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A compact and efficient heat-pump system with a preconditioning concept for electric vehicles

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Abstract

DENSO has developed an innovative concept which provides efficient thermal management including preconditioning for electric vehicles. The thermal conditioning for the cabin and powertrain offers maximum comfort to the user and increases the driving range of the vehicle. The efficient thermal management in the vehicle is provided by a compact water-to-water heat pump system which can harvest heat from the ambient environment even at sub-zero temperatures and excess heat dissipated from the powertrain components, i.e. inverter and the electric motor with possibilities to also include the battery. The system provides simultaneous cold and warm water coolant, which with control logic is used to harvest or reject heat from the cabin and powertrain, respectively. The overall system proves to be 30 percent more efficient compared to a PTC based direct air heating.

Keywords: Heat pump; Electric vehicles; Preconditioning.

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1 Introduction

Driving range limitations and range anxiety is one of the main hurdles for today's electric vehicles (EVs) to gain wide acceptance among consumers. In summer and winter conditions, nearly 40% of the total energy consumption of an EV goes to the cabin thermal conditioning. The range anxiety of the driver may trigger an urge to shut off the cabin climatic control in order to reach the destination without depleting the battery. This is of course an unacceptable limitation of a product with such high price.

The first generation of EVs were equipped with ceramic PTC-heaters (Positive Temperature Coefficient of resistance), currently several EVs are being offered with heat-pumps for better efficiency. PTC-heaters are mainly used due to their low cost, easy to install features and quick provision of heat, which is transferred directly from electricity. The PTC-heater can be implemented in the HVAC-unit to heat the duct outlet air directly or inside the heater-core of the HVAC-unit to heat the water indirectly and warm up the duct outlet air to the cabin. Although the measured efficiency of PTCs is close to 100%, as the electricity is entirely converted to heat, this gives them a Coefficient of Performance (COP) of close to 1. The COP is the relationship between the electrical or mechanical power that is inserted to the system, and the heating or cooling power that is exiting the system. In heat-pump systems, 1 is a relatively low number for the COP, which can reach magnitudes of up to 7 or 8 for conventional refrigerants in most optimal working conditions. This is possible by harvesting heat from one environment (e.g. the ambient) and inserting it into another environment (e.g. the vehicle cabin), even in sub-zero degrees. The heat transfer from one environment to the other is realized by the refrigerant (energy carrier) in the heat-pump system, together with a compressor and expansion valve as actuators, and heat-exchangers as interface for the collection or release of heat to and from any secondary loop or environment.

This paper is organized as follows: Chapter 2 starts with a description of a heat-pump system including a brief overview of most commonly used refrigerants in the automotive industry; Chapter 3 shows DENSO proposal for a compact and efficient heat-pump unit for EVs, which operation and controls are described in Chapter 4. In Chapter 5, a suggestion to further reduce the energy consumption of EVs by an intelligent preconditioning strategy is described and finally, results and conclusion are outlined in Chapter 6.

2 Heat-pump systems for EVs

The principle of a heat-pump system is to collect heat energy from the environment and pump it into another closed environment. As an example, the ambient could be the environment where heat is collected, and the vehicle cabin the closed environment where the heat is pumped into, hence taking heat from the environment and into the cabin. For this process, a heat-pump system is needed where a suitable refrigerant is used as carrier of the transported heat. If this process is reversed (i.e. taking heat from the cabin and dissipating it into the environment), the system would be a conventional Air-Conditioning unit, which is more or less standard in today's vehicles.

2.1 Refrigerants for EVs

Several refrigerants exist for air-conditioning and heat-pump systems in automotive as well as for industrial applications. Due to the low required power levels, safety restrictions, and the very dynamic environment for vehicles, the amount of refrigerants suitable for automotive has been restricted to only a few (Table 1). A detailed comparison for various refrigerants used for mobile air conditioning systems can be found in Shilliday & Tassau (2009) and Vaghela (2017).

Table 1: Comparison of different refrigerants

Parameter	R134a	R1234yf	R744	R290
Global Warming Potential (GWP)	1430	4	1	3
Flammability	A1	A2L	A1	A3
Annual COP (Mid-EU)	o	o	o	+
Max. Performance A/C	+	o	o	+
Max. Performance H/P	-	-	+	+
Enthalpy difference @0°C [kJ/kg]	197.2	163.2	231.1	373.4
Pressure level @80°C [bar]	26.3	25.2	73.6	31.3

2.1.1 R134a

Since several decades, the most used refrigerant in automotive applications is R134a. It has served as A/C dedicated safe and efficient refrigerant and is commonly distributed all over the world. The drawbacks are that it is industrially manufactured and has a global warming potential (GWP, i.e. the global warming effect of a gas compared to a similar mass of CO_2), of more than 1430. Therefore, it is banned in the EU-region for mobile applications and planned to be banned in the U.S. as well as in Japan in the coming years.

2.1.2 R1234yf

Since the EU ban of R134a, it was decided that the R1234yf is an allowed successor for air-conditioning and heat-pump units. Its GWP is only of magnitude of 4, which is below the maximum requirement of 150. Drawbacks are its slightly lower performance in cooling, as well as heat-pump mode, compared to R134a and its categorization as mildly flammable with toxic combustion products. Apart from individual OEMs in the introduction phase of R1234yf, it was accepted as successor to R134a and today it is the refrigerant of standard for vehicles sold in the EU.

2.1.3 R744 (CO2)

CO_2 is considered as one of the top future candidates as a refrigerant for EVs. Especially its good heat-pump performance could be very well utilized in mid-tempered markets such as EU and parts of the U.S. and Asia. Although it has limited cooling performance, R744 was introduced to the market in 2017 for automotive probes (also in hot countries) and can be subjected as refrigerant. A limiting factor is the high working pressure, which requires newly designed components.

2.1.4 R290 (Propane)

Propane has very good features in terms of efficiency and performance for heating, as well as cooling, in heat-pump and refrigeration systems. Its GWP is only slightly higher than the one from CO_2 and considerably lower than the ones from other refrigerants, making it an environmentally good option as refrigerant. Its major drawback is the flammability, why it is not suitable to be used as working fluid inside heat-exchangers directly inside the vehicle cabin as there is a risk of leakage into the cabin. However, if being used in an indirect system (i.e. using heat-exchangers outside the vehicle cabin in a secondary loop) with a safe coolant (e.g. water) in the primary loop, the safety issues could be resolved. The indirect approach would consequently reduce the efficiency of the system, but by using the highly efficient R290 as refrigerant, the total system efficiency could still be higher than using other refrigerants in a direct system.

2.2 Heat-pump systems layout

Depending on the source and sink of the heat transported in the refrigerant, the layout can be categorized in a direct (air-to-air) or indirect (water-to-water) system, which is also decisive on the overall efficiency of the system, as depicted in Fig. 1 and explained next.

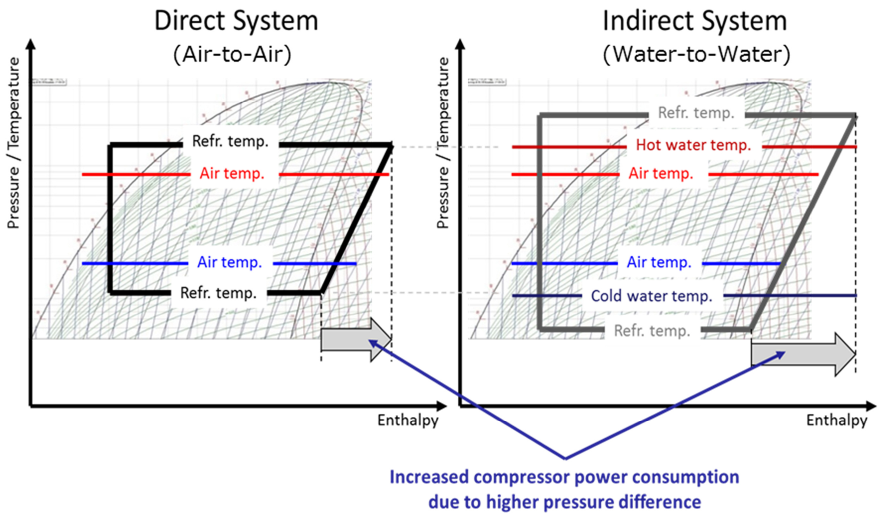

Fig. 1: p-h diagram for air-to-air and air-to-water systems

2.2.1 Direct air-to-air systems

Most of today's conventional A/C systems work in a direct so called air-to-air layout. This means that the condenser is a heat-exchanger between the refrigerant (in its high pressure and temperature working point) and the ambient air where the heat is dissipated directly. Likewise, the evaporator is a heat-exchanger between the refrigerant, in its low pressure and temperature working point, to air in the cabin.

2.2.2 Air-to-water and water-to-air systems

Parts of an air-to-air direct heat-pump system can have a secondary loop for different reasons within a water-to-air or air-to-water constellation. One example is for hybrid vehicles where the main heat from the Internal Combustion Engine (ICE) is cooled with a water circuit and pumped into a heat-exchanger in the HVAC-unit in the cabin like a conventional system. Due to the hybridization of the powertrain, the ICE has a high frequency of engine shutdown times and especially in case of a plug-in hybrid even turns off for longer times when the vehicle is driving on electric power. In this case, the heat from the ICE is not sufficient and the system will need secondary heat-source from either a PTC element or a heat-pump unit. In case of a heat-pump, the system will need to have a heat-exchanger between the refrigerant and the water coolant replacing or assisting the conventional condenser of an air-to-air system. Likewise, it is possible to replace the evaporator inside the HVAC-unit to a water-based heat-exchanger and provide cold water coming from an indirect refrigeration unit.

2.2.3 Indirect water-to-water systems

Finally, if the refrigerant cycle is sealed and working inside two water-based heat-exchangers, we have an indirect water-to-water system. This allows a very compact design due to the fact that the refrigerant and all components can be built within short distances and instead lead the secondary loop of water coolant into and out of the refrigeration unit. Another benefit is the hermetically built refrigeration unit seals flammable refrigerants with the safety measures to release refrigerant through relief safety valves in case of overheating (Fig. 3a).

Furthermore, maintenance and lubrication oil can be minimized in such a compact design. The water-to-water indirect heat-pump unit is described next.

3 DENSO's compact and efficient heat-pump unit

DENSO's compact heat-pump system is depicted in Fig.2 (Caldevilla et al., 2017), which includes an electrically driven compressor, two heat-exchangers for the cold and hot water circuits, a mechanical expansion valve for the refrigerant circuit and a refrigerant storage device. During operation, the compressor drives the refrigerant to transfer heat from the chiller to the condenser, which results on a heat transport from the cold-water circuit to the hot-water circuit. The hot and cold water circuits can be directed in the vehicles thermal management circuit through pumps and valves to single components such as inverter, e-motor, battery and heat-exchangers inside the HVAC-unit as well as for dissipating or harvesting heat in the front heat-exchanger.

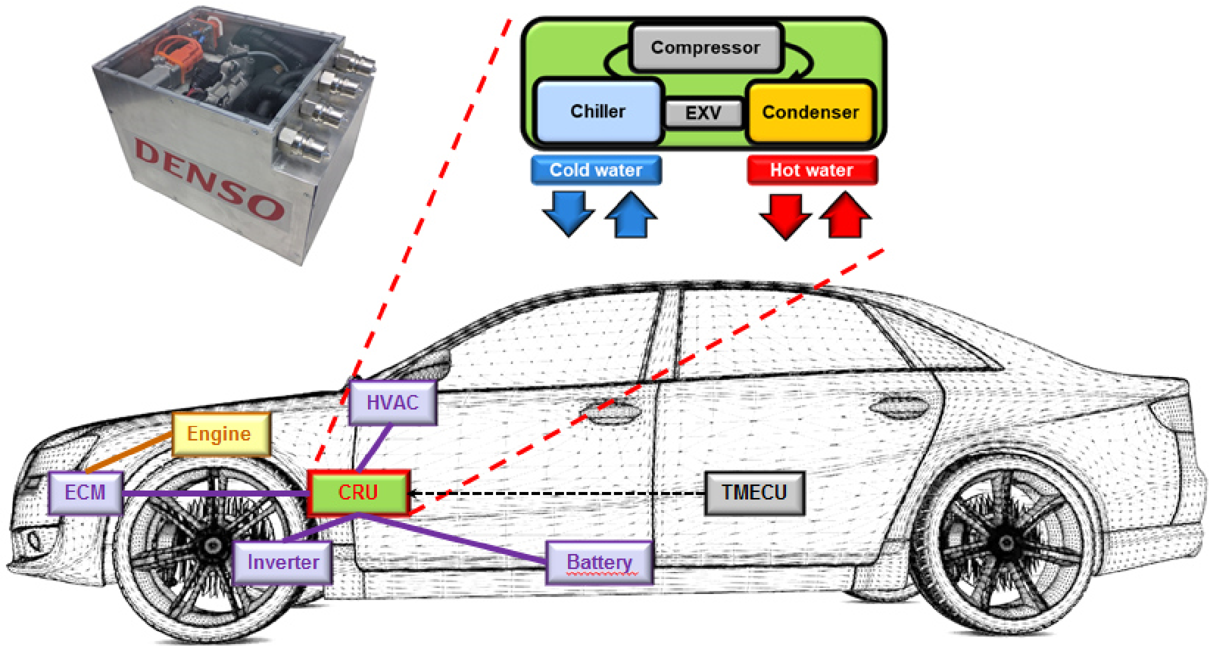

Fig. 2: Compact Refrigeration Unit (CRU) as the heat-pump unit and the preconditioning system architecture

4 Control strategy

The operation of the heat pump unit depends on the different modes. There are mainly three different modes the heat pump unit shall operate at: heating, cooling and dehumidification modes, as explained in Caldevilla et al. (2017). As a special case, de-icing mode is of importance in circumstances when ice is present on the outside heat-exchanger in humid conditions around 0°C ambient temperature. The harvesting of heat from the ambient reduces the temperature around the heat-exchanger to sub-zero and hence firstly condenses the humidity in the air and subsequently freezes to ice on the heat-exchanger. De-icing is not considered in this paper. The individual control for compressor and water circuit valves was realized using a hybrid approach of fuzzy maps and PID control. The automatic mode switching was realized using a combination of rules, and implemented via state logic in the overall auto-climate control architecture.

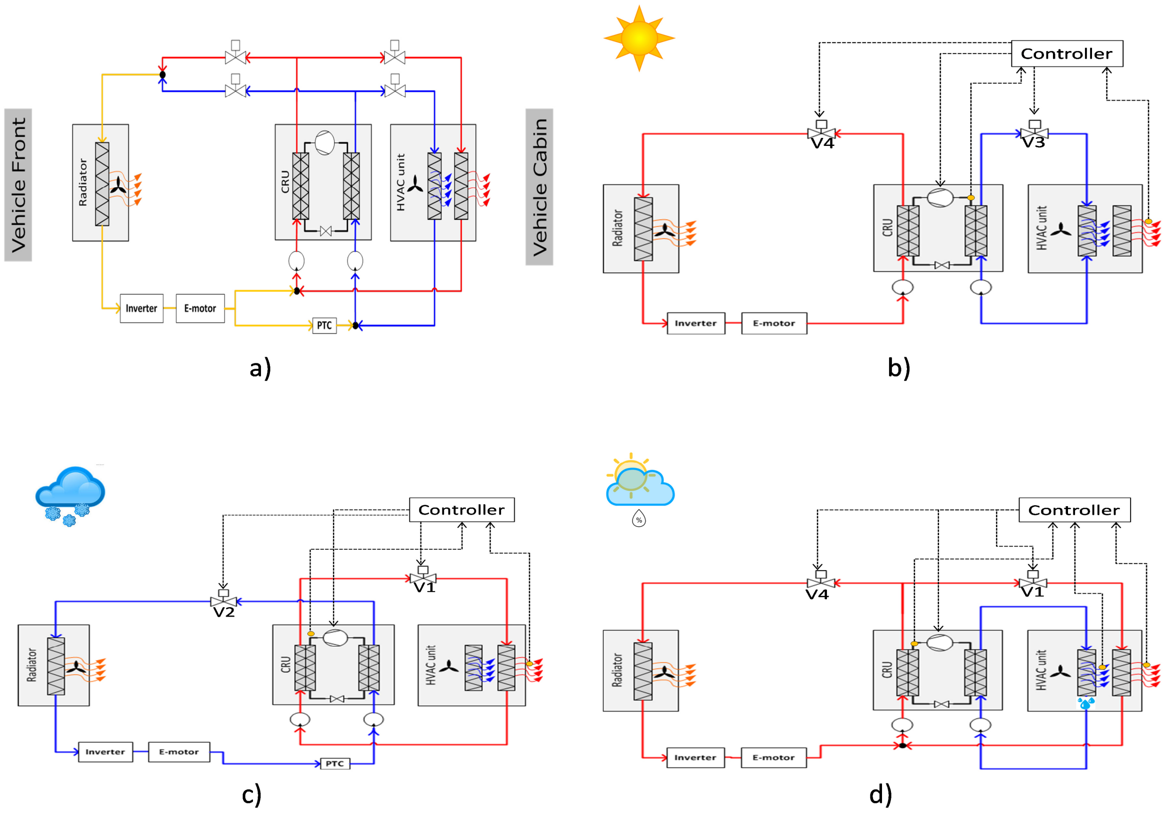

Fig. 3: a) overall system layout with the different modes; b) summer, cabin cooling; c) winter, cabin heating, (d) re-heat mode with water-circuit valves switching to maintain the temperature

4.1 Heating mode

The compressor drives the refrigerant to transfer heat from the chiller to the condenser. The condenser connected hot water circuit, transfers this heat to the heater core while the chiller connected cold water circuit picks up heat from the ambient through the radiator. The feedback control strategy is designed to control the compressor speed and the water circuit valves to achieve a target air outlet temperature on the heater core. The mode of operation is shown in Fig. 3c.

4.2 Cooling mode

The control objective for the compressor is the same as in the case of heating mode. However the control for water circuit valves is reversed. The valves are switched so as to disconnect the heater core and connect the radiator to the hot water circuit respectively. The heat transferred from the condenser to the hot water circuit, is dissipated to the ambient through the radiator, while the cold water in the chiller circuit, cools down the outlet air of the cooler core and heater core. The mode of operation is shown in Fig. 3b.

4.3 Re-heat mode

The control strategy for this mode is a combination of both the above modes. The compressor controls the outlet air temperature at the cooler core to a minimum set temperature so as to condense the water vapour in the air. The hot water circuit valves are switched, between the radiator and heater core with a duty cycle to maintain target air temperature at the heater core. The combination results in dehumidification of the air while maintaining the required air temperature. The mode of operation is shown in Fig. 3d. The switching characteristics with logic states and results are shown in Table 2 and Fig. 4 respectively.

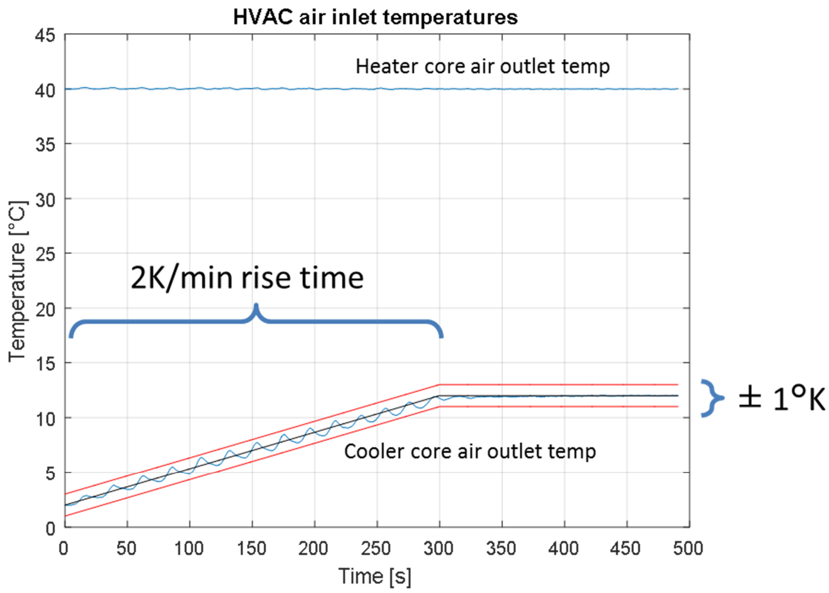

Fig. 4: Dynamic re-heat mode control of the cooler core air outlet temperature with the reference value in black and the tolerance of 1°C in red with the heater core outlet temperature kept at 40°C.

Table 2: Valves Control Strategy for operating modes

	Valves			
Operation Mode	V1	V2	V3	V4
Heating	Open	Open	Close	Close
Cooling	Close	Close	Open	Open
Re-Heat	Duty	Close	Open	Duty

5 Preconditioning

Preconditioning of the cabin has two advantages: firstly, the comfort level is enhanced, as the user will not enter a cold or hot cabin, but a comfortably preconditioned vehicle set to the preferred temperature. Secondly, a smart preconditioning can save energy and increase the driving distance of the EV. The environment for realizing preconditioning consists of a mobile app, which communicates with the vehicle over the cloud, and an internally built-in tablet (HMI, Human Machine Interface) in the EV, that finally communicates over CAN-bus with the vehicle Thermal Management Engine Control Unit (TMECU) through the Gateway (GW), as depicted in Fig. 5 and explained in Caldevilla et al. (2017).

Two different approaches are proposed to realize the preconditioning of the EV: a user-triggered one, where the user purposely triggers the preconditioning start over the mobile app, and an predictive one, where the user does not need to trigger the preconditioning, as the system automatically recognizes the user approach to the vehicle through collection of information from the mobile. The two approaches are described next.

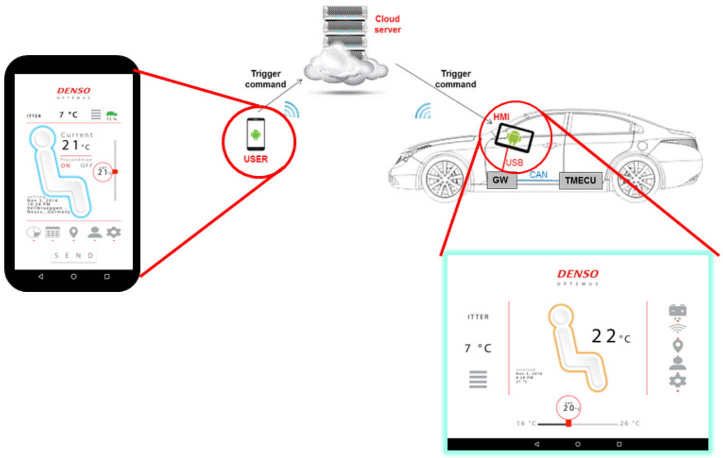

Fig. 5: Preconditioning communication architecture

5.1 User triggered concept

An efficient preconditioning approach is based on the target of tempering the vehicle just-in-time when the user plans to get into it. On the one hand, if the preconditioning function reaches the target temperature before the user arrives, the too early operation will suppose an additional waste of energy. On the other hand, if the vehicle still did not reach the target temperature when the user arrives, the comfort level will not be fulfilled. The user-triggered approach implies the user setting personally the expected time to get into the car, as well as the desired temperature. Therefore, it is not sure, that the preconditioning process will end exactly in the moment when the user gets into the car, as he may finally come earlier or later as planned (e.g. last phone call takes longer as thought).

5.2 Automatically triggered concept

The predictive approach uses an algorithm to foresee the driver's approach to the vehicle through the monitoring of its movements and automatically triggers the preconditioning process, eliminating the necessity for the user to trigger it purposely. The big problem of the predictive approach is that is not completely possible to avoid false alarms (e.g. the user goes out from home carrying the car keys in his pocket, however he does not plan at all to get into the vehicle, but rather to walk to the bakery). These false alarms are completely unacceptable in an EV, as we want to improve the efficiency of the thermal management, which should not precondition the vehicle without reason every time the user leaves his home or office, causing just an additional consumption of energy. Therefore, as far as it is not completely possible for the vehicle to think as a human being (artificial intelligence would be needed for this), a pseudo-predictive approach was selected in the frame of this project. In the case of a parking house, we can assume that when the user pays the ticket at the parking facility, he will go immediately to the vehicle. Therefore, in the predictive approach the user will pay the parking fee with the app (the ticket was previously scanned with the user's smartphone while entering the parking house), and the app will automatically send a message to the vehicle to start the preconditioning process, as it already knows the amount of time available for the preconditioning (i.e. when the user will approach the vehicle).

6 Results and conclusion

The heat-pump system is implemented and operated on an EV and tested on a dyno for evaluation. The ambient conditions are set to 35°C for summer conditions and -10°C for winter conditions. The relative humidity (RH) was set to 40% for the summer conditions but due to the dry air at -10°C the setting of relative humidity is irrelevant. It should be noted that no sun-load was emulated in summer conditions due to simplification of the evaluation of the system.

The cycle that is tested is the WLTC (Worldwide Harmonized Light Vehicles Test Procedure) by firstly fully charging the vehicle, then soaking the vehicle to the operation temperature and finally driving the cycle repeatedly until the battery is depleted. Firstly, the procedure is done with the heat-pump system completely turned off, including the blower inside the HVAC-unit to generate a baseline to be compared to. As seen in Fig. 6, the baseline distance is 112km for 22°C conditions.

In hot summer conditions, i.e. 35°C and 40% RH, with the A/C on to control the cabin temperature to 22°C the distance reduces by 23%, which is comparable to conventional air-to-air A/C systems.

In heating mode, i.e. -10°C the distance is reduced by 45% using conventional PTC-heater and cabin controlled to 22°C. Implementing DENSO heat-pump system and using the same control targets and performance as with PTC-heater, the total distance increases to 80km, which is an improvement by 31%.

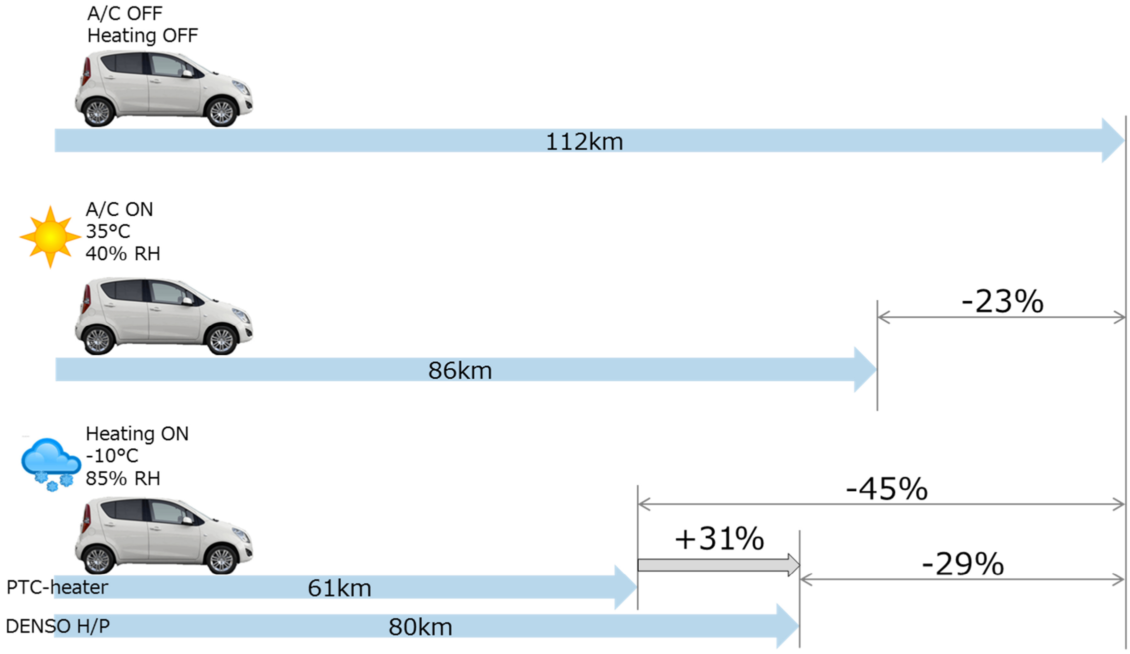

Fig. 6: The compact refrigeration unit increases the driving range by 31% compared to PTC-heater

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