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Efficient cloud-based cabin preconditioning for EVs with a compact heat pump system

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Abstract

DENSO has developed an innovative solution to provide efficient thermal preconditioning of the cabin room for electric vehicles, offering maximum comfort to the user with low energy consumption, therefore improving the driving range of the vehicle. The bigger challenge is to find the optimal time to start the preconditioning of the vehicle, enabling the heating up or cooling down of the cabin room without reducing the driving range of the vehicle considerably. In this paper will be presented a user-triggered as well as a predictive algorithm, which foresees the driver behavior (approach to the vehicle) to achieve the preconditioning of the cabin room upon arrival of the driver. The user-triggered approach is based on the target of preconditioning the vehicle just-in-time when the driver plans to go towards the vehicle for a journey. If the preconditioning function reaches the target temperature before the driver arrives, it will suppose a waste of energy. On the other hand, if the vehicle still did not reach the target temperature when the driver arrives, the comfort level will be infringed. The predictive approach uses an algorithm to foresee the driver's approach to the vehicle through the monitoring of its movements, and therefore eliminates the necessity for the user to trigger the preconditioning system. However, this approach increases the probability of false triggers, which should be avoided. The efficient thermal management in the vehicle is provided by a water-to-water heat pump system which uses ambient heat from the environment even at sub-zero temperatures and is also designed to harvest excess heat dissipated from the power electronics, i.e. the inverter and the electric motor. Finally, a simulation example shows how to reach the targeted cabin temperature by using the low voltage blower initially and the refrigeration A/C successively to precondition the cabin in most efficient way.

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1 Introduction

Cabin thermal management can account for the energy amount corresponding to around half of the driving range of electric vehicles (EVs) in hot summer and cold winter conditions [5]. In recent years, the usage of heat-pumps instead of conventional PTC-elements for heating the cabin have gained more ground due to their superior Coefficient of Performance (COP), which is the ratio between heating/cooling performance to electric/mechanical power, that can be as high as 3-4, compared to PTCs with a COP of maximum 1. This makes heat-pumps 3-4 times more effective than PTCs and hence increases the mileage of EVs considerably. The high COP of heat-pumps is achieved by taking heat from the outer surrounding (even at sub-zero temperatures) through an outer heat-exchanger and by harvesting dissipated heat from powertrain components, e.g. e-motor, inverter and battery which is transferred to the cabin with additional heat converted from the actual work conducted by the refrigerant compressor.

Further increase of mileage for EVs can be reached by preconditioning the cabin before arrival of the driver to the car. Instead of running the heat-pump system on full load in a hot or cold cabin after the driver takes off, preconditioning allows to run the system in an optimally chosen working point (maximum COP) to reach the target temperature at the time of arrival of the driver to the car.

This paper describes an efficient methodology for preconditioning of EVs with the help of an App developed by DENSO and realized by a heat-pump based Compact Refrigeration Unit (CRU). The CRU is a water-to-water heat-pump system based on a natural refrigerant which efficiently provides cold and hot water at the same time to be distributed to the needed components and systems in the vehicle. The paper is outlined as following: Chapter 2 describes the preconditioning strategy and HMI (Human Machine Interface), as well as the App that triggers the preconditioning, followed by the description of the water-to-water based CRU in Chapter 3. Finally, results and conclusion summarizes the paper in Chapter 4 and 5 correspondingly.

2 Preconditioning

There are two main advantages with preconditioning an EV; firstly, the comfort is improved due to the drivers does not enter a cold or hot cabin. Secondly, the electric driving range is increased by reducing the need of going on full compressor power (with low COP) when entering and driving off in a non-conditioned car.

Preconditioning can also be applied to the battery to achieve an optimal battery temperature when the driver arrives to the car, especially in cold winter conditions, which improves the driving range and lifetime of the battery. However, this is not within scope in this paper.

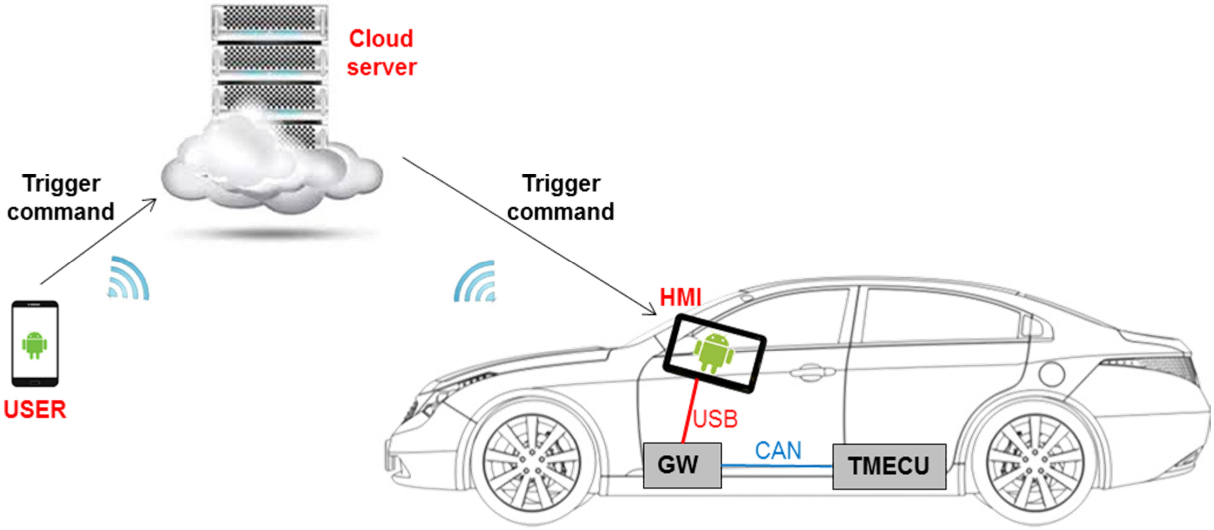

Figure 1: Preconditioning communications architecture

The preconditioning is provided through mobile communication. As depicted in Figure 1: Preconditioning communications architecture, the user may control the preconditioning functionality with an App, which communicates with the vehicle HMI (for this project a tablet) via a cloud server. The HMI sends consecutively the corresponding message through the CAN-bus gateway (GW) to the Thermal Management ECU (TMECU). This high-level controller will finally start the efficient process to reach the target temperature. [5]

2.1 Preconditioning strategy

A. User-triggered Use Case

The user indicates personally the desired temperature, therefore triggering the preconditioning process over the App which calculates the Estimated-Time of Arrival (ETA) from the driver's distance and movements

- The user opens the OPTEMUS-Mobile App on his phone, selects the required temperature and submits the request to the vehicle HMI. The request is sent to the OPTEMUS-Server service which in turn relays the message to the OPTEMUS-Car App. Upon receipt of the request, the OPTEMUS-Car App sets a temperature preconditioning command on the vehicle's CAN bus, which is sent to the Thermal Management ECU (TMECU) for initialization.

B. Predictive Use Case

The vehicle foresees driver's approach through the mobile device carried by the driver and starts the preconditioning process correspondingly. The location is done via GPS and the process is event-triggered (events defined in user's profile: e.g. close house door, switch off lights, switch off computer, approach to vehicle, etc.).

- A pure calculation of user's approach to vehicle (using GPS) could not avoid false alarms completely. To enable the system to foresee the right time for preconditioning, two beacon devices are used: one directly by the user (e.g. car keys) and one located in a control position (e.g. door). When the 2 beacons are close enough to each other (<1m) a temperature preconditioning command will be sent to the vehicle (with no direct intervention of the user).

C. Pseudo-predictive Use Case

The big challenge of the predictive approach is that is not completely possible to avoid false alarms (e.g. the driver goes out of home and has actually the car keys in his pocket; however he does not plan at all to go to the vehicle). Such false alarms are unacceptable, as they just produce additional consumption of energy (instead of the targeted improvement of the efficiency of the thermal management). For the final demonstration it was therefore chosen a pseudo-predictive use case while paying the ticket in a parking house, as we can assume that when the user pays the ticket at the parking facility, he/she will go immediately to the vehicle. Therefore, after making the payment the vehicle can start the preconditioning process, as it already knows the amount of time available for preconditioning (i.e. when the user will approach the vehicle).

- For this purpose a new App was needed: OPTEMUS-Park is a utility mobile application that resides on the same mobile device as OPTEMUS-Mobile. Its main use case is to pay a parking ticket and request the vehicle (over OPTEMUS-Mobile) to precondition the cabin room to a concrete temperature.

2.2 Preconditioning HMI

The HMI is designed in a user-friendly way as seen in Figure 2 and provides information of the temperature in the cabin room (current and desired), approach to the vehicle (time and date), and monitoring of the vehicle status (battery SOC, existing connection over Bluetooth, user profile, general settings). [5]

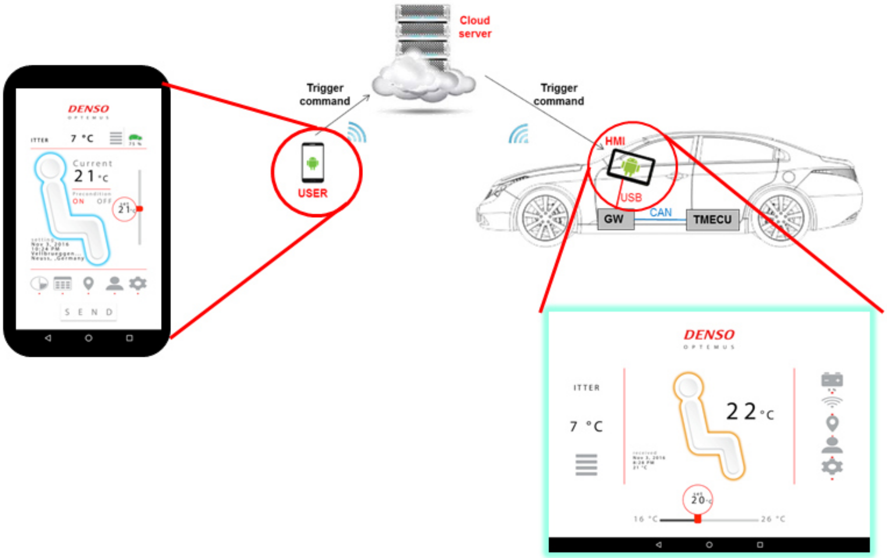

Figure 2: Preconditioning HMI

The HMI provides also connection to an eco-routing functionality (developed by the company IFPEN) over a server, which indicates the most ecological route from the starting point to the destination, as seen in Figure 3. With this information the TMECU can calculate the maximal available energy for the preconditioning process.

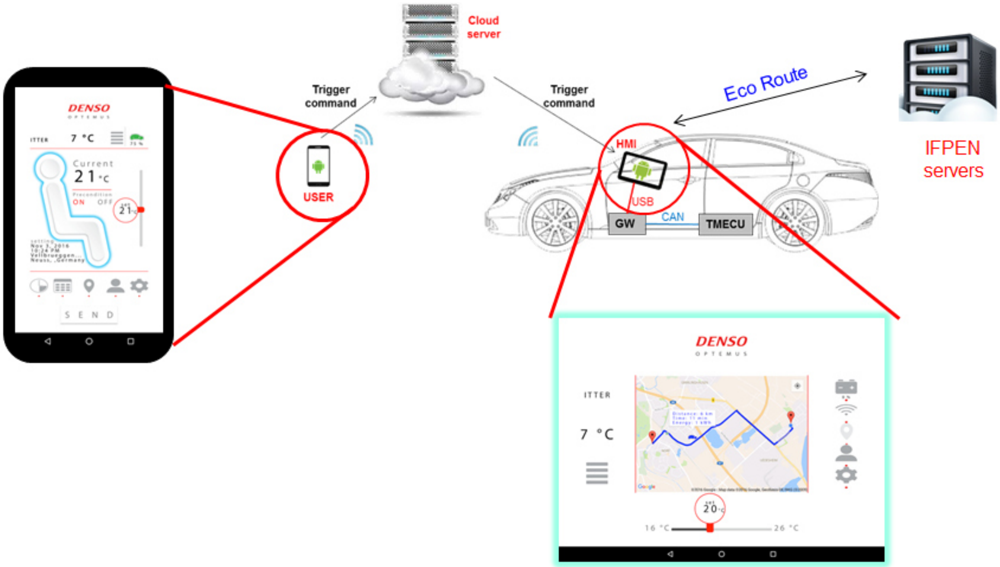

Figure 3: HMI link to eco-routing

For this project were tested the different potential technologies for the communication between the HMI and the CAN-bus: cable, Bluetooth and WiFi, as depicted in Figure 4. For the final demonstration Bluetooth was the chosen one.

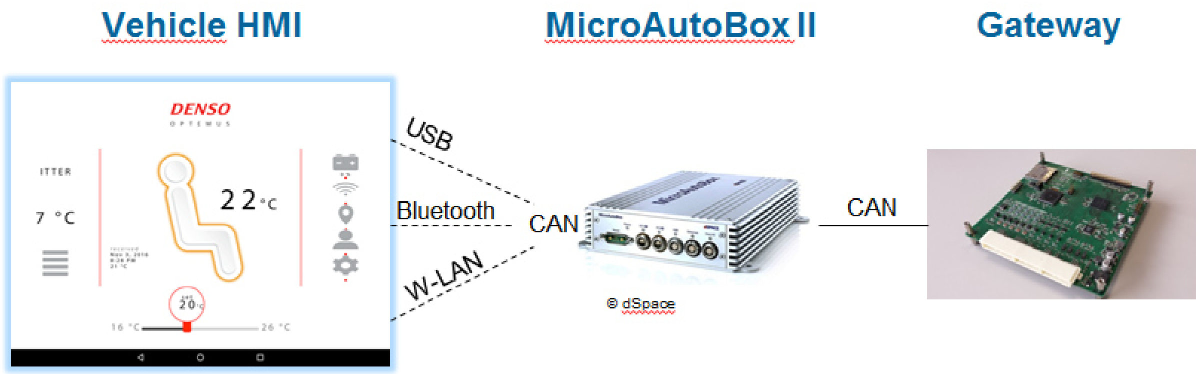

Figure 4: Vehicle communication architecture

3 Compact Refrigeration Unit (CRU)

The Compact Refrigeration Unit (CRU) is a water-to-water heat pump system that has two heat exchangers between the natural gas refrigerant and the water-glycol mixture. When the CRU is operating, the outlet of the electric compressor provides heat and on the other side, between the Expansion Valve (EXV), the temperature decreases, hence provides through the heat exchangers hot and cold water, as depicted in Figure 5. The hot and cold water can then be distributed with water-pumps and valves to the various systems in the vehicle, in particular cabin and powertrain. With this configuration, it follows naturally that dissipated heat from the powertrain, e.g. inverter, e-motor and battery can be harvested by the CRU to be useful heat in the cabin for heating and hence gives a highly efficient heating in comparison to conventional PTC-based heating systems.

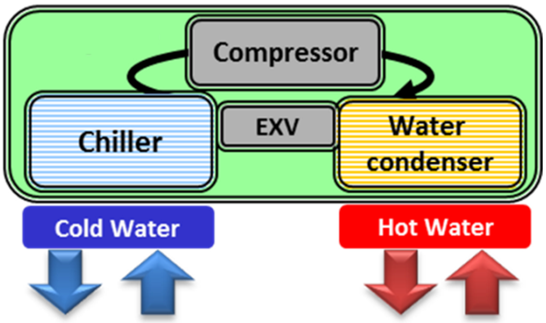

Figure 5: Water-to-water natural refrigerant based Compact Refrigeration Unit (CRU) heat-pump which realizes the thermal conditioning of cabin and powertrain by generating hot and cold water on independent circuits.

The CRU operates to realize the preconditioning set points and is programmed to choose the preconditioning strategy based on the circumstances, such as outside and cabin temperatures. Basically, there are three different states: heating, cooling as well as re-heat mode for dehumidifying the air blown through the cooler-core with low temperature and then passes through the heater-core for the set temperature. The preconditioning is triggered by the HMI and starts initially, regardless of the outside temperature, the system to run on fresh air mode for few seconds to level out any high CO_2 concentrations, humidity and odors in the cabin compartment after standing for a longer time, e.g. overnights parking.

3.1 Heating

From left part of Figure 6, the water flow during heating is depicted. If the target cabin temperature is higher than the outside ambient temperature, heating is realized by the CRU through the distribution of the water. The CRU is initialized to control a target of the heater-core air outlet temperature $T^*_{a,HC,out}$ that enters the cabin. This is a closed loop control realized with the compressor speed as the control variable and feedback comes from the heater-core air outlet temperature $T_{a,HC,out}$.

3.2 Cooling

If the ambient temperature is higher than the requested target cabin temperature, e.g. in warm summer conditions, the cooling mode is activated as depicted on right part of Figure 6. Especially in cooling mode, dehumidification is of importance to decrease the humidity inside the cabin. The difference here, from heating mode, is that the compressor is now controlled to maintain the cooler-core air outlet temperature $T_{a,CC,out}$ and in a secondary control loop, the water circuit is connected with valves to control the air temperature after the heater-core $T_{a,HC,out}$. Here as well, the radiator is controlled to dissipate the cabin heat to the hot environment and the HVAC blower controls the air-flow into the cabin.

3.3 De-humidification

When the ambient temperature is in the range of 0-20° de-humidification mode may be necessary, in both heating and cooling mode, in order to avoid fogging of windows and for increased comfort. De-humidification for heating runs, additionally to hot water in the heater core, also cold water in the cooler core. For cooling, both heater core and cooler core have water pumping inside with the difference that the temperature of the air outlet of the heater core is lower than the cabin temperature in order to cool down the cabin.

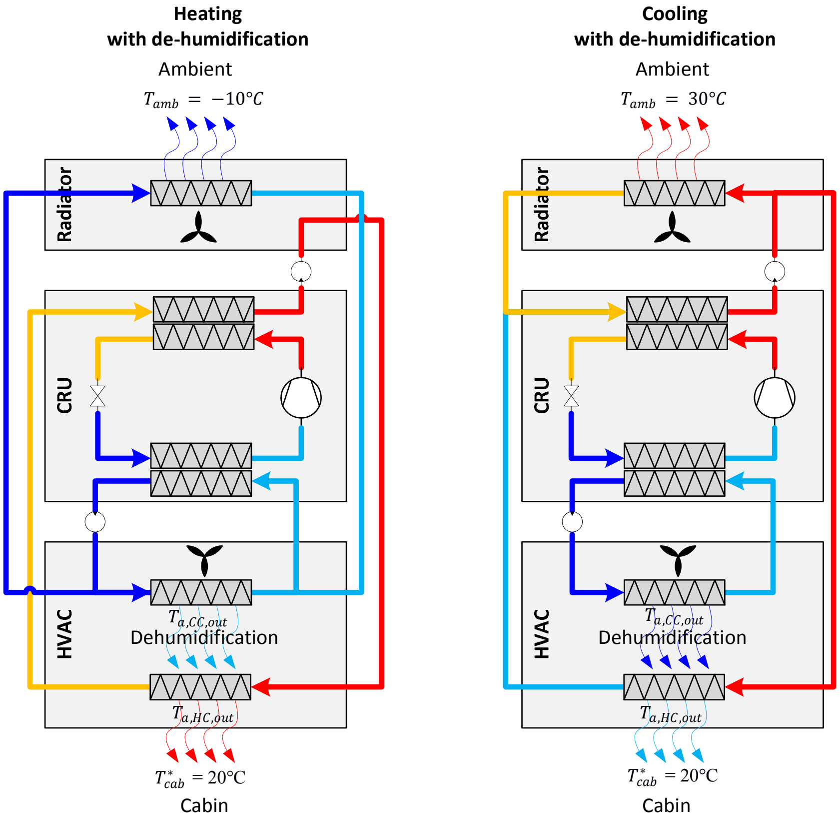

Figure 6: The distribution of water from the CRU is realized with pumps and valves and used to condition cabin and powertrain by switching the valves. Heating mode is efficient by taking heat from the ambient through the radiator.

4 Evaluation

The predictive preconditioning logic detects a temporary stop of the vehicle based on points of interests where the driver is located (e.g. at work, goes for shopping, training, barber, etc.) and when the temperature stop is calculated within a certain time, the algorithm keeps the blower running at low power to mitigate a high increase of the cabin temperature. The benefit is a quicker cool down to the preferred target temperature, a shorter reaction time needed for the CRU to detect driver returning to vehicle and primarily, and a lower overall power consumption for preconditioning. This was simulated and the results are described in the next chapter.

For improved efficiency, recycling mode of the cabin air flow is activated except for the initial phase to level out CO_2-concentration, humidity and odors. After the targeted cabin temperature is reached, the control system runs in a stationary mode until the preconditioning terminates due to driver arrival or other triggers.

In hot and sunny summer conditions, when the vehicle is parked with doors and windows closed and no ventilation is on, the cabin temperature can rise to temperatures as high as 60°C within one hour, as shown in Figure 7. In extreme cases, the cabin temperature can be as high as 80°C and become a dangerous trap for any living being, e.g. children or pets. Simulations show that it is possible to achieve temperature reduction of more than 15°C in the cabin by only running the low-voltage blower, by continuously ventilate fresh air into the vehicle, when the sun load is high. For preconditioning, running the blower in lower speed continuously, assuming the driver is temporarily away from the vehicle is an efficient way to decrease the cabin temperature, as it consequently lowers the power requirement for the CRU to bring down the temperature further to comfortable levels during the preconditioning, once the driver returns to the car. It is shown that 4 hours of ventilation with the blower that runs on 20W electric power, which corresponds to lower blower level, consumes totally 80Wh of energy from the battery, which is a magnitude of 5 compared to utilizing the CRU with the same targeted temperature reduction, as will be explained next.

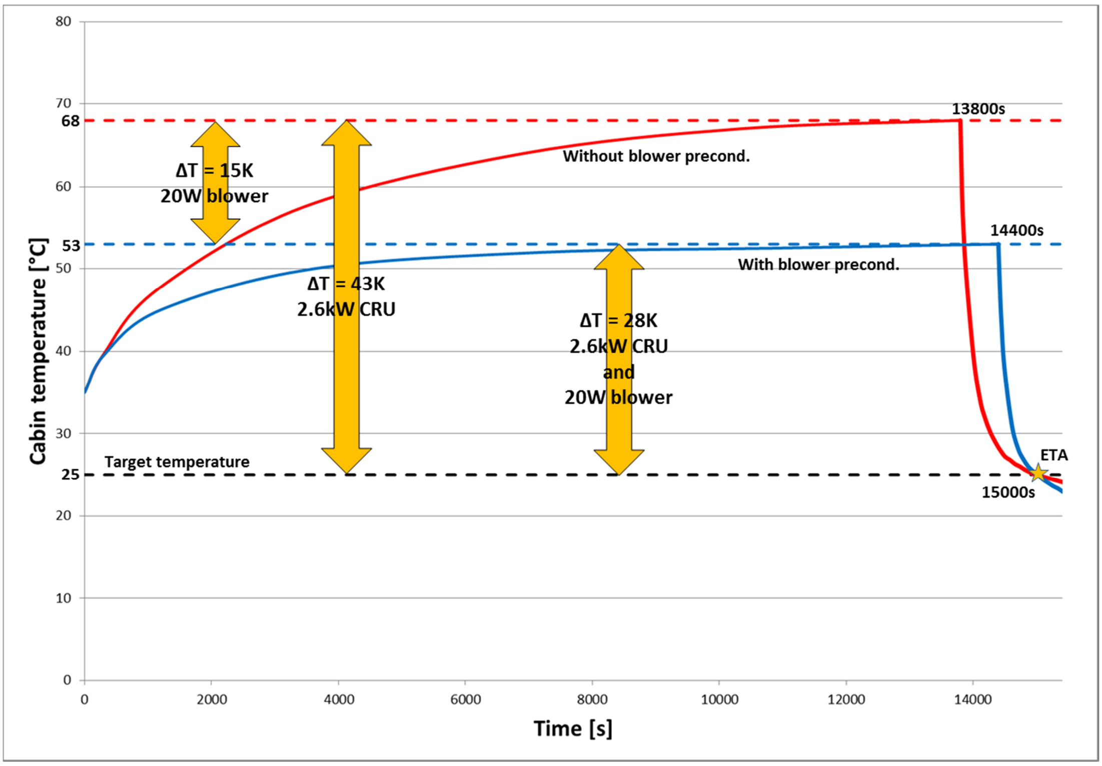

Figure 7: Energy consumption for cabin preconditioning using blower and CRU successively for a mid-sized vehicle in 35°C ambient temperature, 40% relative humidity and 800W/m2 of sun-load.

Running the compressor at its maximum coefficient of performance (COP) from the initial temperature of 53°C (realized by the blower) will reach a room temperature of 25°C after 10 minutes, as shown in Fig8. This timing should be matched with the Estimated Time of Arrival (ETA) of the driver to the vehicle, as explained in Chapter3. By preconditioning the cabin with the blower in advance delays the need for starting the preconditioning with the CRU by 10 minutes and yet reaches the 25°C cabin temperature at the same timing and consequently, saves 434Wh which corresponds to 46% reduction in energy needed for the preconditioning of the cabin.

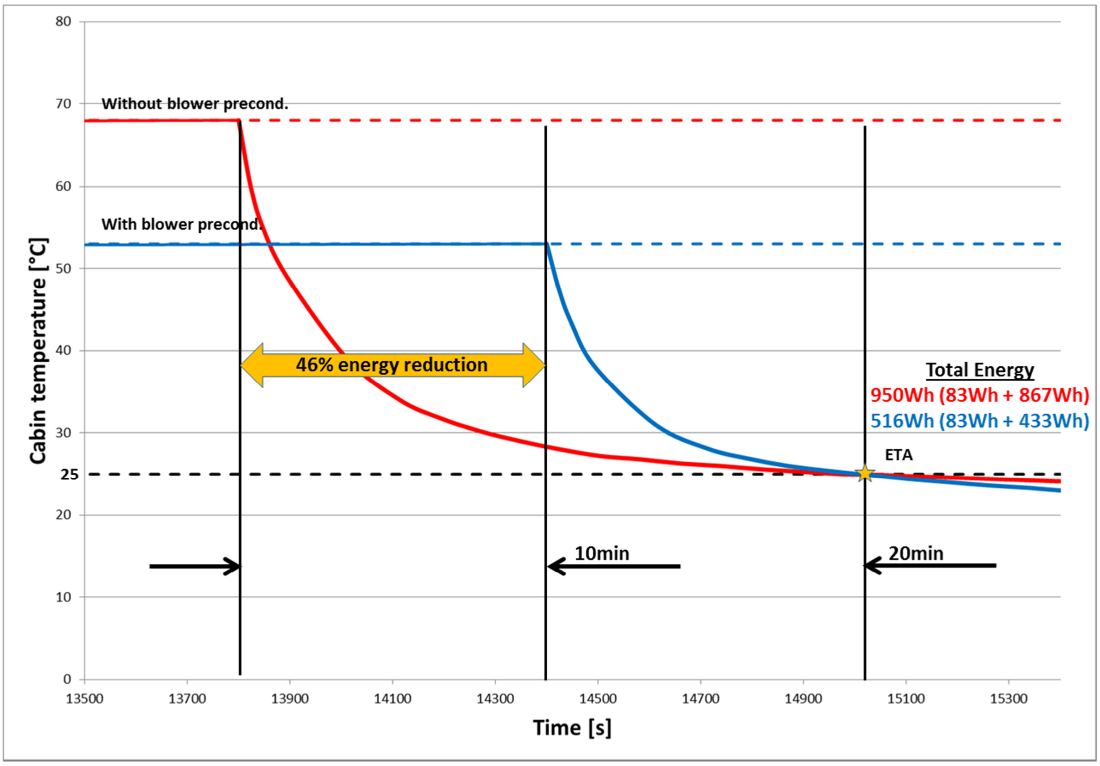

Figure 8: Zoomed in view. Energy reduction of 46% can be achieved by preconditioning with the blower first and yet reach the target cabin temperature of 25°C at the estimated time of arrival (ETA) of the driver.

For heating, the system runs with 100% recycled air mode for an efficient operation. This may cause problems in sub-zero initial temperatures because of frozen water on carpets as well as ice on windshields that will melt and start to evaporate when cabin temperature creeps above zero which can cause fogging from condensation and a humid cabin. Therefore, when the cabin temperature exceeds 5°C, the recycled air is dehumidified through the cooler-core before entering the heater-core for continuing heating up the cabin. At this stage, the cooler-core water temperature needs to be controlled not to go below a target temperature of 2°C for dehumidifying the recycled air to avoid icing of the evaporator. This control is realized through redirecting the water circuit with valves. Finally, when reaching the target cabin temperature, the system runs in a stationary mode with feedback control loops of the heater-core air temperature and the cooler-core air temperature as well as the cabin air blower and radiator fan for control the air flows through the cooler/heater-cores into the cabin and the radiator for harvesting heat from the ambient, until the HMI system terminates the preconditioning due to arrival of the driver or other triggered termination commands. Contrary to the cooling preconditioning, there is no further energy reduction such as running the blower initially. The energy efficiency relies on the good estimation of the ETA and running the CRU at maximum COP.

5 Conclusion

In this paper, a solution to reduce the energy requirement for cabin thermal management is proposed. By reducing energy need, especially in hot summer and cold winter conditions, the driving range of EVs is considerably increased compared to conventional systems as the biggest auxiliary consumer for EVs is the cabin thermal management which can reduce the driving range by up to half.

Firstly, three different approaches for cabin preconditioning are presented. The first one involves a user-triggered (over the cloud) preconditioning, where it cannot be assured that the user will finally approach the vehicle at exactly the time he asked for (maybe earlier, maybe later). The second one is a smart predictive approach, where the vehicle will predict through monitoring when exactly the user will approach it, providing just-in-time preconditioning of the cabin, based on calculated Estimated Time of Arrival (ETA).

However, this approach has the risk of false alarms (i.e. preconditioning of the vehicle because the user is indeed approaching, although he may not be intending to go to the vehicle at all). Finally a pseudo-predictive approach should avoid the risk of false alarms and will use some indirect trigger (e.g. the payment of the parking in a shopping mall) to definitively calculate the ETA and start/finish the preconditioning at the right time.

Secondly, an efficient and compact heat-pump system is presented which can utilize heat from the environment (even at sub-zero temperatures) and harvest excess dissipated heat from the powertrain components. With preconditioning of the cabin compartment, the comfort for the driver is maximized and by operating the heat-pump system in a high efficient working point, the driving range is improved.

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