Heat pump supplemental heating system for motor vehicles

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Abstract: The paper deals with the importance of supplemental heating of motor vehicles and the possibilities of automotive heat pump system utilization. A prototype heat pump system for motor vehicles has been developed, built in a test vehicle and tested at low-temperature working conditions. Results have been analysed and the system compared with the other current-production supplemental heating systems. The proposed automotive heat pump heating system has been found to be superior to other automotive supplemental heating solutions regarding the parameters of performance, fuel consumption and operational behaviour.

Keywords:

1 INTRODUCTION

The fast achievement and maintenance of pleasant passenger compartment temperature and humidity are of crucial importance for a high comfort level of the vehicle. Normally, in cold weather conditions, ventilation and recirculated compartment air is heated by otherwise wasted engine heat via an adequate heat exchanger. However, sometimes the waste heat available is not enough to achieve a comfortable passenger compartment temperature. This is increasingly the case, particularly with recent developments in high-efficiency engines with very low heat rejection rates [such as the direct injection (DI) diesel engine] that are used in mass-produced passenger vehicles. The low heat rejection of these engines has made the heating of the passenger compartments during wintertime a challenge, even in mild climate zones.

In current-production vehicles, comfortable space temperatures are achieved by using supplementary heating devices, such as a PTC heater (electrical air heater), glow plug heater (electrical coolant-heater) or fuel-fired coolant-heater. In view of the power consumption restrictions, low fuel efficiency and high primary cost of current supplementary heating systems, the aim of the project described in this paper was to investigate the use of a heat pump system. The objective was to develop a simple and efficient system able to improve passenger compartment heating without causing any deterioration in the performance and behaviour of the air conditioning system. It is important to note that nowadays nearly all passenger cars in Europe (about 80 per cent) and North America (about 98 per cent) are manufactured with air conditioning (AC) systems, and these already contain most of the components required for a heat pump application.

1.1 Heat pump system architecture

To achieve a fast warm-up of the passenger compartment, it is necessary to use the evaporator of the AC system as a condenser of the heat pump system. This heat exchanger is placed downstream of the conventional heater matrix (the heat exchanger that transfers heat from engine coolant to cold air) within the air conditioning box.

Three secondary heat sources for the heat pump system are available: exhaust gas, engine coolant and ambient air:

1. The amount of heat available in the exhaust gas depends on the engine load, and this is a major disadvantage for utilization of this heat source. In city traffic conditions, when greatest supplementary heating is required, exhaust heat is lowest and will limit the heating performance of the heat pump system.
2. Utilizing the heat available in the engine coolant as a secondary heat source has the advantage that its temperature increases rapidly during the warm-up of the

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car. The problem is that the engine coolant cannot be used at the same time in the heater matrix for heating the passenger compartment.
3. Using the ambient air as the heat source has the best thermodynamic justification since the heat is ‘pumped out’ from the surrounding air. In addition, the conventional heater matrix can be used in the usual way for passenger compartment heating. A potential disadvantage of ambient air as the heat source is frost formation in the air-to-refrigerant heat exchanger under certain conditions.

Taking into consideration the calculated performances and assumed behaviour of different heat pump systems, as well as number, type, dimensions and costs of the components to be added to the air conditioning system, it was decided that the heat pump with ambient air as the heat source has the best prospects for high-performance supplementary heating, with minimized fuel consumption increase at a competitive price. To verify this, a heat pump system, with R134a refrigerant as its working fluid, has been designed, built in a test vehicle and tested. This paper describes the results of this programme.

2 SYSTEM DESCRIPTION

The layout of the combined air conditioning/heat pump system is shown in Fig. 1. The system consists of a compressor, a four-way valve, an interior heat exchanger [used for refrigerant evaporation during AC operation, and for refrigerant condensation during heat pump (HP) operation], a two-way expansion device, an exterior heat exchanger (used for refrigerant condensation during AC operation, and for refrigerant evaporation during HP operation) and accumulator and refrigerant routings (pipes and hoses). With the exception of the four-way valve, the two-way expansion device instead of an orifice valve and some additional routings, all the components of the combined system exist already in a standard AC system.

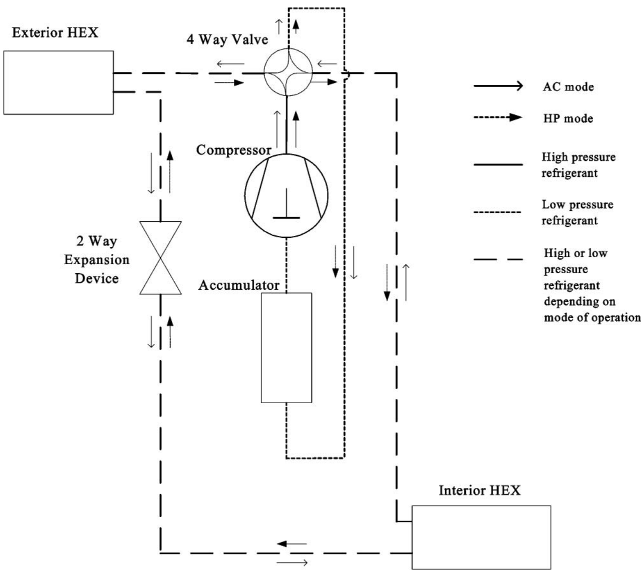

Fig. 1 Scheme of R134a AC/HP system

The R134a heat pump system was designed to preheat the air in front of the heater core with 1.5–3 kW supplemental heating power. The rest of the heating load was to be supplied by engine coolant through a conventional heater matrix. Cold air passed through the interior heat exchanger was then heated to a certain temperature by the heater matrix. After reaching a stable coolant and/or passenger compartment temperature, the heat pump was switched off.

2.1 Test procedure and results

The heat pump system was built in the test vehicle which had a 1.8 l DI diesel engine. The vehicle was fully instrumented for measuring all relevant temperatures, pressures, velocities and fuel consumption. Tests at different ambient and driving conditions were performed. Besides collecting data relevant for the system analysis, subjective passenger compartment comfort evaluations were also performed. The procedure for evaluating the heat pump system test results and their comparison with the corresponding data for baseline heating and the other supplemental heating systems will be explained in the following example.

A test was run at an ambient temperature of −11 °C, with moderate constant driving conditions (50 km/h in third gear). During the heat pump test the refrigerant loop low pressure stabilized at about 1.1 bar almost immediately after the system was switched on, while the high pressure needed about 3 min to reach a stabilized pressure level of 9 bar (Fig. 2). During the rest of operation the high pressure continued to increase slowly and reached 10 bar before the heat pump was switched off (after 13 min). The corresponding temperatures of refrigerant condensation inside the interior heat exchanger were 32 °C after 3 min and 42 °C after 13 min. The outlet temperatures of air preheated in the interior heat exchanger ranged from 30 °C (after 3 min) to 36 °C (after 13 min). The air was, afterwards, further heated by the coolant in the heater matrix, before being blown into the passenger compartment at considerably higher temperature (Fig. 3) than in the case of baseline heating.

The shape of the temperature curves shown in Fig. 3, with a characteristic temperature jump after 3–5 min, is the consequence of the applied test procedure: air was blown into the compartment through defrost registers until its temperature reached 35 °C, and from that moment the airflow was switched to the foot registers. During the test the heat pump system reached a stable supplementary heater output of about 1.9 kW after only

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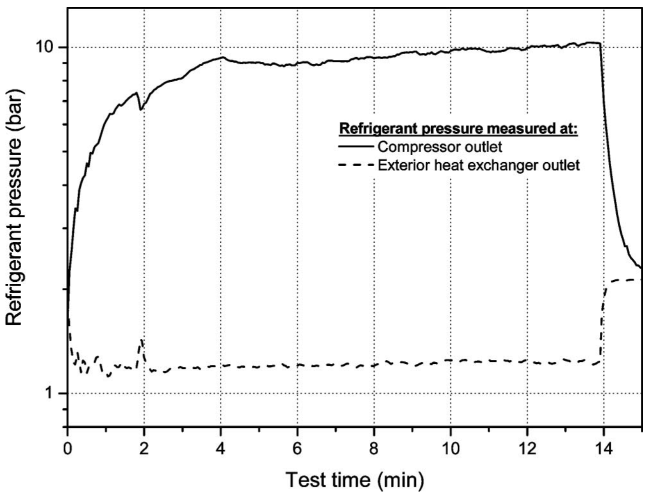

Fig. 2 Refrigerant pressures during maximum heat performance testing at $T_{amb.average} = -11\,^{\circ}C$ (at 50 km/h constant speed in third gear)

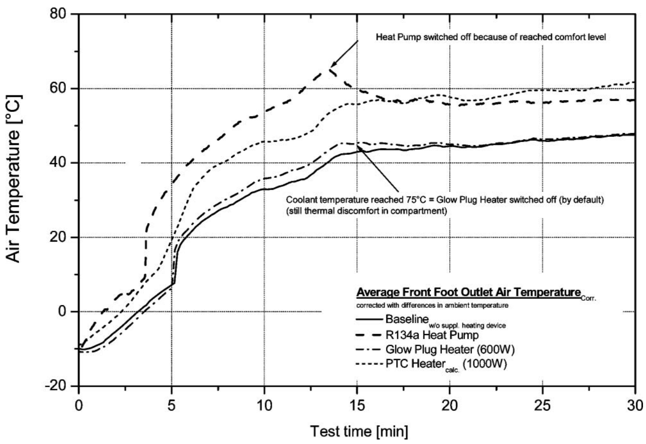

Fig. 3 Average temperatures of air blown into the compartment (through the front foot register) during maximum heat performance testing at $T_{amb.average} = -11\,^{\circ}C$ (at 50 km/h constant speed in third gear). R134a heat pump versus baseline, glow plug heater and PTC heater

2 min (Fig. 4). The heat pump was switched off after 13 min because the comfort level in the passenger compartment had been reached, as well as a sufficient performance level of the conventional heater for further compartment temperature maintenance.

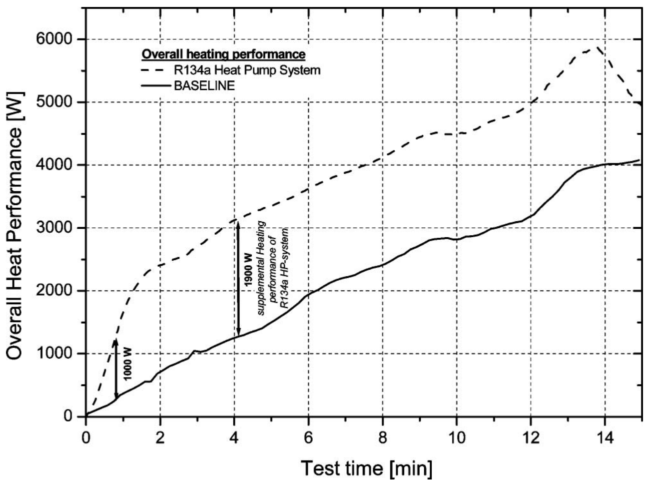

Fig. 4 Overall heat performance during maximum heat performance testing at $T_{amb.average} = -11\,^{\circ}C$ (at 50 km/h constant speed in third gear)

It is important to note that the heat pump system provides almost instant heating of the passenger compartment. For example, the level of 1 kW overall heating power was reached after 30 s of operation, compared with 3 min in the case of baseline conventional heating.

The results achieved with the heat pump system were also compared with those available from other supplementary heating systems currently in use, namely the glow plug heater (electrical coolant-heater) and PTC heater (electrical air heater). Tests were carried out using the same vehicle and on the same driving track under the same ambient condition. The air blower level and the driving conditions were also the same in each case. To increase the comparability, the observed air temperatures were corrected with the differences in the ambient temperatures during the tests.

The differences between the systems quickly became obvious by comparing the average temperatures of air at its inlet to the passenger compartment (Fig. 3 and Table 1). For example, after 15 min the average air temperatures at the outlet of the front foot air registers that were reached during one set of tests were 43 °C for the baseline heating, 45.5 °C with a 600 W glow plug heater, and about 56 °C with a 1000 W PTC heater. With the heat pump system the average outlet temperature after 15 min would have been about 68 °C, which is 25 K

Table 1 Comparison of different heating systems at $T_{amb.average} = -11\,^{\circ}C$ (at 50 km/h constant speed in third gear)

Heating system	Average front foot outlet air temperature (°C)		Time needed to achieve comfort (min)	Average fuel consumption (l/100 km)
	After 7 min	After 15 min		
Baseline heating	25.3	43.0	>30	5.12 (100%)
Glow plug heater (600 W)	27.4	45.5	>30	5.80 (113%)
PTC heater (1000 W)	35.5	56.0	30	6.35 (124%)
Heat pump system	44.4	68.0	13	5.96 (116%)

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higher than in the case of baseline heating. These results have shown that the heat pump system can heat the same amount of ambient air to a higher temperature during the same time as other proposed systems. Additionally, neither the glow plug nor the baseline heater system reached a pleasant subjective comfort rating during the 30 min test. The 1000 W PTC heater reached a pleasant comfort rating at the end of the test. In contrast to the other supplementary heating systems, the heat pump reached pleasant comfort after 13 min. The heat pump system was switched off after 13 min, and the average temperature of air blown into the passenger compartment decreased slightly in the following minutes. That did not cause any thermal discomfort.

Behaviour similar to that described was detected in most of the performed tests. Of course, at higher ambient temperature and/or higher engine load, heating of the passenger compartment is faster and the heat pump can be switched off after a shorter period. For example, in the test performed at an ambient temperature of $-3\,^{\circ}\mathrm{C}$ (Figs 5 and 6), the comfort level was reached after only 8–9 min of heat pump operation, and the heat pump could have been switched off.

2.2 Fuel consumption

The heating performance of a supplementary heating device is of course the most important parameter, but it is also very important to develop a system with high fuel efficiency. The importance of a high fuel efficiency of supplemental heating systems has increased in recent years with the increased attention to cold start emissions and emissions caused by comfort and climate devices.

Fuel consumption data from the engine control unit were used to calculate instantaneous fuel consumption in litres of fuel per 100 km and the average fuel consumption during the tests. Of course, the instantaneous fuel consumption under cold engine conditions was very high for all the observed cases and influenced the values of average fuel consumption.

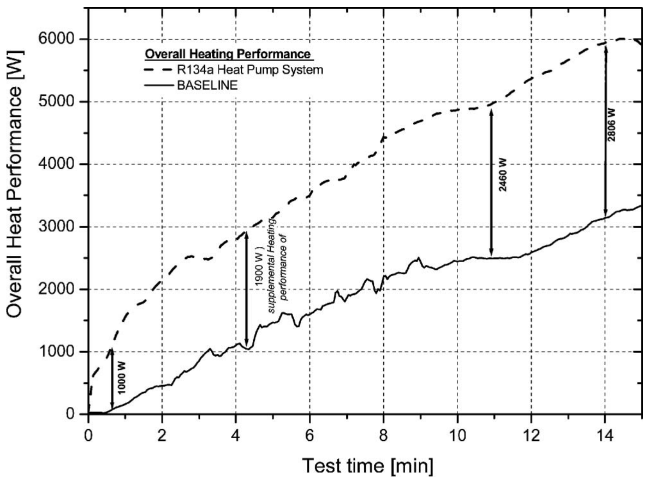

Fig. 6 Overall heat performance during maximum heat performance testing at $T_{\mathrm{amb.average}} = -3\,^{\circ}\mathrm{C}$ (at 50 km/h constant speed in third gear)

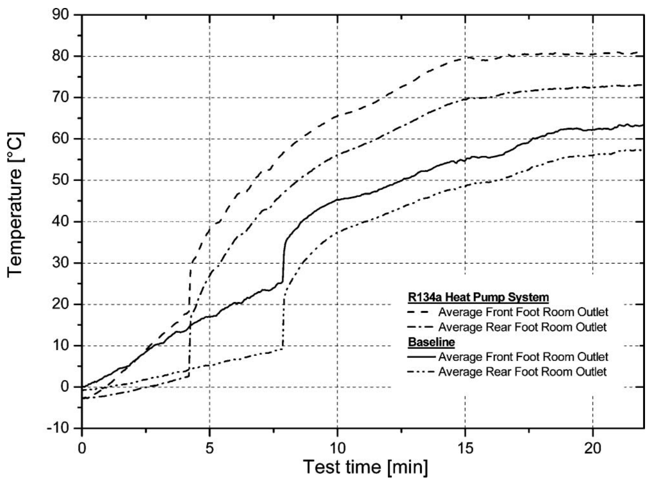

Fig. 5 Average temperature of air blown into the compartment (through the front and rear foot registers) during maximum heat performance testing at $T_{\mathrm{amb.average}} = -3\,^{\circ}\mathrm{C}$ (at 50 km/h constant speed in third gear). R134a heat pump versus baseline

During the 30 min warm-up test at 50 km/h in third gear, the 1.8 l diesel engine with baseline heating consumed on average 5.1 l of fuel per 100 km (Table 1). With the 600 W glow plug heater, the average fuel consumption increased by about 13 per cent to 5.8 l/100 km. The 1000 W PTC heater caused an increase in the average fuel consumption of 24 per cent compared with the baseline. The R134a heat pump system caused an increase in the average fuel consumption of 16 per cent compared with baseline heating.

It can be concluded that the fuel consumption of the proposed R134a heat pump system is within the range of the 600 W glow plug heater, but the heat performance is considerably higher than the heat performances of both the 600 W glow plug heater and the 1000 W PTC heater.

2.3 Ice formation issues

During some of the tests, frost layers of different thickness, depending on ambient and operating conditions, were observed. Functional blockage of the exterior heat exchanger was never experienced, regardless of the amount of frost on the surface. Even after a 1.5 h long-distance drive test, with the heat pump constantly running, at an ambient temperature of $-1\,^{\circ}\mathrm{C}$ and a relative humidity of 90 per cent, the exterior heat exchanger did not stop extracting heat from ambient air. Considering a common duration of heat pump operation before switching to heater matrix heating only, it was concluded that the frost formation issue is not of primary importance.

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3 CONCLUSION

The proposed R134a heat pump system is capable of supplying the passenger compartment with a significant amount of supplementary heat. The output of the test system was usually in the range 1.5–3 kW, depending on the ambient temperature and driving conditions. Supplementary heat was supplied almost instantly after the heat pump was started, no matter how cold the engine. During the presented tests, preheating of the air in the interior heat exchanger takes a significant load from the conventional heater matrix. Preheated air enters the heater core at higher temperature compared with the conventional baseline heating system, so the amount of heat extracted from the coolant is lower, the coolant is heated faster and the engine reaches optimal working temperature in a shorter time.

Frost formation on the air side surface of the exterior heat exchanger was detected during some of the tests but showed only a very small influence on the heat performance of the heat pump system.

Finally, the proposed heat pump system showed a significantly better heat performance—fuel consumption ratio by compression with those of the glow plug heater and PTC heater supplementary heating systems.

REFERENCES

1 **Kampf, H., Kunberger, O.** and **Weinbrenne, M.** Klimatisierung von Fahrzeugen mit kraftstoffsparenden Motoren. *PKW-Klimatisierung*, 1999, pp. 1–23 (Expert Verlag).

2 **Shafai, E., Wimmer, R.** and **Geering, H. P.** A new control approach for heat pump heating systems. In Proceedings of 7th International Energy Agency Conference on *Heat Pumping Technologies*, Beijing, China, May 2002, pp. 146–157.

3 **Rice, C. K.** DOE/ORNL heat pump design model, overview and application to R-22 alternatives. In Proceedings of 3rd International Conference on *Heat Pumps in Cold Climates*, Wolfville, Nova Scotia, Canada, August 1997, pp. 43–66.

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