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Performance evaluation of a waste-heat driven adsorption system for automotive air-conditioning: Part I – Modeling and experimental validation

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ABSTRACT

Adsorption systems driven by engine waste heat are one of the possible alternatives to the conventional automobile air conditioning in terms of energy savings and environmental issues. Assessment of this issue are carried in a two-part study. In this first part I, theoretical and experimental investigations were performed on a two bed, silica gel adsorption chiller for automotive applications. A prototype adsorption system with a total weight of about 86 kg was developed and tested to driven by low-grade waste heat. The single adsorbent bed consisted of three plate-fin heat exchangers connected in parallel. An improved non-equilibrium lumped parameter model was developed to predict the transient performance of the system. The model is fully dynamic and takes into account the mass transfer resistance and pressure drop for each component of the system. The results showed that the model is able to accurately predict the dynamic performance of the system under different operating conditions and configuration modes with a short calculation time. The tested chiller was able to produce an average cooling capacity of about 2.1 kW with a COP of 0.35 at the rated operating conditions. Heat recovery system results in increasing the COP by 43% and the cooling power by 4%.

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1. Introduction

Energy savings and environment-friendly applications are becoming one of the important topics nowadays due to the rapid population growth and increase in the standard of living. Hazardous gasses from automobiles exhausts and chemically synthetic refrigerants used in the traditional vapor-compression refrigeration cycles (VCRC) are of the major pollutants of our environment [1,2]. In addition, transportation is one of the major users of primary energy and burns most of the world petroleum. The most common method for refrigeration and air conditioning systems in different applications is employing VCRC due to its high COP [3,4]. However, the use of these systems leads to a considerable high-grade energy consumption and environmental pollution. The negative impacts of the VCRS become more pronounced in automotive and transportation applications where the compressor is powered by mechanical energy from the internal combustion engine.

Thermally driven adsorption cooling systems (ACSs) can use natural working fluids (such as water or ammonia) as a refrigerant and have the ability to be driven by a low-grade heat source such as solar energy and waste heat from automobile engines or industrial applications [5,6]. Therefore, these systems can be considered one of the possible alternatives to VCRSs (e.g. automobile applications) in terms of energy savings and environmental issues. The exhaust heat from the engine can be used to supply the required thermal energy input to the adsorption chiller. The waste heat usually constitutes 60–70% of the total energy used in internal combustion engines (ICE) during energy conversion processes [7,8].

Different experimental and theoretical studies have been performed on the adsorption cooling systems processes [9–13]. The majority of the existing studies are related to the development of mathematical models. Recent developments are focusing on dynamic models which can give a more clear idea about the transient behavior of the heat and mass transfer processes in the adsorbent bed, especially when heat-source is variable, as in the case of

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automobile applications. The majority of researchers propose zero-dimensional models [14–23] while some have focused on one-dimensional models [24–27]. Two and three-dimensional models can also be found in the literature by Refs. [28–32] and [33,34] respectively. However, the main differences between the different models generally occur in the simplifying assumptions, numerical solution method, components design and application of the modeled system. Table 1 listed a summary survey of experimental and theoretical studies based on adsorption cooling systems driven by engine waste heat.

It can be noticed that systems which have lower heat source temperature have higher COP than those with higher heat source temperature. It may be due to the fact that the heat losses related to the alternate heating/cooling of the bed increase by raising the bed's temperature. Silica gel-water pair can be efficiently used with a maximum desorption temperature of 80–90 °C, which is suitable for adsorption systems driven by low-temperature heat sources, as it is the case of the engine cooling circuit of automobiles which normally lies between 90 and 95 °C. Few experimental data and calculations on adsorption chillers powered by engine waste heat with heat recovery system can be found in the literature [44]. The system performance with heat recovery could be improved up to 50% [45–47].

All the existing models up so far contain certain simplifications in the basic equations that result sometimes in numerical instabilities Douss et al. [48]. Therefore, there is a need for more reliable dynamic models and, in particular, to predict the entire system components of any sorption systems includes the evaporator, condenser, adsorbent beds, valves, and other heat exchangers.

In part I of this study, modeling and experimental testing of an adsorption chiller system powered by engine waste heat is investigated. The system performance was evaluated with and without heat recovery operation mode. An improved non-equilibrium dynamic model of the adsorption/desorption process in transient regime is developed to simulate the behavior of the silica gel (Sorbil A)/water adsorption system under different configuration modes. The model incorporates all system components in order to simulate the full dynamic behavior of the entire system. In addition, the model can estimate the instantaneous operation, performance, and efficiency of each component. Moreover, the kinetics of the desorption/adsorption processes, the thermal inertia of all the involved components, including the fluid circuits, and the operation of the valves between components can be estimated. This will allow understanding the non-equilibrium adsorption/desorption process in transient regime.

As a comparison between the proposed model and those existent in the literature is that the flow between the components is based on the pressure difference between them. The pressure inside the adsorber is based on state equation and mass conversation. This makes the model able to capture the most important characteristics of the dynamics of the system. In addition, different valve operation strategies or automatic operation (reed valves) can be evaluated with the present model. However, the developed model has been validated with the actual experimental measurements in dynamic conditions and under different operation strategies such as the inclusion of a heat recovery process. The experimental data were performed at the Energy research Centre of the Netherlands, Petten (ECN).

In part II of this study, the validated model is used to simulate and optimize the transient performance of an on-board adsorption chiller (implemented in a vehicle) under actual operating conditions and obtain comfortable temperatures in the cabin[4].

2. Design and description of the adsorption system

The cooling water temperature at the outlet of automotive engines normally lies between 90 and 95 °C [5]. Therefore, a great amount of thermal energy (waste heat) can be recovered from the engine's coolant cycle at those temperatures. In addition, the water temperature could be increased by heat recovery operation from the exhaust gasses in order to provide an increased temperature heat source.

The proposed adsorption system was designed and tested under the framework of the TOPMACS project for automotive air conditioning applications [49] where the experimental tests are performed at the ECN laboratories. The system consists of two sorption beds named BED 1 and BED 2 connected to a condenser and an evaporator, an expansion device and four check valves to direct the refrigerant vapor flow, a condensate valve connected to a liquid level control in the evaporator and four three way valves to direct the heating and cooling water circuits alternately to both adsorbent beds as shown in Fig. 1. As shown in the figure, the system also involves three independent secondary water loops: a secondary water loop to heat the bed (Heating Water Loop), a secondary water loop to cool first the condenser and then the bed (Cooling Water Loop), and a secondary water loop to provide heat to the refrigerant in the evaporator (Chilled Water Loop). The adsorbent beds operate in counter-phase in order to allow a continuous useful effect: when the first bed is in cooling mode the second one is in regeneration mode. The hot water is sent to one of the two beds, depending on the position of the valves in the liquid circuit. The cooling water is

Table 1
Summary of studies related to the use of engine waste heat (exhaust gasses and/or water coolant) to drive adsorption cooling systems.

Heat source	Ref.	Heat source (°C)	Pair	SCP Wkg-1	COP	Cooling temp (°C)	Cooling power (KW)	Application	Study type
Engine waste heat gasses	[35]	210–230	zeolite–water	N/A	0.38	18	3.4	locomotive	E
	[8]	350–450	zeolite–water	164–200	0.25	10	6.5–10.0	locomotive	E[a] + T[a]
	[36]	400	zeolite–water	N/A	0.2–0.3	7	5	locomotive	E
	[14]	255–296	zeolite–water	25.7	0.38	10	45	truck	E + T
	[37]	200–250	zeolite–water	N/A	0.25	3.0–5.0	2.8–4.0	locomotive	E
	[38]	325	zeolite 13x –water	180	0.4	0.7–16.2	0.002–0.0105	truck	E
	[39]	220–250	zeolite–water	N/A	0.21	5–18	3.0–4.2	locomotive	E
	[16]	200	activated carbon–methanol	400	0.25	15–25	0.65	Diesel engine	T
	[17]	250	zeolite–water	N/A	0.436	7–15	2.015	truck	E + T
	[18]	80–90	zeolite–water	N/A	0.6	10	5	truck	E + T
	[40]	400–600	zeolite–water	N/A	N/A	11	2.5	truck	E
Engine coolant water	[19]	270–450	zeolite 13x –water	45	0.41	10	N/A	automobile	T
	[41]	90	activated carbon–ammonia	650–800	0.22	20	1.6–2.0	automobile	E
	[42]	87	silica gel–water	208	0.62	12	3.6	automobile	E
	[43]	90	N/A	300–600	0.25–0.45	8–14	1–2.3	truck	E

[a] E–refers to experimental study and T refers to theoretical study.

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