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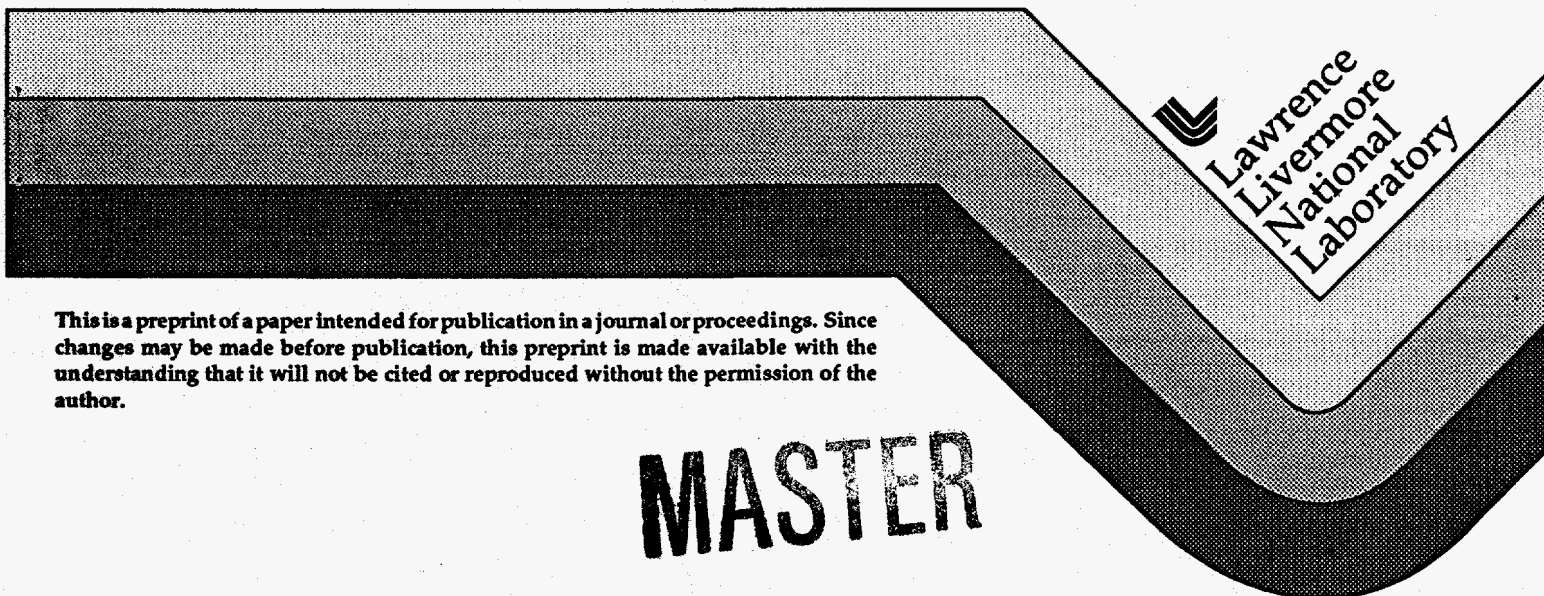
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## Adsorption Air Conditioner for Electric Vehicle Applications

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ADSORPTION AIR CONDITIONERS FOR  
ELECTRIC VEHICLE APPLICATIONS\*

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ABSTRACT

This paper shows an analysis of the applicability of an adsorption system for electric vehicle (EV) air conditioning. Adsorption systems are designed and optimized to provide the required cooling for four combinations of vehicle characteristics and driving cycles. The resulting adsorption systems are compared with vapor compression air conditioners that can satisfy the cooling load. The objective function is the overall system weight, which includes the cooling system weight and the weight of the battery necessary to provide energy for air conditioner operation. The system with the minimum overall weight is considered to be the best, because a lower weight results in an increased vehicle range.

The results indicate that, for the conditions analyzed in this paper, vapor compression air conditioners are superior to adsorption systems not only because they are lighter, but also because they have a higher COP and are more compact.

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## INTRODUCTION

Heating and air conditioning (HVAC) requires far more energy than any other car accessory. Electric vehicles (EVs) have a low energy storage capacity, and HVAC may consume a substantial amount of the total energy stored, considerably reducing the vehicle range, which is one of the most important parameters for EV acceptability.

Adsorption systems are well suited for EV applications because they can provide cooling when the vehicle is operating without consuming any battery energy, except for the small amount required for accessories. The system can then be regenerated during the vehicle charge period.

This paper analyzes the applicability of adsorption systems to provide EV air conditioning. Adsorption systems are designed and optimized for the cooling loads existing in four combinations of vehicle equipment and driving scenarios. The resulting designs are compared with a vapor-compressed air conditioner that can satisfy the required cooling load. The figure of merit used is the overall weight of the system, which includes the weight of the battery required to provide the energy for operating the system. The best air conditioner is the one that can provide the required cooling with the minimum overall weight. Overall weight is used as a figure of merit because reducing the weight of the EV reduces the energy necessary for traction and therefore increases the range of the EV.

## VEHICLE DESCRIPTION AND LOAD CALCULATION

In this analysis, air conditioning loads are calculated for four combinations of vehicle characteristics and driving scenarios. The four cases being analyzed are:

Case 1: Short range electric vehicle, used for two trips daily, each lasting 30 minutes. All the vehicle windows are made of regular glass, with heat absorbing coating on the top 0.10 m of the windshield.

Case 2: Short range electric vehicle, used for two trips daily, each lasting 30 minutes. All the vehicle windows are made of heat reflecting (hot mirror) glass. Also, a solar powered fan operates whenever the vehicle is left in the sun, to reduce hot soak temperature.

Case 3: Full range electric vehicle, used for two trips daily, each lasting 60 minutes. Same vehicle characteristics as for Case 1.

Case 4: Full range electric vehicle, used for two trips daily, each lasting 60 minutes. Some vehicle characteristics as for Case 2.

In addition to these characteristics, all the EVs have the dimensions of subcompact vehicles; operate with the minimum allowable amount of external air flow rate; and have an extra layer of insulation in the roof. The vehicle trips are as follows. The first trip starts from comfort conditions (by cooling and protecting the vehicle from the sun during the charge process). The second trip starts from full hot soak conditions. Load calculations consider two occupants.

The cooling load in the first trip (starting from comfort conditions) is calculated by using steady-state estimates of the heat transfer due to insolation, conduction, ventilation, and metabolic load. The load calculation from hot soak uses a two-dimensional radiative model of the vehicle interior, along with a model that simulates the transient thermal conditions inside the vehicle. The air conditioner power at the start of the second trip is calculated as the required power to cool the air inside the EV down to comfort conditions ( $T_{db} = 25^{\circ}\text{C}$ , and specific humidity,  $w = 0.012 \text{ kg H}_2\text{O/Kg air}$ ) in 15 minutes. After reaching comfort conditions, the air conditioner power is controlled to keep the comfort conditions for the rest of the trip. The outdoor design conditions are,  $T_{db} = 43^{\circ}\text{C}$ ,  $T_{wb} = 22^{\circ}\text{C}$ . Cooling load calculations are used in the following sections to design appropriate air conditioners for the four cases considered in this paper.

## THE ADSORPTION SYSTEM

Figure 1 is a schematic of the adsorption system used for EV air conditioning. All heat exchanger surfaces (including the adsorbent bed) are made of aluminum for reduced weight and enhanced heat transfer. Adsorbents release energy (the heat of adsorption) during the adsorption process. This energy has to be withdrawn from the system to obtain good cooling performance, because high temperatures reduce the capacity of the adsorbent to adsorb vapor. Cooling of the adsorbent is obtained by constructing the adsorbent bed as a plate-fin heat exchanger, with a coolant (water) running inside the tubes, and with the adsorbent pellets stored between the fins.

Among the several pairs of adsorbent and adsorbate available, zeolite and water are selected for the present analysis. This combination is chosen because zeolite can adsorb large amounts of water, and because water has the highest density and latent heat of vaporization of all the common liquids (Tchernev and Emerson, 1988). This results in a large cooling effect per unit mass of adsorbent, and thus a small adsorbent mass to satisfy the cooling load.

Other adsorption air conditioner configurations have been described and analyzed in the literature (see, for example, Miles and Shelton, 1991), and are known to have a higher COP than the configuration used for this analysis. However, these configurations are not very well suited for EV applications, because they require regeneration during operation, which may consume a substantial part of the EV energy.

## ANALYSIS AND OPTIMIZATION

The main simplifying assumptions used in this analysis are as follows.

1. The heat exchangers, including the adsorbent bed, can be analyzed as operating in steady-state, with the effectiveness-NTU method (Kays and London, 1984). The use of this method is considered a good approximation for the present analysis, because heat exchanger temperatures vary slowly as a function of time.

2. The adsorption bed is isobaric throughout. This assumption is valid due to the large voids existing between the adsorbent particles, the high porosity of the particles and the relatively low flow rate of adsorbate (Guilleminot et al., 1987; Aittomaki and Harkonen, 1988).

3. Temperature changes inside the adsorption bed occur slowly, so that there is a local equilibrium between the vapor phase and the adsorbate concentration at all locations in the adsorption bed.

4. The evaporator temperature is constant throughout the process. Controlling this temperature involves operating the evaporator valve so that only the precise amount of vapor flows into the adsorbent, generating the required cooling power to compensate for the heating load into the vehicle.

The analysis is based on a distributed model of the adsorption bed and lumped models of the other system components. A set of equations is used to describe the adsorption system. This set of equations includes the energy balance equation for the adsorbent, the equilibrium equations for the adsorbent-adsorbate system, an equation for the heat of adsorption, a model for calculating the effective thermal conductivity of the adsorption bed, and efficiency-NTU correlations for the bed cooler heat exchanger, evaporator and condenser. The resulting system of equations is solved iteratively, by guessing initial values of system pressures and temperatures, and iterating until reaching convergence. Bed temperatures and concentrations are obtained from the energy balance equation for the adsorbent, by using an implicit, finite difference method. When convergence is obtained, the process is complete, and the program moves to the next time step. The process is concluded when the vapor pressure inside the bed is equal to the vapor pressure of the water in the evaporator, because at this point no more evaporation can occur, and the adsorption process stops.

When the analysis of the adsorption process is complete, the conditions for desorption are calculated. During desorption, the adsorption bed is electrically heated.



Desorption results include the temperature and the water concentration in the adsorbent as a function of time; the time period required for desorption; and the COP for the overall process.

The adsorption system designs resulting from the analysis are then optimized for the four cases being considered in the paper. As previously discussed, optimum designs have a minimum overall weight. Adsorption systems are optimized with respect to four independent variables: the distance between the fins inside the adsorption bed,  $2d$ ; and the three-dimensions of the bed cooler heat exchanger,  $a$ ,  $b$ ,  $c$ , where  $a$  and  $b$  are measured perpendicular to the air flow direction, and  $a$  and  $c$  are measured perpendicular to the coolant flow direction. In addition to this, the bed cooler heat exchanger fan is selected from a set of three fans (with input power respectively equal to 50, 83, and 108 W) as the fan that provides the optimum characteristics for system operation.

## RESULTS

Table 1 lists, for the optimum designs, the weight of the different adsorption system components; the total weight of the adsorption and the vapor compression air conditioners; and the volume and COP for the adsorption system. The weight calculations assume that the EV uses high performance lead-acid batteries (Hardin, 1992), which represent the best developed and least costly technology. The weight calculations for the vapor compression air conditioners assume a system COP equal to 2.2, as an average of the values reported by Ikeda et al. (1990). The weights for the vapor compression air conditioner components are estimated from correlations obtained from the weight of current electric air conditioners.

The system weights shown in Table 1 indicate that vapor compression air conditioners are up to 20% lighter than adsorption systems. In addition to this, vapor compression air conditioners are more compact, and have a higher COP. These factors make vapor compression systems better EV air conditioners, for the conditions analyzed

in this paper. However, new developments and heat transfer enhancements in adsorption systems (Mei, et al., 1992; Guilleminot et al., 1993), may result in more favorable conditions for applying adsorption systems to EV air conditioning.

## CONCLUSIONS

This paper has shown an analysis of the applicability of adsorption systems to provide EV air conditioning. Adsorption systems are designed and optimized for four combinations of vehicle characteristics and driving schedules. The systems are optimized with respect to four decision variables and the selection of a fan. The results show the overall system weights for all the configurations. The overall system weights are compared with those for vapor compression air conditioners that can provide the required cooling load.

The results indicate that vapor compression air conditioners are superior to adsorption systems for the conditions analyzed in this paper, not only because they are lighter, but also because they have a higher COP, and are more compact. However, heat transfer enhancements in adsorption beds may make EV adsorption systems more attractive in the near future.

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Table 1. Optimum designs for the adsorption air conditioners, including system weight by component, battery weight to provide the required energy; overall weight for the zeolite-water adsorption air conditioner and the vapor compression air conditioner; and adsorption system volume and COP, for the four cases being considered in the analysis.

Case Number	1	2	3	4
System Component	Weight in kg			
Adsorbent	28	19	44	32
Adsorbent Storage	27	19	38	29
Water	8	8	11	10
Evaporator	4	4	5	4
Condenser	4	4	5	4
Bed Cooling HZ, pump and fan	6	5	6	6
Air Cooling HX, pump and fan	6	5	6	6
Battery Weight	4	4	9	9
Overall Weight for Adsorption System	87	68	124	100
Overall Weight for Vapor Compression Air Conditioner	72	56	111	89
Adsorption System Volume and COP				
Volume, liters	106	76	150	117
COP	0.27	0.30	0.26	0.29

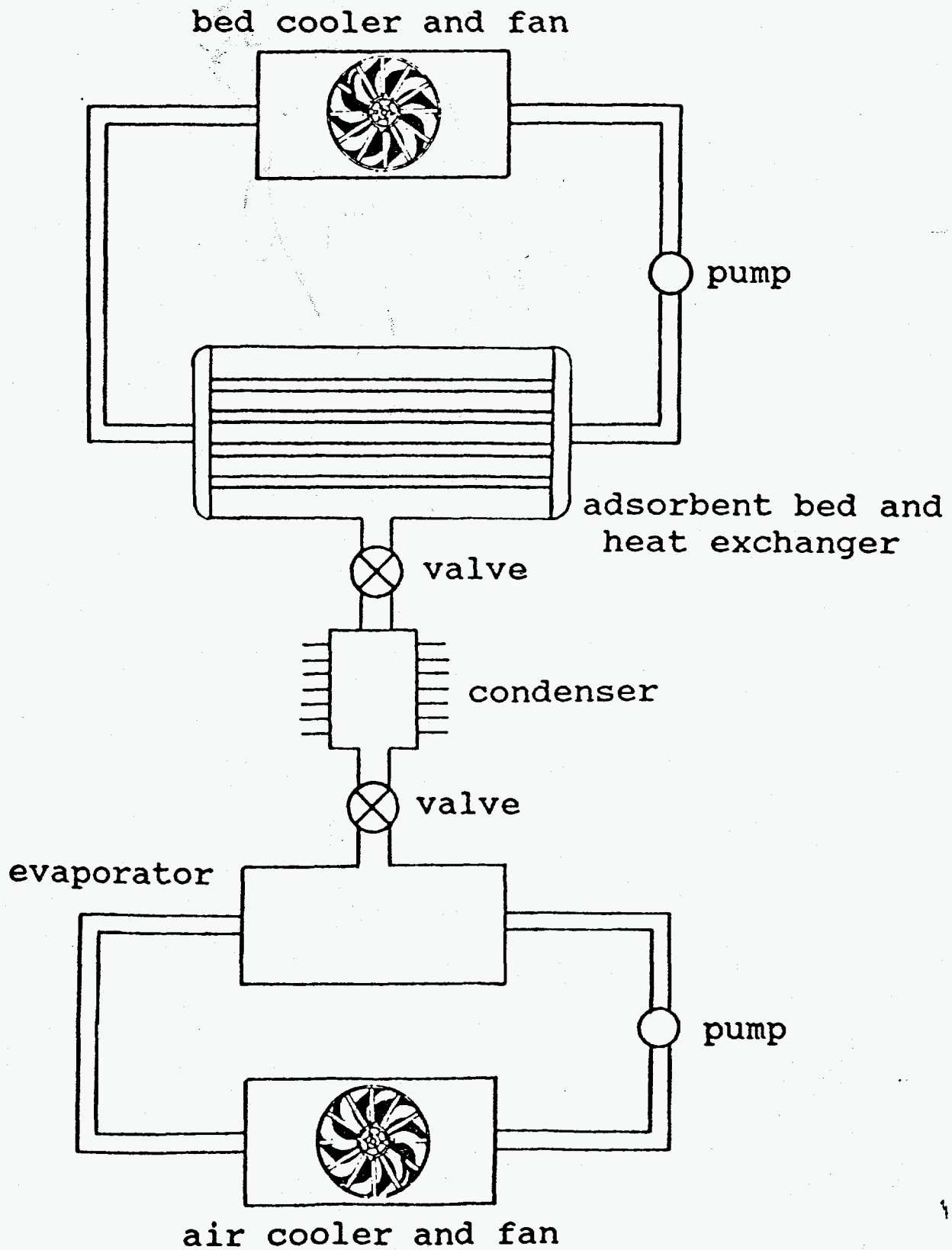


Figure 1. Schematic diagram of an adsorption air conditioning system.