

# Silicagel-water adsorption cooling prototype system for mobile air conditioning

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## Abstract

A prototype adsorption cooling system was developed for the purpose of on-board test of mobile air conditioning driven by waste heat from the engine. The system was designed, constructed and first tested in the laboratory of ECN. The performance under various static operating conditions was determined in the laboratory. The system can produce 2 kW of chilling power with a COP of 0.4. The prototype was afterward installed in the Fiat Grande Punto demonstration car by CRF. The system was connected to the heating and cooling systems of the car and tested. The performance in the car was comparable to the performance in the lab, indicating that system integration was successful. A waste heat driven adsorption cooling system can be applied for comfort cooling purposes in a car. The amount of waste heat that is freely available in the engine coolant circuit as well as its temperature level is sufficient to drive the adsorption cooling system and to produce enough cold to keep comfortable interior temperatures.

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#### 1. Introduction

The use of conventional air-conditioning (AC) systems in cars and trucks contributes to the greenhouse gas emissions through losses of refrigerants with a high global warming potential, as well as through the additional fuel consumption related to the use of AC systems. Both the EU directive (EU, 2006) on the use of fluorinated refrigerants for mobile air conditioning (MAC) systems as well as lowering the  $CO_2$  emission targets for the automotive sector force the car manufacturers to look for more sustainable ways for climate control of the vehicle interior. Sorption cooling technology can potentially provide a more sustainable alternative than conventional compression cooling technology. Thermally driven sorption cooling systems can reduce both the direct impact (avoid the use of high GWP refrigerant) and the indirect impact (reduction of the additional fuel consumption) of MAC's on global warming.

The use of free waste heat from the engine to drive a sorption cooling system was subject of previous studies, (Christy, 2004; Lambert, 2006). These studies focused on the use of the heat from the exhaust gasses as driving energy for the sorption system. The amount of waste heat present in the exhaust and in the jacket cooling water was investigated in more detail in the initial stage of the TOPMACS project (de Boer, 2008), showing that in normalized European driving conditions (NEDC) the waste heat in the engine coolant is sufficient to drive a sorption cooling system.

The present study deals with the development of a thermally driven adsorption cooling system for on-board test and demonstration. The study was done as part of the EU funded TOPMACS project. A lab-scale prototype of a silicagel-water adsorption cooling system was developed and tested in the laboratory within the first phase of the project (de Boer, 2008). The results of these tests indicated that the silicagel water adsorption cooling system can provide sufficient chilling power at the required efficiency. It should in principle be able to cool down the passenger compartment by using the available waste heat in the engine coolant to drive the adsorption AC system. This was the starting point for the next development phase, the on-board silicagel-water adsorption cooling prototype. The goal of this phase is to test and demonstrate the performance in the real application.

The paper describes the development of the prototype, the tests and results under laboratory conditions, the integration and installation in the demonstration-car, and results of the on-board tests.

# 2. Adsorption cooling system development

#### 2.1 Overall system lay-out

A passenger car of the type Fiat Grande Punto was selected as the demonstration car. This car is representative for a modern European B-segment (compact) car. It has a 1.4 dm<sup>3</sup> petrol engine. Because the size of the thermal compressor section of the adsorption cooling system was too large to allow installation in the original engine bay, the prototype was installed in the trunk space. Because of the trunk location in the car an air cooled condenser could not be applied. Instead, a water cooled condenser is used. The heat rejection of the adsorption system from the condenser and the cooled silicagel reactor is done by an additional cooling water circuit that removes the heat through a radiator in the front of the car. The cold produced in the evaporator is transferred to a chilled water loop. The chilled water loop is pumped through the cabin air-cooler for cooling down the air that re-circulates in the passenger compartment. The system components and liquid circuits lay-out are shown in Figure 2.1. Each liquid circuit has a pump, a flow measurement device and temperature sensors at the inlet and outlet of the thermal components. The hot water circuit (or engine cooling water loop) has an exhaust gas heat exchanger (EGHE) which transfers part of the heat of the exhaust gas to the hot water. This reduces the time required to reach steady state operating temperatures of the engine. It also reduces the start-uptime of the sorption cooling system.



Figure 2.1 Process flow diagram of installation of the adsorption cooling system P=pump, T= temperature sensor, F= flow sensor, PH=parking heater, EGHE=exhaust gas heat exchanger

The target operating conditions for flow rates, temperature and thermal powers are given in Table 2.1.

	Temperature [°C]		Flow setpoint		Power	
	min	setpoint	max	m³/h	l/min	kW
Heating - supply - return	5 5	90 85	95 90	0.72	12	4,0
Cooling (condenser incl.) - supply - return	5 5	33 40	45 60	0.72	12	6,0
Chilling (evaporator) - supply - return	5 5	15 11.4	45 45	0.48	8	2,0

 Table 2.1
 Target operating conditions of the adsorption chiller

### 2.2 Prototype adsorption cooling system

The adsorption cooling system consists of a water cooled condenser, an evaporator, two silicagel reactors, check valves to direct the refrigerant vapour flow, a condensate valve connected to a liquid level control for the evaporator and four three way valves to direct the heating and cooling water circuits alternately to both silicagel reactors. Temperature sensors are installed inside the reactors, the evaporator and the condenser and pressure sensors are mounted on the condenser and evaporator. Temperature sensors are also installed to measure the inlet and outlets of the liquid circuits of the system. A PLC system controls the operation of the liquid circuit valves based on the readings of the temperature differences between the inlet and outlet of the hot water circuit. A design drawing of the prototype system and a picture of it are shown in Figure 2.2.



Figure 2.2 Design drawing and picture of the prototype adsorption cooling system

The thermal compressor section of the adsorption system consists of two reactors. Each reactor has three tube-fin heat exchangers connected in parallel. The fin side of each heat exchanger is filled with 1 kg of silicagel grains. The reactors are connected to a housing that contains the gravity operated refrigerant check valves. The condenser has three heat exchangers (automotive evaporators) connected in parallel and contained in a stainless steel envelope. It has internal reinforcements to withstand the forces of the internal vacuum. The evaporator has four tube-fin heat exchangers (automotive heater cores) that lie horizontally in 2 sections on top of each other. Each heat exchanger has a water layer at the lower part of the fin side.

The overall weight of the system is 86 kg, not including the weight of the water in the circuits for heating, cooling and chilling, the refrigerant water in the evaporator, and excluding the thermal insulation.

#### 3. Laboratory measurements and results

Laboratory measurements were done at ECN to verify the proper operation and thermal performance of the system before installing it into the car. The system was connected to a heating water circuit, a cooling water circuit and a chilled water circuit. The flow rates and temperatures of these circuits were set according to expected values for the on-board situation, during normalized European driving cycles. All thermal elements have an internal temperature sensor and a pressure sensor. The three external water circuits all have a flow sensor and have temperature measurements at the inlet and outlet of the adsorption system. This allows the measurement of all the thermal powers transferred by the sorption system. The laboratory tests conditions are static with constant flow rates, according to the set-points defined in Table 2.1. Figure 3.1(left) shows the temperatures of the three water circuits during 2 operating cycles. The thermal powers transferred by the operation of the system are shown in the graph on the right.



Figure 3.1 Left: Measured inlet and outlet temperatures of the heating, cooling and chilled water loop during a laboratory test. Right: Thermal powers over time of the heating, cooling and chilled water circuits during 2 operating cycles. Condensation and evaporation powers ( $P_{cond}$  and  $P_{evap}$ ) are plotted on the right y-axis

Figure 3.2a, b and c show the measured chilling power and COP at varying operating temperatures during the laboratory tests. The typical inlet temperatures for heating, cooling and chilled water are 90°C, 33°C and 15°C, respectively. The tests were conducted by varying only one of the inlet temperatures at the same time. The measured thermal power of evaporation and the system COP are plotted against both the average inlet (solid lines) and outlet temperatures (dashed lines) of the respective water circuits. Also the effect of changes in the cycle time on the performance was studied.



Figure 3.2 Chilling power and COP of the adsorption cooling system under laboratory test conditions with varying operating temperatures (a, b and c) and with varying cycle times under nominal operating temperatures (d)

 $\leftarrow$ 

b

d

#### 3.1 Laboratory performance overview

A convenient way to plot the thermal performance of an adsorption cooling system over a broad range of different operating temperatures is based on the use of the reduced temperature,  $T_{reduced}$ . (Núñez, 2004), defined as

$$T_{reduced} = \frac{T_{cool\_in} - T_{chill\_out}}{T_{hot\_in} - T_{cool\_in}}$$
[1]

 $T_{reduced}$  is the ratio between the *temperature lift* achieved by the 'heat pump' and the *temperate fall* used to drive the system. The temperature lift is the upgrade of heat from the evaporator temperature (chilled water outlet) to the cooling water temperature. The temperature fall is the difference in temperature between the heating water inlet and the cooling water inlet. Using the reduced temperature enables to plot all measurements at various temperature conditions in a single performance curve, see Figure 3.3.



Figure 3.3 The chilling power (left) and COP (right) versus T<sub>reduced</sub> for the laboratory tests at different operating temperatures. P<sub>nominal</sub> is 1.5 kW at T<sub>reduced</sub> of 0.4

# 4. On-board installation and tests

After the lab-test at ECN the adsorption cooling prototype system was installed in the trunk of the car by CRF in Turin, Italy. (Figure 4.1) The water circuits for heating, cooling and chilling (see Figure 2.1) were connected to the adsorption system. In these tests the effect of the system integration and the performance in more dynamic operating conditions with fluctuating flow rates and temperatures is studied.



Figure 4.1 The prototype adsorption cooling system installed in the trunk of the Fiat Grande Punto

A full series of test under varying operating conditions has not been performed yet, but several trial runs were done both in climatic chamber conditions as well as in the garage of CRF. In these trials the car was not actually driving but still in static position. The engine was running and an air flow was blown on the front of the car. The performance of the adsorption system was measured during these trial runs and the results are plotted in Figure 3.3. It can be seen that the chilling power and COP are not much changed compared to the results obtained in the laboratory. The small changes are probably caused by the differences in flow rates between the laboratory measurement and the on-board measurement. This makes the control system to automatically adapt its cycle time for heating and cooling of the silicagel reactors. In the on-board trial runs the cycle time was on average longer than in the lab-tests which results in slightly higher COP and a small decrease in chilling power. During these trials the ambient temperature was high, leading to high cooling water temperatures and to reduced temperatures in the range of 0.5 to 0.6. The cold produced was in the range of 800 Watt, which is sufficient to keep a car cabin at comfortable temperature, but which is maybe too low to get the internal temperature of a car cabin down to comfortable levels after it was parked in the sun.

# 5. Conclusions and discussion

A prototype adsorption cooling system for use as a mobile air-conditioning system was designed and constructed. The performance of the system was measured in the laboratory under varying operating temperatures and cycle times. Depending on the operating temperatures, the system can deliver up to 2.5 kW cold at a COP in the range of 0.3 to 0.5.

The adsorption cooling system was placed in the trunk of a car and connected to a cooling water circuit, a chilled water circuit and to the engine cooling water circuit as the driving energy source. In the trial runs on the car it was demonstrated that the adsorption system operates stable under fluctuating conditions of temperature and flow rates of engine cooling water circuit. The chilling power obtained on the car is sufficient to maintain comfortable temperatures inside the car cabin. Higher chilling powers can be obtained by reducing cooling water temperature. This can be achieved by improved heat rejection.

The results of the work presented in this paper, demonstrate that the concept of a waste heat driven adsorption cooling system can be applied for comfort cooling purposes in a car. The amount of waste heat that is freely available in the engine coolant circuit as well as its temperature level is sufficient to drive the adsorption cooling system and to produce enough cold to keep comfortable interior temperatures. The technology can in this way contribute to a reduction of the fuel consumption of a car, as well as to a reduction of emission of high GWP refrigerants of the conventional AC systems.

The development of adsorption cooling technology for MAC application requires further research and development effort. These efforts should include:

- reduction of system volume and weight,
- application of an air cooled condenser and a direct driven evaporator.

#### Nomenclature

- AC Air-conditioning
- MAC Mobile Air-conditioning
- NEDC Normalized European Driving Cycle
- HFC Hydro Fluoro Carbon
- RH Relative Humidity
- COP Coefficient of Performance
- LPM Litre per minute

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