Thermally operated mobile air-conditioning system

Development and test of a laboratory prototype

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Abstract

The use of air-conditioning (AC) systems in cars and trucks contributes significantly to the greenhouse gas emissions. Incoming regulations on the use of HFC refrigerants require new solutions for mobile AC systems. Thermally driven sorption cooling systems provide an opportunity to drastically reduce the global warming impact of the AC use. At ECN, a laboratory prototype of a silicagel-water adsorption cooling system was developed. It uses the available heat from the engine cooling water circuit to produce comfort cooling. The test results show that the adsorption cooling system is able to provide sufficient cooling power at the required efficiency.

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1. Introduction

Both the EU directive [1] 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 find 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. Sorption cooling systems use natural refrigerants such as water or ammonia, and can be driven by low-grade waste heat from the combustion engine. This technology allows a reduction of the direct CO_2 emissions of MAC systems to zero, as well as a significant reduction in the fuel over-consumption (the indirect CO_2 emissions), because it does not take mechanical power from the engine.

The EU funded TOPMACS (**T**hermally **OP**erated **M**obile **A**ir-**C**onditioning **S**ystems) project aims at the development of innovative MAC systems for cars and trucks. The project consortium consists of CRF, IVECO, Valeo and Treibacher AG, as industrial partners and CNR-ITAE, University of Warwick, Stuttgart University, Technical University of Valencia, and ECN as research partners. Within the project four different laboratory prototypes of solid sorption cooling systems are developed based on:

- Metal Hydride
- Activated Carbon- Ammonia
- Zeolite - Water
- Silicagel –Water.

The four systems are tested for temperature conditions occurring during normal driving cycles.

This paper describes the prototype developed by ECN for use in a car. It uses silicagel-water working as the working pair. It includes the design and construction of the adsorption cooling system and the results obtained on the tests under thermal conditions derived from the Normalized European driving cycle (NEDC).

The research and development challenges were:

- to fulfill the cooling requirements using the available waste heat as driving source under NEDC conditions;
- to design and built the prototype taking into consideration the volume and weight constraints for mobile applications.

The results obtained with the laboratory prototype are discussed in relation to the system requirements:

- cooling performance,
- efficiency
- weight and volume restrictions.

2. System requirements

The process for the design of the laboratory prototype was initiated with the analysis of the amount and the temperature levels of the heat available in the cooling water circuit of the engine.

As a reference car the Fiat Stilo (Figure 2.1) was selected with a 1.9 JTD engine. 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 amounts of waste heat.

Figure 2.1 *Picture of the Fiat Stilo reference car*

2.1 Waste heat availability

For definition of the thermal requirements of the new AC system the Normalized European Driving Cycle (NEDC) is applied. This driving cycle consists of an urban part at lower driving speed, at the beginning of which the engine in the first 400 seconds is heating up from cold start conditions to stationary operating temperature. The last section of the NEDC consists of a highway driving part at speeds up to 120 km/h. This driving cycle can be considered as representative for the typical car-use in Europe and is normally used to measure fuel consumption as required by EU regulations.

The use of the NEDC allows the evaluation of the impact of the use of the new AC system on the changes in fuel over-consumption and CO_2 emissions, in comparison to the conventional compressor driven AC systems. An analysis was made by CRF of the amount of waste heat available during the NEDC in the different parts of the cooling water circuit. The analysis assumes that the thermal energy going to the cabin heater and to the radiator can both be used as a source to drive the cooling system. Figure 2.2 presents the results of this analysis.

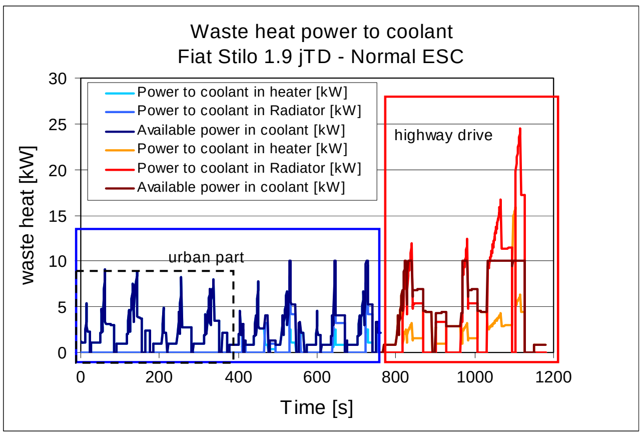

Figure 2.2 *Thermal power levels available as waste heat during the NEDC in the urban and highway drive parts*

From the figure it is clearly seen that due to the frequent changes in driving speed, the available waste heat is also very strongly fluctuating. This is a complicating factor in the definition of the specifications for a thermally driven cooling system. As a first approach averaged values for the available waste heat were calculated for the three sections: urban part *transient* (0-400 seconds), urban part *steady state* (400-800 seconds) and highway drive (800-1200 seconds).

Two different climate conditions are taken into account for the analysis of the available waste heat as well as for the required cooling power. The selected conditions are normal European 'summer climate' conditions and 'severe' European summer climate conditions.

These are:
- Normal European summer climate: 28°C and 50% relative humidity (RH)
- Severe European summer climate: 35°C and 60% relative humidity

Table 2.1 presents the waste heat availability for these climate conditions.

Table 2.1 *Averaged available waste heat in engine coolant circuit of reference car during NEDC*

NEDC stage	28°C 50%RH	35°C 60%RH
	Waste heat availability	Waste heat availability
	[kW]	[kW]
Urban 'transient'	2.30	2.38
Urban 'steady state'	2.31	2.48
Highway drive	7.32	7.92
Overall	4.05	4.35

The temperature level of the waste heat is 90°C when the steady state condition is reached.

2.2 Cooling power requirements

The required cooling power to achieve comfortable cabin temperatures was evaluated by CRF. The cooling power and temperature levels delivered by the conventional AC system in the reference car were determined in the NEDC both under normal and severe summer conditions. The delivered cooling power also varies during the NEDC. A higher cooling power is required at the start of the driving cycle to bring down the temperatures to the cabin set point temperature. The set point temperatures are 20°C at normal summer conditions and 23°C at severe summer conditions. The recirculation mode of the AC system was set at maximum in the analysis to reduce the cooling requirements as much as possible.

Averaged cooling power values were calculated in the time sections of 0 to 400 seconds (urban, transient) and from 400-1200 seconds, where there is a steady state cooling demand. In addition to the cooling power analysis during NEDC also the cooling power requirements for the 'Cool Down' test were analysed. This test method is often applied by the car manufacturers as acceptance test for the AC system. In this test the cabin is soaked in sunlight and has a very high temperature up to 60°C. In the 'cool down' test the temperature at the head level of the driver should be reduced to an acceptable level within a certain time limit. This test generally requires much higher cooling powers than under normal driving conditions. The required cooling powers under the different test conditions are shown in Table 2.2.

Table 2.2 *Averaged required cooling powers for the reference car under different test conditions*

	NEDC 28°C 50%RH	NEDC 35°C 60%RH	Cool down
Peak power [kW]	1.2	2.0	4.0
Steady State power [kW]	0.5	0.65	2.0

2.3 Efficiency requirements

For the new thermally driven AC system the required cooling power is derived, taking into account only the conditions during NEDC. Therefore a cooling power of 2 kW should be delivered by the system. The required minimum COP (ratio of the amount of cold produced over the heat consumed) for the new AC system should be 0.84, which is a high value for a cooling system driven by heat of maximum 90°C. This condition refers to peak power delivery under severe summer conditions. For this situation the use of an additional fuel burner (parking heater) is considered to supply additional thermal power for those situations where the amount of waste heat from the engine is not sufficient. For the other conditions in the NEDC the required COP values are around 0.5 and lower.

2.4 Weight and volume targets

For the integration of the thermally driven system in the reference car the overall system volume and weight should remain within strict limits. For the current research project it was considered acceptable by the car manufacturers to have a weight of the new system of maximum 35 kg and to have a target volume for the sorbent reactor section of 16 dm^3.

3. Laboratory prototype system design

The working principle of an adsorption cooling system using a solid adsorbent material is explained already many times in literature. The basic lay-out consists of a condenser, an evaporator and a thermal compression part that has at least two adsorbent reactors. The two adsorbent reactors are repeatedly heated and cooled to establish a 'thermal compression' of the refrigerant vapour. Cooling of the adsorbent results in adsorption at low pressure of the refrigerant, followed by heating of the adsorbent resulting in desorption of the refrigerant at higher pressure. Adsorption and desorption are batch processes. Heating and cooling of the reactors occurs in anti-phase to obtain a quasi continuous cooling process.

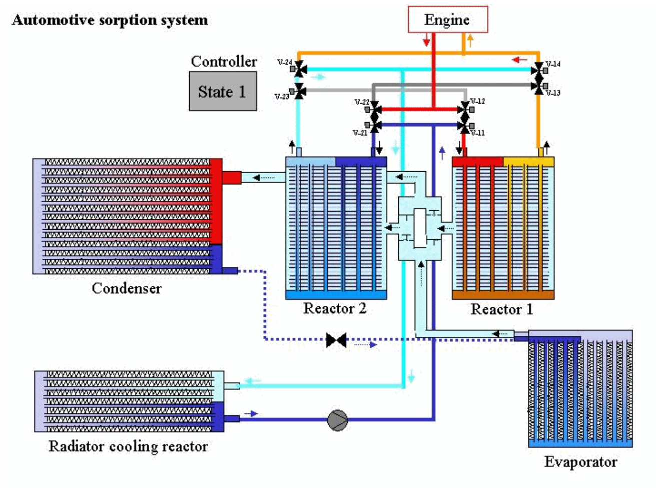

Figure 3.1 *Schematic drawing of the system lay-out*

Figure 3.1 contains a scheme of the components of the laboratory prototype. It has two reactors connected to liquid circuits for heating and cooling. Valves in the liquid circuit are controlled by a PLC system. A water cooled condenser and a water 'cooled' evaporator are applied in the laboratory setup.

The water circuits connected to the system for heating, cooling and chilling water are all temperature controlled. Hot water storage with electrical resistance heating simulates the heat coming from a combustion engine. The cooling water circuit is connected to a rooftop cooling system (dry cooler) supported with a thermostatic bath to have good control over the cooling water temperatures. A thermostatic bath is connected to the evaporator, in order to control the chilled water inlet temperature to the evaporator.

The focus in designing the prototype system was on the compactness of the sorbent reactors. Aluminium tube-fin heat exchangers from automotive applications are used for heating and cooling of the silicagel. Figure 3.2 shows a picture of the heat exchanger assembly of one reactor.

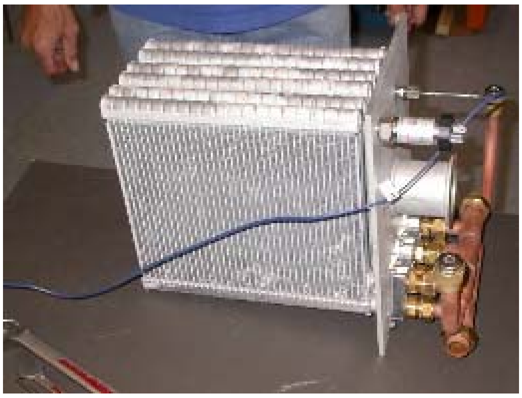

Figure 3.2 *Picture of the heat exchanger assembly of a sorbent reactor*

One reactor contains three heat exchangers connected in parallel. The sorbent heat exchanger specifications are given in the table below.

Table 3.1 *Dimensions and weight of a single sorbent heat exchanger*

Heat Exchanger	
Material	:Aluminium
fin height	:5 mm
fin period	:3 mm
Fin thickness	:0.1 mm
Fin depth	:38 mm
Weight	:1012 g
Ext. dimensions	:260*260*40 mm
Volume	:2.7 dm^3
Heat transfer fluid	:0.48 kg
Sorbent	
Silicagel (dry)	: 1010 g
Grain size	: 0.2-1 mm
Metallic net	: 40 g

The heat exchanger assembly has an aluminium containment. The two reactors are connected to a central chamber that contains vacuum check valves to prevent the flow of refrigerant in the reverse direction. The picture below shows the two sorbent reactors after construction.

Figure 3.3 *Picture of the 'thermal compressor' section of the adsorption cooling prototype system*

The volume of the sorbent reactor assembly is 30 dm^3. The weight is 24 kg and it contains in total 5.7 kg of silicagel.

3.1 Instrumentation and control

The system is equipped with temperature sensors, at all the inlet and outlet tubes of the liquid circuits connected to the evaporator, condenser and the two sorbent reactors. Each of these components has a flow meter in the liquid circuit installed to calculate the thermal powers transferred, as well as the COP of the cooling system. In addition, pressure sensors are mounted on the reactors, the condenser and evaporator to analyse the internal pressure changes and pressure drop during operation of the system. All signals are collected in a data logger connected to a PC.

The operation of the system is semi-automatic. The temperatures of the external heating and cooling circuit and the flow rates are set manually to the desired values. The operation of the valves to direct the heating and cooling water circuits to the two reactors are controlled by the PLC. The cycle time for heating and cooling of the reactors can be simply adjusted by changing the settings of the PLC program.

4. Tests and results

The tests on the system were performed in close collaboration with the partners of the project to have comparable test conditions for the different prototypes in development at the different laboratories. The tests were performed under stable supply temperatures and flow rates, because the equipment for heating and cooling was not designed to simulate the dynamic conditions that can occur in a driving car.

4.1 Initial tests

The first tests performed on the prototype were to analyse the influence of changes in the cycle time on the performance of the system. In this test the inlet temperatures to the system are:

- 90°C heating inlet,
- 33°C cooling water inlet,
- 20°C chilled water inlet.

A typical plot of the thermal powers measured under the conditions above is given in Fig.6. The figure shows 4 lines: heating and cooling of the reactor (left y-axis) condensing power and evaporation power (right y-axis).

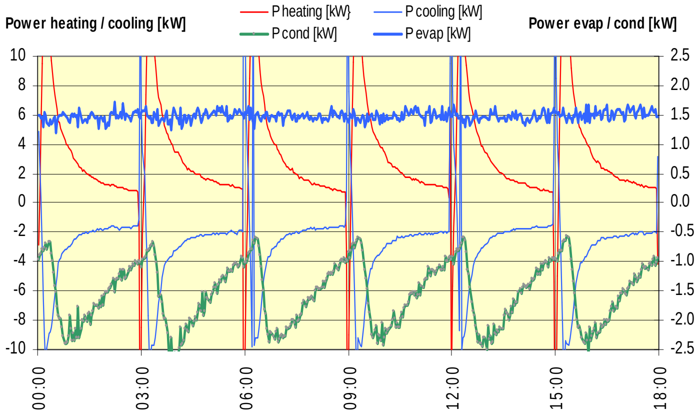

Figure 4.1 *Thermal powers of a test run at 6 minutes cycle time. (the x-axis is the time in mm:ss)*

The thermal powers transferred for heating and cooling the reactors show strong changes during a cycle, caused by the batch type operation of the process. The condenser also shows power fluctuation between 0.5 and 2.5 kW during a half cycle. The power measured at the evaporator is very stable, which is caused by the high thermal inertia of the evaporator itself. This thermal storage function fully reduces the power fluctuation at the evaporator to a stable operation.

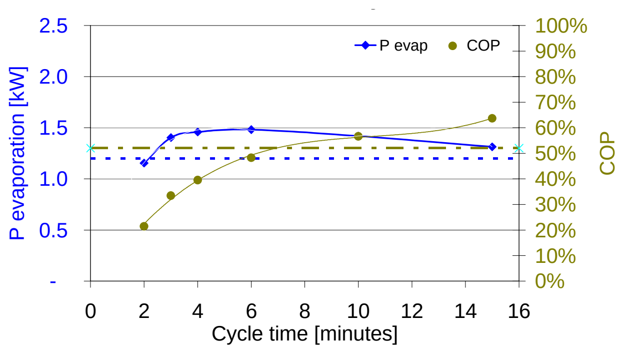

Figure 4.2 *Plot of the chilling power and COP with variation of cycle time*

Figure 4.2 shows a plot of the cooling power and COP measured with different cycle times. The dotted horizontal lines represent the required cooling power and COP for the specific test condition. The COP of the system increases from 20% to 65% when the cycle time increases from 2 to 15 minutes. At lower cycle times more heat is wasted by the system to heating and cooling of metal of the heat exchangers and the silicagel, resulting in the lower COP values. At cycle times less than 4-6 minutes also a decrease in cooling power is observed, indicating that the utilization of silicagel is too low, caused by the relatively slow heat transfer of the silicagel bed.

On increasing the cycle time the COP increases, while the cooling power shows a slight decrease from going from 6 minutes to 15 minutes. Cycle times between 6 and 10 minutes give a fair compromise between cooling power and COP for the present system.

The system was slightly modified after analysis of the results of the first series of tests. The pressure drop between the evaporator and the sorbent reactors was initially almost 7 mbar. This pressure drop was reduced to about 4 mbar, through the removal of a wire mesh and a local restriction in vapour connection line. This reduction of pressure drop increased the overall performance significantly.

4.2 2nd test series

The following set of test conditions was applied to characterise the system performance:

- 90°C heating water inlet
- 33°C cooling water inlet
- 20-15-10°C chilled water inlet
- Variation in flow rate through sorbent reactors: 6-9-11-12-15 litre per minute.

Figure 4.3 shows a graph of the results obtained, with different chilled water inlet temperatures. The cooling power at 20°C inlet temperature to the evaporator has increased to 2.4 kW. The reduction of the pressure drop in the vapour line from the evaporator resulted in an increase from 1.5 kW to 2.4 kW. The chilled water outlet temperature obtained is 12°C. When the chilled water inlet temperature is decreased to 15°C the chilling power drops to 1.6 kW, and at 10°C inlet only 0.7 kW is produced. Also the COP drops when lowering the chilled water temperature.

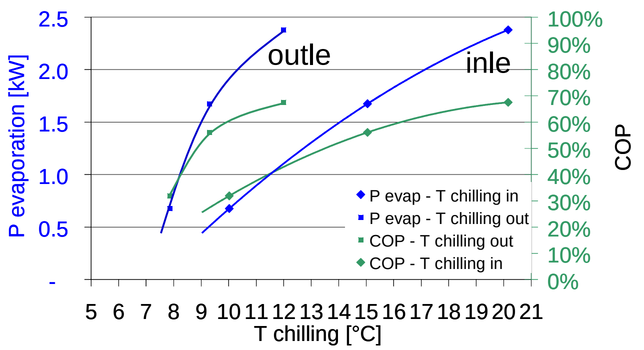

Figure 4.3 *Plot of the chilling power and the COP as a function of the chilled water temperature*

The results presented above are obtained with a flow rate of 12 LPM through the sorbent reactors. When varying this flow rate only moderate changes in cooling power occur, see Figure 4.4.

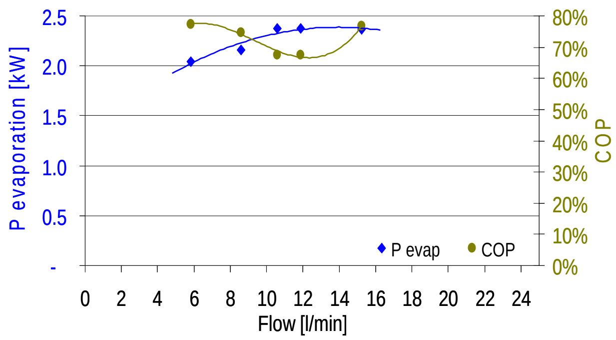

Figure 4.4 *Plot of the chilling power and the COP as a function of the flow rate through the sorbent reactors*

5. Conclusion and outlook

From the work described in the previous sections it can be concluded that:

- The adsorption cooling system based on silicagel-water has the potential to provide sufficient cooling power at the required efficiency for cooling the car cabin just by using the available waste heat of the engine to drive the cooling system.
- The pressure drop in the vapour phase between evaporator and condenser has a strong impact on the overall performance of the system and should thus be kept as low as practically feasible.
- On lowering the temperature level of the chilled water circuit a strong decrease in the performance of the adsorption cooling system is observed.
- The size and weight of the sorbent reactors should be further reduced in future prototypes to allow their integration in the engine compartment of a car.

The work done on the laboratory prototype shows that adsorption cooling technology has the potential for application as a waste heat driven mobile AC systems. This technology could provide a solution to reduce the direct and indirect CO_2 emissions that are presently related to the use of compressor based MAC systems.

Other potential benefits of this technology relate to the mechanical decoupling of the engine and the AC system. A thermally driven MAC system can still operate for a certain time when the engine is stopped, just using the sensible heat present in the engine and its cooling water circuit. A parking heater could be added to provide heat to the system when there is insufficient heat form the engine, and would also allow pre-cooling functionality.

However, in addition to further reduction of the size of the sorbent reactors, further work is also needed to develop more compact evaporators and condensers for water as refrigerant.

The next stage of development is focused on the development of an on-board prototype of the adsorption cooling system. Due to its size this prototype will be mounted in the trunk of the car. Although still too large in size, the development and test of this system as on-board prototype will provide relevant information on all technical aspects dealing with the integration of a new technology that is interfering with the thermal management of the combustion engine.

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

Acknowledgement

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References

1. European Union, directive 2006/40/EC relating to emissions from air-conditioning systems in motor vehicles, *Official Journal of the European Union*, 161, 12-18 (2006).