP systems operating under typical Korean summer conditions could not maintain indoor comfort when the evaporating temperature exceeded 0°C. As illustrated in Fig. 3(a) and Fig. 3(b), the performance of all adsorbents was evaluated at evaporating temperatures of 7 °C, 10 °C, and 15 °C. Increasing the evaporating temperature resulted in higher SA temperature and humidity. Among the MOFs, MIL-100(Fe) achieved the highest average SA temperatures—23.4 °C, 25.3 °C, and 26.8 °C at 7 °C, 10 °C, and 15 °C, respectively—due to its strong sorption heat release that enhances air-side heating.

Maintaining low SA humidity allows greater flexibility in selecting optimal operating conditions. Operating at elevated evaporating temperatures reduces the system's compression ratio, lowers compressor workload, and enhances COP. Unlike conventional heat pump systems that require coil reheating to reach comfortable temperatures, the DCHP system naturally provides air within the comfort range due to (1) higher evaporating temperature operation and (2) partial transfer of sorption heat from the desiccant to the air stream.

The moisture removal capacities (MRCs) for silica gel, aluminum fumarate, CPO-27(Ni), and MIL-100(Fe) were 6.13, 7.33, 8.22, and 7.62 g/kg, respectively. Among all materials, MIL-101(Cr) achieved the greatest humidity reduction, with an MRC exceeding 8 g/kg—approximately 30% higher than that of silica gel. This superior performance stems from its rapid adsorption kinetics, high water uptake, and large surface area. Overall, MIL-101(Cr) delivered the best system performance, achieving a COP slightly above 8, demonstrating its strong potential for efficient automotive air conditioning applications.



(a) (b)

Figure 3. SA results: (a) temperature, (b) humidity.

5. Conclusion

This paper conducts a numerical analysis of a novel heat pump system that integrates DCHP technology into automotive air conditioning applications. The key conclusions drawn from this study are as follows:

- An increase in evaporating temperature from 7°C to 15°C led to higher SA temperature and humidity for all desiccants; however, the DCHP system effectively sustained ASHRAE comfort conditions through efficient dehumidification. Operating at higher temperatures also reduced compressor load and enhanced overall efficiency, making it advantageous for EV applications.

- MOF-based adsorbents notably enhanced system performance. MIL-101(Cr) achieved the highest MRC (8.90 g/kg) and lowest SA humidity, while MIL-100(Fe) produced the highest SA outlet temperature, reaching 26.8°C at 15°C evaporating temperature.

- Unlike conventional heat pumps that require reheating due to low SA temperatures, the DCHP system naturally provides comfortable air temperatures through sorption heat release and elevated evaporating operation, eliminating reheating needs and reducing energy use.

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