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Performance evaluation of a waste-heat driven adsorption system for automotive air-conditioning: Part II - Performance optimization under different real driving conditions

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ABSTRACT

In this part, Part II, of a two-part study, the validated model of part I is integrated into a general vehicle model in order to predict the performance of the system under real driving conditions. The overall model takes into account all the system components to simulate the dynamic performance of the entire system and predict the cabin temperature at the available waste heat. The system was implemented in a Fiat Grande Punto vehicle and the experimental tests were performed at the Centro Ricerche Fiat (CRF), Italy laboratories. Different design configurations were investigated to explore further improvements of the performance. Results showed that the model was able to well predict the transient performance of the system under different start-up and ambient conditions as well as the normal operating conditions. Using two radiators instead of one radiator increases the cooling capacity by 7.0% and decreases the cabin temperature by 9.1%. At the warming up period, the adsorption system faces serious difficulties to start producing the required cooling. Possible strategies to avoid this problem were studied and compared. In general, it has been proved that the amount of engine waste heat available is sufficient to produce enough cooling to keep reasonably comfortable temperatures in the cabin.
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1. Introduction

The global energy demand for refrigeration and air conditioning systems is rapidly increasing, especially in developed countries. This increase is responsible for the fossil fuels depletion and the greenhouse gas emissions due to the use of electrically driven vapor compression machines (VCRSs) [1].

At present, nearly all automotive air conditioners use traditional VCRS driven mechanically by the car engine. For a 1200 kg car running at 56 kmh^{-1}, the traditional air conditioning system can add up to 5–6 kW power drawn from the engine [2]. Moreover, the fuel consumption can increase by up to 70% for a B class car on an urban cycle under severe ambient conditions (35 °C and 60% RH) [3]. These systems reduce the automotive driving performance and increase the fuel consumption and exhaust gas emissions. Therefore, the searching on energy efficient, renewable, and cheap cooling technology is an important goal in the transportation industry.

In automobiles applications, methods of utilizing the waste energy from the automotive engine to drive the car air conditioning system are worthy of investigation. Overall, the efficiency of a diesel engine is about 35–40% and the rest of the energy is lost mainly to the engine coolant loop and the engine exhaust gasses [4]. The temperature of the engine coolant water is about 90–95 °C for cars and 80–90 °C for trucks [5]; while the temperature of the exhaust gas discharged from the tailpipe comes within 150–450 °C [6].

In recent years, thermally driven adsorption A/C systems have witnessed and increasing interest in automobile applications due to the fact that this system is quit, long lasting, cheap to maintain, and environmentally friendly [7–9]. In addition, it can be driven by a low-grade heat source (80–150 °C) like waste heat from automotive engines [10]. In this way, it reduces fuel consumption and exhaust gas emissions. Moreover, the Montreal Protocol, Kyoto Protocol, and Vienna Convention had agreed to phase out HCFCs and CFCs.

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However, still there is no working adsorption A/C systems available at the market for automobiles at present, because of its low efficiency and large weight [11,12]. The need for efficiency improvement promotes scientists to develop new system designs, working pairs, and mathematical modeling [13]. Most of the works are carried out on adsorption and physicochemical properties of different adsorbent-adsorbate pairs [14], different types of adsorption-desorption process, such as heat and mass recovery operations [15,16]. Moreover, many studies have been carried out to improve and optimize the design and operating parameters that affect system performance [17–20].

The application of adsorption cooling systems for automotive air conditioning has attracted significant research work. In 1993, Suzuki [21] made a preliminary study to explain the technological limits in the application of an adsorption system to passenger cars' air conditioning. He concluded that the adsorbent material and the adsorber design to improve heat transfer characteristics are the most important issues for the application of adsorption cooling systems in automobiles.

A number of researchers had investigated the adsorption cooling system for automotive application and prototypes had been built and tested with different working pairs and bed configurations. Vasta et al. [22] developed and tested an adsorption A/C system for a truck cabin. The system powered by the thermal energy coming from the engine coolant loop of the truck. Results showed that the system was able to deliver an average cooling power of 2 kW and keep the truck cabin temperature around 24 °C. Verde et al. [5] constructed and tested a zeolite-water pair adsorption A/C system for a truck cabin. The overall weight and volume of the prototype were about 60 kg and 170 dm^3 respectively. A dynamic model was proposed to simulate the engine operation through a standard driving cycle to estimate the amount of waste heat available at the exit of engine hydraulic loop, the cooling capacity and the temperature and humidity of the air in the truck cabin. The proposed system can produce an average cooling power of about 2–3 kW. Tamainot-Telto et al. [23] designed an adsorption prototype with activated carbon-ammonia pair. The system was powered by the waste heat (at 90 °C) from the engine coolant water loop. An average cooling power of about 1.6 kW with an average COP of 0.22 were obtained. Wang et al. [24] presented a zeolite-water adsorption A/C system for locomotive operator cabin. The system can deliver cooling effect of 5 kW and COP of 0.25. The chilled water produced was about 8–12 °C for the fan coil in the locomotive cabin. Jiangzhou et al. [25] developed an adsorption prototype for a locomotive cabin air conditioning employing zeolite-water pair. The weight of the prototype was about 300 kg. The system can produce a cooling power of about 4.5 kW with COP of 0.25. Zhang [4] designed and tested an automobile adsorption chiller using zeolite-water pair driven by the waste heat of a diesel engine. A specific cooling capacity of 25.7 W kg^{-1} at COP of 0.38 was obtained.

At present, mathematical modeling is the most commonly used technique to predict the performance of an adsorption cooling system. There are several mathematical modeling techniques including the lumped-parameter simulation, distributed-parameter simulation and dynamic simulation [26]. However, the modern developments are focusing on dynamic models which give a more clear idea about the dynamic behavior of the transient heat and mass transfer processes occurring in the beds [27–29]. However, further studies and improvement on these systems are needed in order to enhance and optimize their performance, especially at the strongly dynamic conditions of automotive application with a huge variability of the ambient conditions, and waste heat.

In this part, Part II of a two-part study, performance, and optimization of a silica gel-water on-board adsorption system are investigated based on the validated dynamic model proposed in the first part of this paper, Part I [30]. The overall model was used to simulate the performance of the entire system (engine, adsorption system, heating and cooling circuits, chilled water circuit and cabin) under real driving conditions of a car. The model is able also to estimate the waste heat available at the engine cooling loop, calculate the cooling capacity and monitor the temperature and humidity of the air at the cabin, as a function of the vehicle velocity, ambient temperature and sun radiation. The system performance, as well as the cabin temperature, was analyzed under real driving conditions of start-up strategies and different ambient conditions. In addition, some parametric studies had been carried out to evaluate the system performance under different design (layout) configuration and operation strategies in order to explore further improvements of the system performance.

2. Description of the on-board adsorption A/C system

Fig. 1(a) shows a picture of the on-board adsorption A/C system in the laboratory and Fig. 1(b) shows the system fitted in a passenger vehicle. Fiat Grande Punto vehicle with a 1.9 JTD engine was selected as a reference car. The choice for this diesel engine is justified as it represents a worst case situation, because this engine is very efficient and therefore produces relatively low amount of waste heat. The system was designed and tested under the framework of Topmacs project for automobile air conditioning

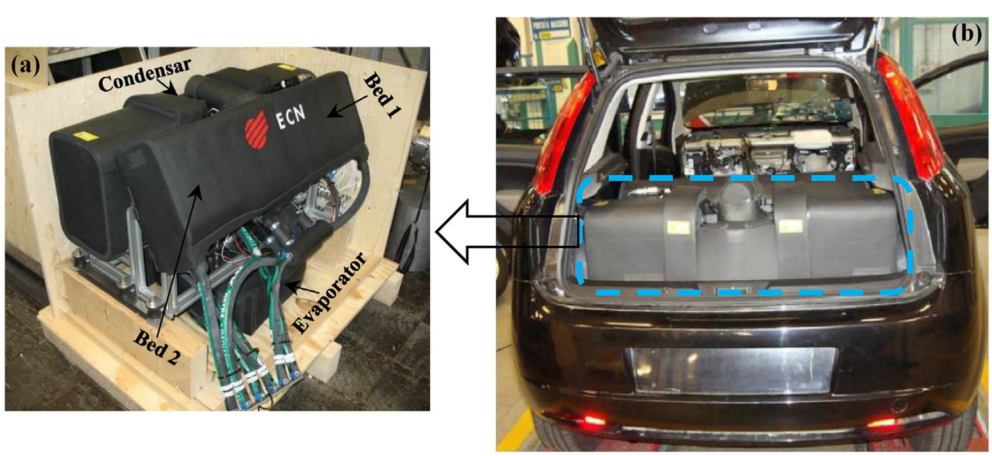

Fig. 1. Picture of the proposed on-board adsorption A/C chiller: **(a)** in the laboratory and **(b)** installed in the vehicle.

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