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Efficiency analysis of semi-open sorption heat pump systems

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ABSTRACT

Sorption systems traditionally fall into two categories: closed (for chilling and heat pumping) and open (for dehumidification). Recent work has explored the possibility of semi-open systems, which can perform heat pumping or chilling while utilizing ambient humidity as the working fluid of the cycle, and are capable of being driven by solar, waste, or combustion heat sources. The efficiencies of closed and open systems are well characterized and can be accurately determined from four temperatures (one for each of the main components—desorber, absorber, condenser and evaporator). In this work, the performance potential of semi-open systems is explored by adapting expressions for the efficiency of closed and open systems to the novel semi-open systems. A key new parameter is introduced, which involves both the ambient dry bulb and ambient dew point temperature, since both are critical to semi-open absorber operation. The dew point temperature is necessary to capture the absorption performance, while the dry bulb temperature is needed to calculate sensible heat transfer with surrounding air.

1. Introduction

The residential sector in the United States consumed a total of 22.1 quadrillion Btu (quads) of primary energy in 2010, which is 22% of the total primary energy consumption in the US [1]. Two of the main processes that consume this energy are space cooling and water heating. To reduce cooling energy consumption, an approach involving separate sensible and latent cooling (SSLC) is receiving significant attention [2–4]. Such SSLC devices can significantly reduce primary energy consumption, as the latent cooling (dehumidification) is achieved by liquid desiccant systems. In liquid desiccant systems, a salt solution (absorbent), hygroscopic in nature, absorbs water vapor from the ambient air in the absorber, thereby dehumidifying the air and reducing the salt concentration of the solution. The solution is re-concentrated in the desorber by adding solar, waste, or combustion heat to desorb water vapor, which is rejected to the outside air. Significant work is reported in the literature to operate open liquid desiccant–based systems to achieve dehumidification driven by solar heat [5–8]. However, adapting such an open liquid desiccant system for the purpose of heating has not been explored in great detail.

An open liquid desiccant system can be implemented as a heat pump with the addition of a condenser to condense water vapor from the desorber. Such a system would then be a semi-open absorption heat pump. Semi-open systems have various advantages over conventional closed sorption heat pumps (see Table 1). The two systems are compared in Fig. 1. First and most important, since water vapor in the ambient air is used as a refrigerant in a semi-open system, the need for the evaporator is eliminated and the system operates predominantly at atmospheric pressure. The lack of vacuum allows simpler designs: since the system operates at ambient pressure, with only small hydrostatic pressure differentials, wall thicknesses can be very small. The thin walls can allow low thermal resistance even with low thermal conductivity materials, enabling polymers to potentially be used to fabricate the heat and mass exchangers [2], replacing expensive metal-based vacuum-tight designs and thereby reducing the weight and the cost of the system. There is no need of an auxiliary vacuum pump to purge a buildup of noncondensable gases. Additionally, an inexpensive, non-hermetic solution pump can be used. The solution pump also operates at a lower pressure differential, as there is only a hydrostatic total pressure difference between the system low and high sides. In short, the semi-open architecture enables a low-cost liquid desiccant–based system that can be produced for even residential-scale application.

There are certain challenges associated with semi-open

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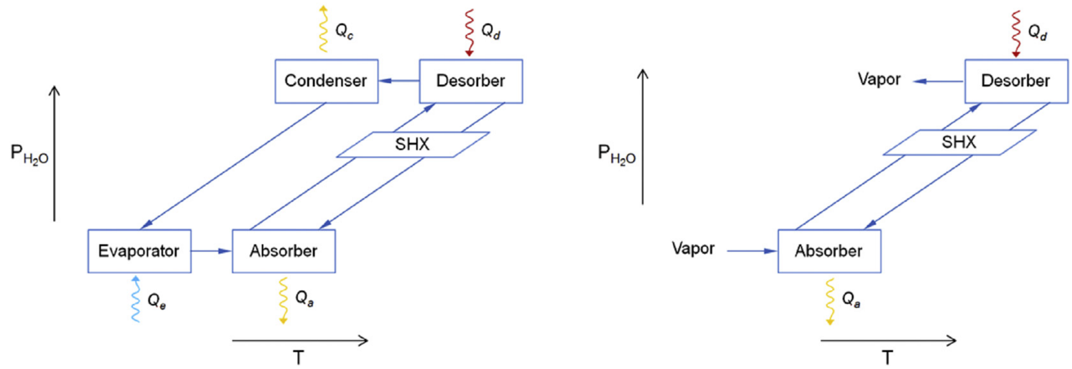

Fig. 1. Traditional closed (left) and open (right) sorption systems.

Table 1
Components in semi-open systems are of lower cost and complexity.

Component	Traditional closed sorption	Semi-open sorption
Vessel materials	Carbon steel	Polymer
Solution pump	Hermetic, with hydrostatic plus 1–15 kPa variable head	Nonhermetic with constant hydrostatic head
Vacuum requirements	Periodic vacuum pumping	None
Vessel pressure rating	Must withstand full vacuum (34 ft)	Only hydrostatic pressure differentials (~2 ft)
Evaporator	Required	Not required

absorption systems. First, the concentration of noncondensable gases (primarily N_2 and O_2) in the absorber is very high, which impedes the absorption process and leads to lower absorption rates than in closed absorption cycles. To overcome lower absorption rates, a higher absorption area is required in an open absorption system than in a closed system for an equal amount of vapor to be absorbed. Second, in a semi-open absorption system, the performance of the absorber varies with the ambient dry bulb temperature, as there is direct sensible heat transfer at the solution–air interface. Although this heat transfer may be beneficial under favorable conditions (high ambient dry bulb and low heat transfer fluid [HTF] temperature), typically the system designer will prefer to minimize the heat transfer, since the dry bulb temperature is typically below the solution temperature. This challenge can be addressed by implementing a thermal barrier like a membrane [9–13], which allows mass transfer of vapor but impedes heat transfer from the interface to the air side. Membrane technology can also enable absorption enhancement techniques like micromixing (demonstrated numerically by Bigham et al. [14] and experimentally by Nasr Isfahani et al. [15]) or can be combined with a finned structure as demonstrated in Mortazavi et al. [16].

Given the advantages of semi-open systems, it is important to establish the thermodynamic limits of operation of such a system. This paper explores the merits of the semi-open system with respect to theoretical limits to performance. Challenges inherent to the architecture—specifically the constant presence of noncondensable gases and the thermal interaction between the absorber and ambient air—are taken into account to establish the performance of the device. The presence of noncondensable gases is accounted for by using experimental mass transfer coefficient values measured in the presence of noncondensables. For the effect of ambient dry bulb temperature, a new parameter "α" is introduced. A system of equations is developed to solve for α. Using energy balances, semi-empirical relations, and equations of state (EOSs) for the solution, simulations are performed based on this equation set to study the performance of the semi-open system in different ambient conditions. For computations in this work, aqueous lithium bromide solution (LiBr) is used as an absorbent.

2. Theory

2.1. Theory: efficiencies of closed and semi-open systems

The traditional classes of closed and open sorption systems are depicted in Fig. 1. The closed system contains four heat exchangers operating at pressures isolated from ambient. It can provide cooling at the evaporator and/or heating at the absorber and condenser. The open system operates at atmospheric pressure, absorbing water vapor from air, dehumidifying it, and rejecting water vapor to another air stream (typically outdoor air). It provides dehumidifcation at the absorber.

In heating mode, the efficiency of the closed system can be expressed as a coefficient of performance (COP), the ratio of component heat loads shown in Equation (1). The terms in the numerator sum to the useful heat delivered by the device. The denominator describes the high-temperature heat (from solar, waste, or combustion) that is consumed to drive the device.

$$COP_{htg} = \frac{absorber\ heat + condenser\ heat}{desorber\ heat}. \quad (1)$$

Equation (1) can be expanded with qualitative terms as in Equation (2):

$$COP_{htg} = \frac{absorption + solution\ sensible - vapor\ sensible + condensation + vapor\ desuperheating}{desorption\ + solution\ sensible} \quad (2)$$

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