32nd Electric Vehicle Symposium (EVS32)
Lyon, France, May 19 - 22, 2019

Adaptive Cabin Air Filter System for energy efficient filtration for e-vehicles

[1]Jerome Migaud, [2]Matisse Lesage, [2]David Chalet, [3]Thomas Heininger, [3]Christoph Krautner, [4]Matthias Heinzmann, [4]Bernd Bauer, [4]Martin Klein

[1] MANN+HUMMEL France S.A.S, Laval, fr.info@mann-hummel.com

[2] ECOLE CENTRALE DE NANTES, LHEEA Lab. (ECN/CNRS), Nantes, contact@ec-nantes.fr

[3] MANN+HUMMEL GmbH, Marklkofen, info@mann-hummel.com

[4] MANN+HUMMEL Innenraumfilter GmbH & Co. KG, Himmelkron, info@mann-hummel.com

Summary

One of the key challenges for e-mobility is to increase the cars driving range. Simultaneously the demands on the quality of the cabin air are significantly increasing. The protection of the passengers from ultrafine particles by HEPA filters or harmful gases by adsorption leads to filtration products that no longer can be implemented in the air conditioning system (HVAC). New installation spaces in electric cars offer the opportunity to adapt an intelligent filter system upstream of the air conditioning system. The system consists of three, individually adjustable filter stages that are activated depending on the air pollution level of the environment and driving conditions (traffic jam, tunnel, city, outback). This always ensures the best air quality in the interior of the car and reduces energy consumption of the air conditioning system.

Keywords: air conditioning, energy consumption, heat pump, pollution, simulation

1 Introduction

Depending on the air pollution level, the rising health impact (e.g. deaths, lung cancer, bronchitis episodes for children and asthma attacks) can be reviewed [1, 2]. In addition, economists from the World Bank group [3] calculated the costs generated by air pollution. Furthermore, the World Health Organization published regularly updated Air Quality Guidelines (AQGs) which are based on all scientific publications regarding air pollutions and health impact. The AQGs should help governments and the world community to refine concentration threshold values for short term and long term exposure to harmful pollutants. Pollutants to be taken into account are at least PM10, PM2.5, ozone (O_3), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and carbon monoxide (CO). It is also necessary to consider the risks due to Volatile Organic Compound (VOC) and Carbon Dioxide (CO_2) for mobile applications and especially in confined environment with people like inside passenger's cars cabins [4]. Not only the health, but also the safety, and comfort have to be guaranteed (temperature, humidity,…) to the car driver and passengers, and with the additional constraint to minimize the energy consumption. In order to improve the air quality, MANN+HUMMEL introduces new technologies for cabin air filtration. The technologies comprise new filter layers with high-performance adsorbent materials to remove unpleasant odours, mould growth and allergens [5]. In order to remove the amount of very fine particulates from the air exceeding a certain concentration level referred as "healthy", the existing standard cabin air filtration can be enhanced by HEPA filter elements, which are commonly applied for filtration purposes in clean rooms and in none transportation applications. The HEPA element is implemented to a complex system with two air quality sensors placed inside and outside the cabin. Different active flaps control the flow from the exterior to the cabin, changing in the same time the pressure losses, the recirculated air in the cabin, and the filtration efficiency. As the recirculation rate of the air in the cabin has a direct impact on the CO_2 concentration and the thermal load applied to the HVAC system; it has to be controlled to maximize the air quality and the comfort, and minimizing the energy consumption, and impact on vehicle autonomy.

A system simulation approach is described here to demonstrate the need of a smart control of the air quality in the cabin, showing the influence and potential on energy savings.

2 New Architecture for Smart CAF System

In existing cabin filtration systems the filter element is generally part of the HVAC system with limited available filter space to improve filtration performance and lifetime significantly to meet increasing requirements for cabin air quality. Existing systems with more than one filter element are designed for mandatory filtration through all filter elements, not allowing adjustment of filtration stages based on varying environmental factors.

The opportunity offered by electric cars is a higher flexibility in positioning and design (size/shape) of additional filter elements because more installation space is available due to the non-existing internal combustion engine. Consequently, the challenge with electric cars is how to maximize their driving range. The heating up and cooling down of outside air for the car cabin drains the battery and therefore reduces the amount of energy available to power the vehicle. Therefore, intelligent operating modes and filtration concepts are required.

Against this background, MANN+HUMMEL has come up with FreciousSmart – an adaptive cabin air filter system, especially for electric cars, which continuously ensures always clean air inside the car regardless of the different driving conditions and air pollution combined with an increased service lifetime of the HEPA filter and minimized energy consumption.

The adaptive cabin air filter system (Figure 1) consists of

- three filter elements: interior air filter, ambient air filter and HEPA filter,
- air quality sensors for outside air and interior air, continuously measure and monitor the air quality, and
- flaps/ doors to regulate air path through needed filter elements as required by driving conditions and contamination levels, filter housings and air ducts.

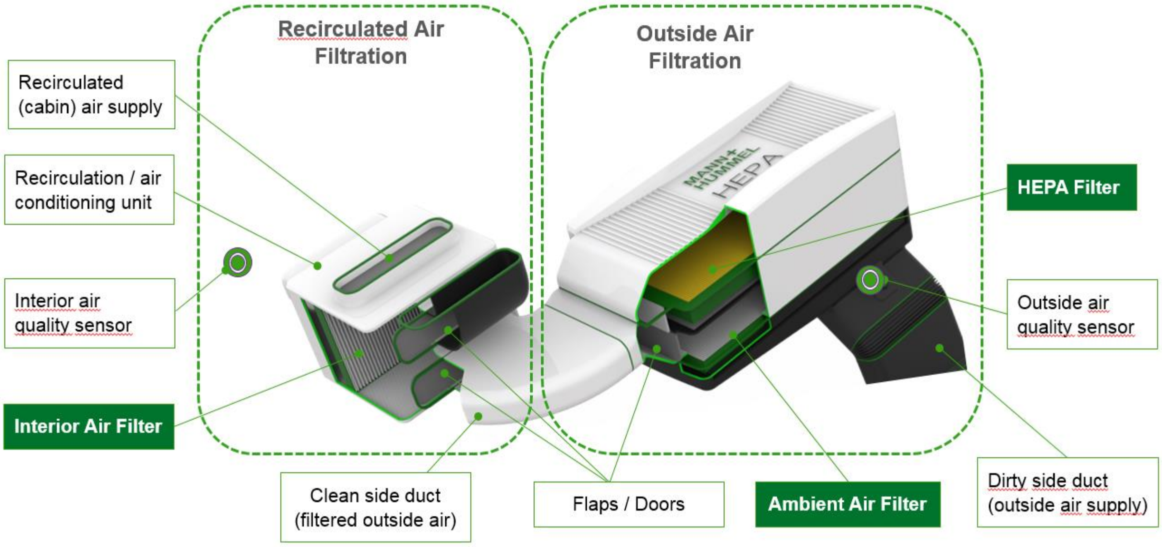

Figure 1: Architecture of FreciousSmart

FreciousSmart enables the air conditioning system to operate with a maximized amount of recirculated air, which saves energy due to minimized heating and cooling of outside air. In this process sensors continuously detect and monitor the quality of the interior (cabin) air and the outside (ambient) air.

The interior air sensor is placed inside the cabin of the vehicle to measure internal air conditions like CO2 concentration, relative humidity, temperature and the concentration of particles and pollutants, respectively. Consequently, it is determined how much outdoor air is actually required to keep the comfort level and to avoid fogging on the windscreens which is a safety issue. Simultaneously, the outside air sensor recognizes the degree of contamination of the ambient air with particles and pollutants and decides which filtration efficiency is required to clean the outside air.

The cabin air filtration system can be configured to use a variety of air intake modes and fluid pathways through regulating flaps and doors based on the sensed data and allows a dynamic adaptation to various driving environments (traffic jam, tunnel, city, outback).

The preferred mode to save energy is the recirculation mode, which can be used if the ambient air quality is good. When the system runs in recirculation mode, the interior air filter is sufficient to offer effective protection of the passengers inside the car by retaining coarse particles (PM10, fibers), volatile organic compounds, which might be released by plastic components, and allergens and pollens from the environment. The HEPA filter and ambient air filter not activated.

If there is an increased requirement for outside air supply due to a lack of fresh airflow resulting in low O2 and high CO2 concentrations (passengers breathing), and the outside air is more contaminated, the ambient air filter is needed. This filter retains airborne particles and in particular respirable particulate matter (PM2.5). Furthermore, it removes harmful gases such as nitrogen dioxide, ozone, sulfur compounds and ammonia. Pollens from the ambient air are also retained.

For extremely polluted outside air, for example, in a traffic jam or during travel in tunnels, an additional high efficiency particulate air filter (HEPA) can be activated. The HEPA filter even separates so called ultra-fine particles, airborne particles which have a size of less than 0.1 µm, and therefore offers the highest protection against critical outside air contamination.

A HEPA filter is, however, expensive. Thus, the target must be a single use it when it is actually needed. The adaptive system allows bypassing the HEPA filter by controlling a flap based on sensor data and using the ambient air filter as a pre-filter stage. Thus, the service life of the HEPA filter is considerably extended and energy consumption can be reduced.

3 Filtration technology

In order to offer a superior air quality in the cabin the filtration technology of the system is designed in a way to deal with all relevant particulate and gaseous pollutants of a wide range (Figure 2).

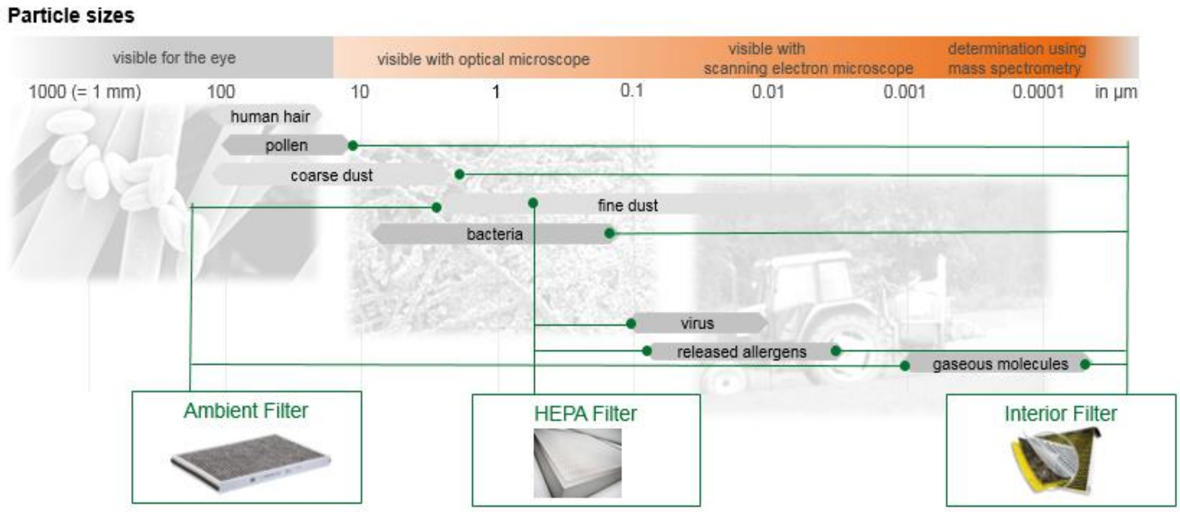

Figure 2: Overview Particle Size Range

The system contains three filter-stages: The ambient and the HEPA filter (outside air filtration) and an interior filter (recirculated air filtration). Each filter is designed to an optimum referring to its filtration task. Usually cabin air filters have to deal with pollutants from outside as well from inside the cabin and thus have to deal with a quite wide range of pollutants in a single stage. In the outside air filtration part where two filter elements are installed the clear focus is on particles and gases coming from the outside environment. Particle Fractions in focus here are PM10, PM2.5 and PM1 for the ambient air filter plus gaseous pollutants like NO2, ammonia (NH3), and hydrocarbons. The second filter of the outside air stage is a HEPA (high efficient particulate air) filter dealing with the very fine particles < 0,1 µm that passed the first filter stage. The ambient air filter consists of a multilayer filter media, which includes a prefilter layer, a fine fiber layer and several layer of adsorbents and optionally a functionalized nonwoven layer that is especially optimized towards gas concentration reduction (e.g. ammonia).

The second filter collects the ultra-fine particles that penetrated through the Ambient filter. For this task a HEPA filter media according EN 1822-1:2009 is used, which removes 99.5% at the most penetrating particle size [6]. Usually this kind of filter media is used for application in clean rooms and operating rooms. The HEPA filter element requires a very tight sealing in the filter housing to ensure that fine particles are separated in the filter media and do not bypass at the interface between the filter edges and the surrounding housing. To compensate the relative high air restrictivity of such media types the filter size needs to be adjusted to ensure that a sufficient amount of air can be transported through it. This leads to larger dimensions of this filter element compared to a standard cabin air filter. A reason why this kind of media class cannot be easily used in vehicles with internal combustion engine as design space here is very limited there.

Another important aspect is the lifetime (service interval) of such filter elements. As the fiber structure is very tightly packed the airflow can be restricted quite quickly if the dust load toward the filter element is too high. Therefore, it is of crucial importance to protect this high valuable HEPA filter from fast clogging which would make a replacement necessary. Out of this reason, the ambient filter needs to be carefully chosen and designed to protect the HEPA Element from fast loading. Figure 3 shows the loading curves of combinations of an ambient filter plus a HEPA element. These two filters were installed in a container, which is placed close to a heavy traffic road. Highly polluted air was sucked through the two concepts and the differential pressure increase of the filter element combination was monitored. As the HEPA Filter element was in both cases identical, only the ambient air filter in front of the HEPA influenced the overall loading curve (pressure drop increase) of the combination. This study demonstrates that the choice of filter media and the design are also of high importance for the following filter elements and their functional behavior.

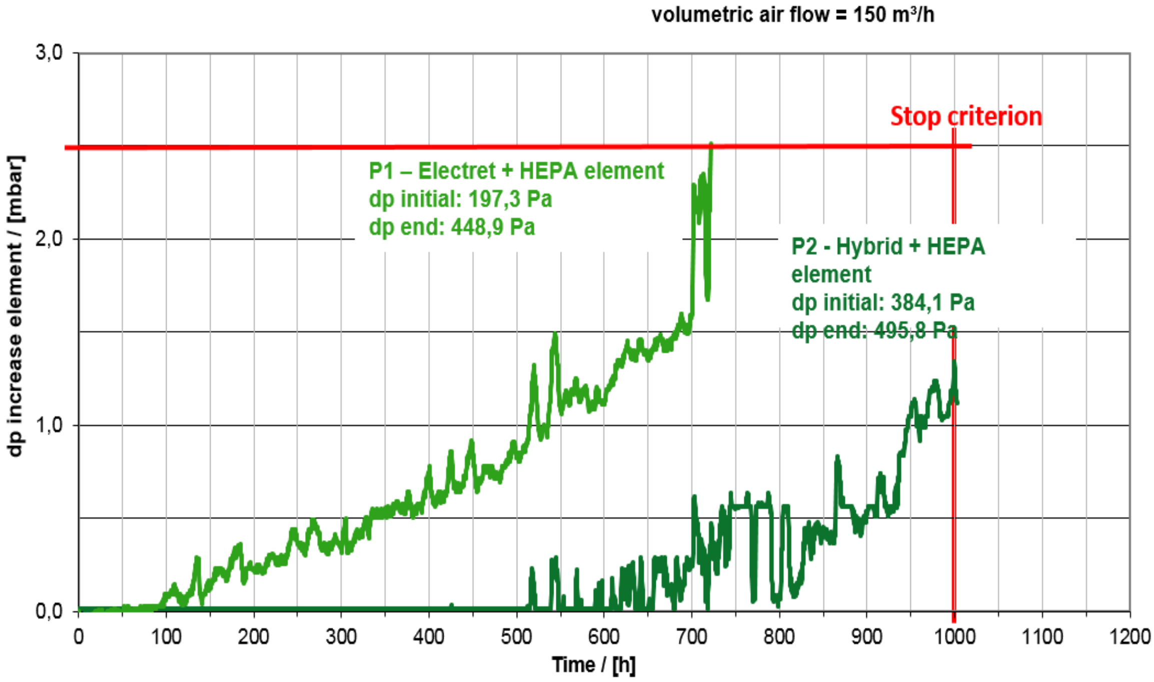

Figure 3: – Loading Curves of two combinations of filter elements

The last filtration stage is placed in the inside air housing. This interior filter has focus on particles and gaseous pollutants coming from the interior by recirculation of the air. Therefore, the adsorbents are specifically designed to manage with emissions coming from the material used in the interior (VOC´s). Preferably, the cabin filter media also includes a biofunctional layer on the downstream side in order to inhibit the growth of bacterias and moulds and reduce the concentration of allergens inside the cabin [7].

4 Performances of the system

The objective with the 1D simulation code is to evaluate the energy performances of a HVAC system equipped with the FreciousSmart concept. The two main elements of the model (refrigerant loop and cabin air circuit) and their compounds are described in this part (a scheme is available on Figure 4).

Heat pump:

A reversible heat pump is chosen for the heating and cooling of the cabin. The fluid used is the R134a. The heat pump model can be divided into different elements. Starting from the compressor a four-way switch guides the fluid to the condenser (cabin side in heating mode, outside air side in cooling mode) where it releases heat to the air, and then to the thermal expansion valve that controls the superheat at evaporator outlet by regulating the mass flow rate. Finally the fluid goes through the evaporator (outside air side in heating mode, cabin side in cooling mode) in which the air is cooled. An accumulator is used to store the latent liquid excess upstream the compressor. The latter increases the pressure (and thus temperature) of the gas refrigerant.

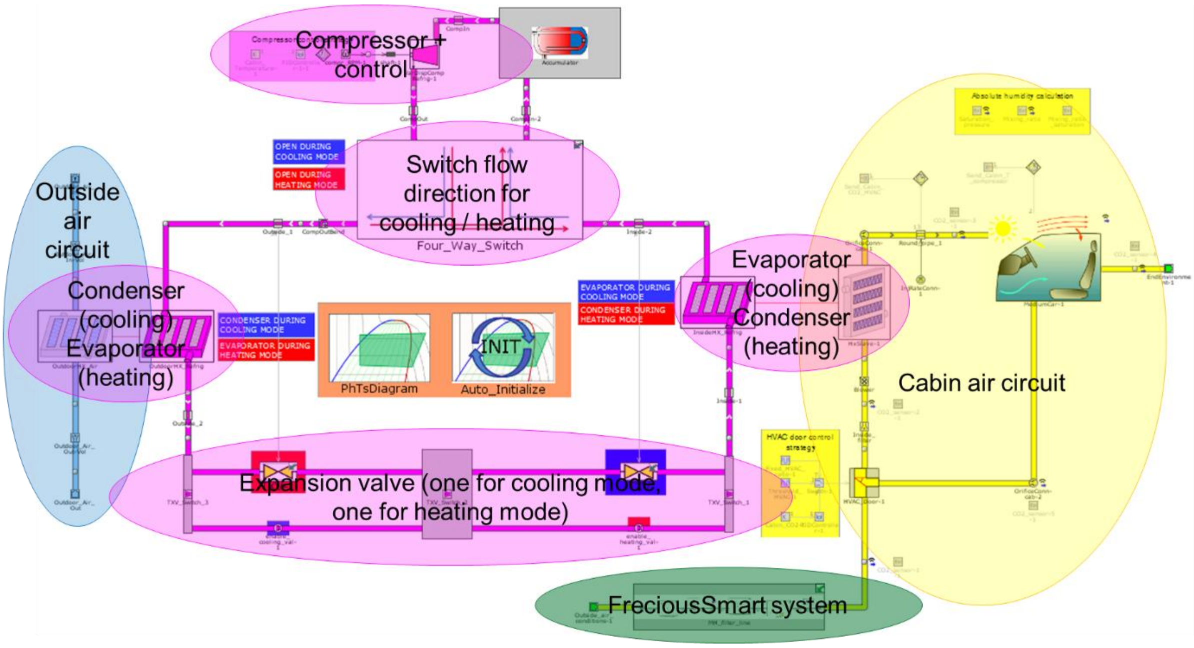

Figure 4: Full HVAC model developed in GT-Suite software

The real behaviour of the heat pump system is ensured by Gamma Technologies from manufacturer supplied data.

The compressor model relies on a measured map performance data with a fixed displacement (170 cm3). A PID regulator is implemented to adjust the rotational speed (from 0 to 2000 rpm) in order to stabilize the cabin temperature at a given target. For example in heating mode the compressor is at full speed until the targeted temperature is obtained in the cabin. Then the rotational speed is progressively reduced to stabilize the temperature.

Air circuit:

The elements of the air circuit are the FreciousSmart system with HVAC door, blower, heat exchanger, cabin model, and connection pipes.

The air is provided by an ambient air module that specifies its pressure, temperature and composition (including CO2 concentration). First the air goes through the FreciousSmart system, i.e. the ambient and HEPA filters before entering the HVAC door which controls the amount of recirculated air coming from the cabin. A control of the door position is implemented to minimize the energy consumption for the heating or cooling of the cabin, while maintaining an acceptable CO_2 comfort level for the passengers. In this mode a PID regulator controls the HVAC door position to manage a maximum CO2 level of 1100 ppm inside the cabin. For example the door is closed (only recirculation) until the CO2 concentration reaches the limit due to the passengers exhalation. Then the door progressively opens to stabilize the CO2 level inside the cabin at 1100 ppm. This mode will be referred as the "OPTI" mode, and the consequences of such control compared to a classic fixed ratio will be discussed in this chapter.

The FreciousSmart system has been discretized from 3D model into 0D model using the GEM3D tool in the software. From the energy analysis point of view the filter elements can be perceived as pressure losses at the inlet of the cabin air circuit. Calibration data is provided from tests realised in MANN+HUMMEL facilities in Germany. The worst case scenario is considered and the three filters are in active position (mode 3, outside air goes through all media).

At the HVAC door outlet there is successively the interior filter (part of FreciousSmart), the blower, the heat exchanger and finally the cabin. An injector located at the cabin inlet simulates the CO_2 exhalation rate from the passengers. The volumetric flow rate is fixed at 18.75 L/h. With a density at body temperature (37°C) of 1.74 kg/m3 it leads to a mass flow rate of 32.6 g/h per passenger. In the model CO_2 sensors are implemented in each branch.

The cabin is a mono-zone volume that computes the thermal balance of the air inside a vehicle. Approximate calibration is provided by Gamma Technologies for a medium car cabin (i.e. VW Golf) and includes a wide range of parameters: component materials, masses and geometry (doors, roof, floor, windshield and windows), passengers' moisture, as well as heat input from occupants and firewall. Sky radiation, soak temperature and humidity are taken into account in the calculations. The exits of the cabin are the branch going to the HVAC door for recirculation, and a pressure relief branch for breathing to ensure pressure regulation in the cabin.

An external module in implemented to compute the absolute humidity inside the cabin as it is a comfort constraint.

Simulation settings:

Three scenarios are considered with different ambient conditions (see Table 1). In the COLD case the HVAC system runs in heating mode while in the other cases it is in cooling mode. In the MEDIUM scenario, although the outside and targeted temperatures are the same (19°C), the system is in cooling mode due to the heat input from passengers and solar radiation.

Table 1: Three ambient settings for simulation

		COLD	MEDIUM	HOT
Ambient pressure	bar	1.01325		
Ambient temperature	°C	-16	19	30
Mixing ratio	$g/kg_{\text{dry air}}$	0.8	5.5	19.0
Ambient CO_2 concentration	ppm (%)	400 (0.4)		
Solar flux	W/m^2	250	500	1000
Water emission per person	g/h	30	65	100
Heat emission per person	W	75		
CO_2 emission per person	L/h	18.75		

The temperature target is 19°C in COLD and MEDIUM scenarios, 25°C in HOT case. The blower is controlled to have a 250 m3/h total air flux going through the 2.5 m3 cabin volume. The number of passengers inside the cabin (including driver) is variable from 1 to 5. The HVAC door position is fixed at a value from 0 to 1, which corresponds to the amount of outside air flowing inside the cabin. For instance with an HVAC door position set at 0.38 the proportion of outside air and recirculated air going through the cabin is respectively 38% and 62%.

The simulation time for each case is set at 1200 seconds to allow complete temperature stabilisation inside the cabin. The computational time is around 5 minutes for each case.

The purpose of the simulation is to evaluate the possible energy gains with this system by varying the recirculation door element of the system. Five positions are considered: 1 (100% outside air), 0.8 (80% outside air), 0.5 (50% mix), 0 (recirculation) and OPTI mode. Simulation results show that in OPTI mode the amount of fresh air required to stabilize the CO_2 level at 1100 ppm depends on the number of occupants in the vehicle (see Table 2). For example with one passenger in the cabin it is possible to decrease the amount of fresh air down to 13% (ambient CO_2 concentration at 400 ppm).

Table 2: HVAC door position required to stabilize CO_2 concentration at 1100 ppm

Number of passengers	Average HVAC door position in OPTI mode
1	0.13
2	0.30
3	0.50
4	0.68
5	0.84

In the UK (in 2016) the average occupancy in a 4-wheeled car is around 1.6 passengers per vehicle [8]. This figure drops to 1.2 regarding business and commuting trips [9]. Until the end of the current study two occupants are considered in the vehicle.

Several parameters are monitored to evaluate the comfort like humidity (relative and absolute), temperature and CO_2 concentration. Energy savings are assessed through the power consumption of the compressor in the refrigerant loop, and the blower in the cabin air circuit.

Results:

The cabin temperature in the COLD scenario with different recirculation ratios is displayed on Figure 5.

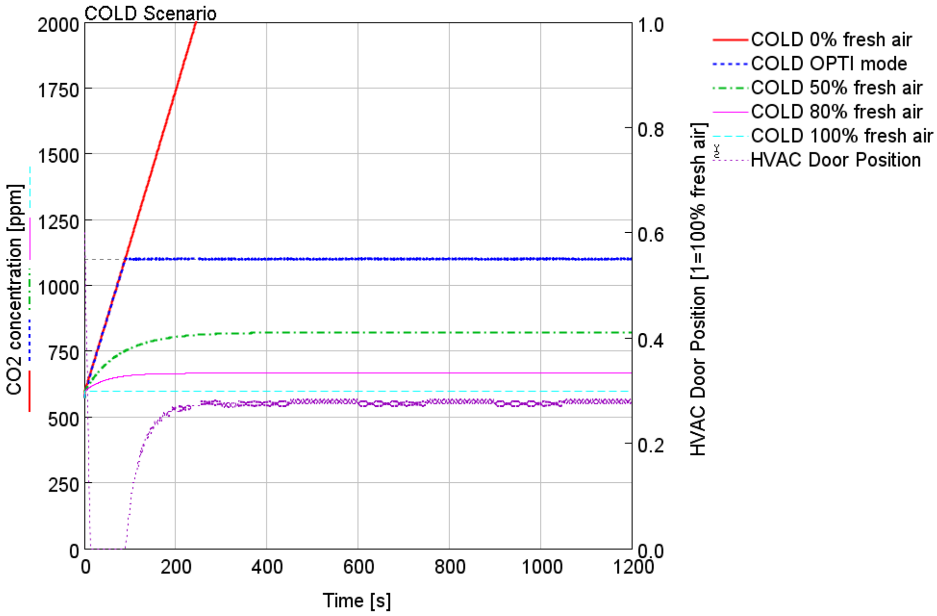

Figure 5 – Cabin temperature in COLD scenario

The time to reach the 19°C decrease from 1068s to 400s as the recirculation door is closed. Indeed, by closing the HVAC door, the heat pump system has to heat less fresh air (-16°C) and more pre-heated air which already went through the heat exchanger. In the 0% fresh air case, the cabin air circuit is a closed loop and only recirculated air has to be heated.

Table 3: Power analysis in COLD scenario

HVAC door position	100% fresh air	80% fresh air	50% fresh air	OPTI mode	0% fresh air
Compressor Power [kW]	3.26	3.14	2.91	2.69	2.30
Blower Power [kW]	0.16	0.15	0.14	0.13	0.12
Convective heat transfer at cabin side [kW]	3.39	3.15	2.77	2.46	2.02
Convective heat transfer at outside air side [kW]	-1.80	-1.65	-1.44	-1.26	-0.98
Compressor isentropic efficiency [%]	49.8	51.4	53.8	54.2	49.8

The consequences on the compressor power in the refrigerant loop are displayed on Table 3. The average compressor power to heat the cabin at 19°C for 1200s is 3.26kW in the 100% fresh air case. This value is decreased to 2.30kW when the HVAC door is fully closed. This 0% fresh air case is the one that leads to the minimum energy consumption of the heat pump. However by closing the HVAC door the cabin air is not renewed over time. There are two main consequences on air composition.

First the relative and absolute humidity levels are rising to high levels and according to simulation results there is fog formation on front windshield and side windows. Besides being of high discomfort, this fog is a serious security threat for the driver.

Then the closing of HVAC door leads to a very high increase of the CO_2 concentration levels (see Figure 6). The consequences on health can be very harmful and can decrease the ability to safely drive a vehicle. For instance the cognitive responses to tests regarding basic activity or information usage become marginal and dysfunctional for CO_2 concentrations above 2500 ppm [10]. To address this issue the OPTI mode has been implemented in the model, limiting CO_2 concentration at 1100 ppm. The opening of the HVAC door in the OPTI mode is displayed on the second axis on Figure 6; its behaviour is as described previously in the article.

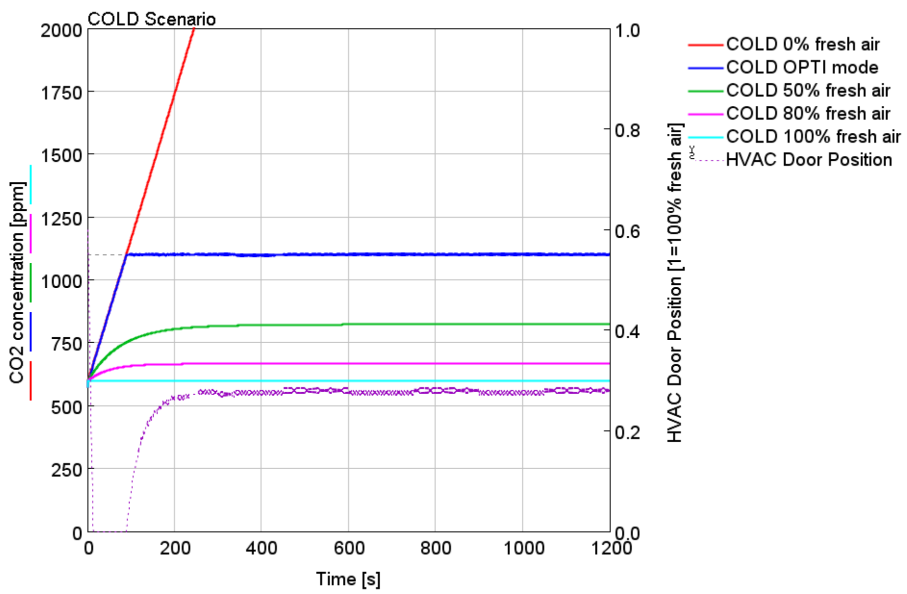

Figure 6: Cabin CO_2 concentration and HVAC door position in COLD scenario

Similar analysis can be performed for the HOT scenario (see Table 4). Results in the MEDIUM scenario are similar but with much less amplitude. Indeed the outside air and cabin temperature target being both at 19°C the heat pump has only to manage the heat input from passengers, solar flux and firewall source.

Table 4: Power analysis in HOT scenario

HVAC door position	100% fresh air	80% fresh air	50% fresh air	OPTI mode	0% fresh air
Compressor Power [kW]	3.05	2.44	1.92	1.61	1.15
Blower Power [kW]	0.13	0.13	0.12	0.12	0.12
Convective heat transfer at cabin side [kW]	-3.92	-3.33	-2.68	-2.27	-1.54
Convective heat transfer at outside air side [kW]	5.57	4.54	3.69	3.15	2.16
Compressor isentropic efficiency [%]	62.8	64.5	54.8	47.7	37.3

Eventually for the three scenarios the best optimization between cabin comfort and energy savings is achieved by setting the HVAC door position with the OPTI mode (stabilization at 30% of fresh air with two passengers). Compared with the common case 100% fresh air the power gains at compressor in COLD, MEDIUM and HOT scenarios are respectively 18%, 19% and 47%.

The consequences on the range of an electric vehicle can be roughly estimated using equation 1. The maximum range value is 300km, the specified range is 6.6km/kWh and the average speed is 33km/h.

$$Range_{gain/loss} = Range_{max} - \frac{Range_{max}}{1 + \frac{Spec_{range} * Power}{Speed}} \quad (1)$$

With this calculation the estimated range gain in COLD, MEDIUM and HOT scenarios are respectively 41km, 13km and 5km. Compared with the maximum range of an electric vehicle these values are relatively significant. The simulation results have shown that the FreciousSmart system linked with a smart control on the HVAC door position can accomplish a healthy cabin comfort while considerably reducing the energy consumption of a heat pump system used to heat or cool the cabin.

5 Conclusion

Lots of efforts are done today to reduce the sources of pollutants in cities and their impact on human health. At least in the transportation domain, it is known that changing from conventional combustion engines to electric mobility will not be enough, as it remains particles coming from mechanical wear (braking systems, tires, turning parts, etc…). More generally, it is also necessary to protect people from pollutants coming from industry and building heating systems. All the measurements done continuously until today concerning air quality are accelerating the end consumer acceptance to ask for new value and mobility services, as at least to be better protected against external pollutants during the transportation. MANN+HUMMEL has developed different technologies in cabin air filtration domain to solve some of the challenges. First, it is then possible to offer a better protection based on biofunctional filtration technologies to protect passengers from allergens, microorganisms and from VOC, and second an advanced control and reduction of fine and ultra-fine dust particles and external gases (NOx, NH_3, …). Those technologies concerning HEPA filtration and smart control are requiring sensors and active flaps to monitor pollution level inside the cabin. Even more, it is possible to use CO_2 and humidity sensing inside cabin, to minimize air recirculation, and then to reduce the required energy for thermal comfort. Targeting then some set points given by numerous health studies for the different pollutants and gases, different strategies for air flow control through the different possible filters will be possible to maximize the thermal comfort and air quality, consuming less energy as possible. As shown in this article with system simulation, the impact of air recirculation ratio on energy consumption is really important and more significant for battery electric vehicles. This system approach using simulation for joining thermal comfort and air quality is needed not only for proving additional value to end consumer, but also to create new specifications, at least for new filters, new sensors, and components used in HVAC systems.

Acknowledgments

The work in this article is done in a joined International Teaching and Research Chair entitled "Innovative Intake and Thermo-management Systems" between MANN+HUMMEL and Ecole Centrale de Nantes. The authors want to thank Dr Haitham Mezher and Gamma Technologies for their technical contributionList acknowledgments here, if appropriate.

References

[1] Kunzli et.al., 2009, *Evidence based public health - the example of air pollution*

[2] Kuenzi et.al., *Responses of lung cells to realistic exposure of primary and aged carbonaceous aerosols*, Atmos. Environ., 68, 143–150, 2013.

[3] World bank report, 2016

[4] Usha S., *Is CO2 an Indoor Pollutant? Direct Effects of Low-to-Moderate CO2 Concentrations on Human Decision-Making Performance*, Environmental Health Perspectives • volume 120 | number 12 | December 2012

[5] Heininger T., et.al., *From Good to Best: New Cabin Air Filters for Cleaner Air*, FKFS2017

[6] DIN EN 1822-1:2011-01, *High efficiency air filters (EPA, HEPA and ULPA) - Part 1: Classification, performance testing, marking*; German version (EN 1822-1:2009)

[7] Piry, A., et.al. (2011). *Improved Protection from Allergens Due to Cabin Air Filters with Polyphenols*. ATZ worldwide eMagazine. 113. 28-31

[8] UK Department for Transport statistics, Table NTS0905, retrieved January 15, 2018, from https://www.gov.uk/government/statistical-data-sets/nts09-vehicle-mileage-and-occupancy

[9] UK Department for Transport statistics, Table NTS0906, retrieved January 15, 2018, from https://www.gov.uk/government/statistical-data-sets/nts09-vehicle-mileage-and-occupancy

[10] Satish U,. et.al. *Is CO2 an Indoor Pollutant? Direct Effects of Low-to-Moderate CO2 Concentrations on Human Decision-Making Performance*. Environmental Health Perspectives 2012;120 (12):1671-77.

Authors

Bernd Bauer studied process engineering at the Nuremburg University of Applied Sciences. He started his career at MANN+HUMMEL in 2007 as a development engineer and project manager for cabin air filters. Since 2014 he leads the Design Department for Cabin Air Filters at MANN+HUMMEL, Germany.