Interior air conditioning for electric vehicle EVA

New approach on vehicle interior cooling to increase comfort and reduce energy consumption

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***Abstract*— TUM CREATE's EVA is a fully electric, purpose built electric taxi. One main feature is the novel cabin air conditioning. In this paper this new concept is explained which aims at the improvement of thermal comfort at reduced energy consumption. The focus is on cooling in hot and humid ambient conditions. Starting from a standard Heating, Ventilation and Air Conditioning (HVAC) unit, a fully independent four zone air conditioning is realized by designing a new air distribution box. Air outlets in the roof enable local cooling close to the body. The challenge of the geometrical integration of the air ducts and outlets is discussed and evaluated to minimize noise, reduce unwanted heat loss and prevent discomfort through draught. The seats provide passive and active ventilation. The choice of cover and cushion material and the integration of fans meet the problem of thermal discomfort through high contact surface temperatures and increased sweat production.**

Keywords—thermal comfort; car air conditioning; human thermal modeling

I. INTRODUCTION

The present work was conducted within TUM CREATE, a research collaboration between Technische Universität München (TUM) and Nanyang Technological University Singapore (NTU), funded by Singapore's National Research Foundation (NRF). TUM CREATE's areas of research focus on electromobility from the molecule to the megacity. For the past two years about 30 research associates and young professionals within TUM CREATE have been working on the project EVA, an electric taxi for tropical megacities. Key features of the vehicle include super-fast charging, a novel air conditioning concept, lightweight carbon reinforced plastic (CFRP) body, innovative child seats and a personalized infotainment system. This paper focuses on the reasons, the concept and the realization of the interior air conditioning of EVA.

Main focus in the design of the interior climatization lay on maximizing the thermal comfort. According to the Comfort Pyramid by Bubb (Figure 1), thermal comfort takes up a significant role in the overall feeling of comfort. Absence of thermal comfort or even existence of thermal discomfort is more notable than discomfort arising by anthropometric collisions. Considering the safety issues in a driver's workplace a fully functioning and well-tuned HVAC system is mandatory to ensure the driver's alertness at all times.

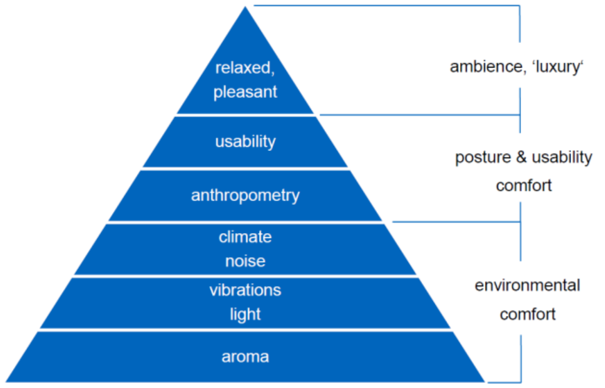

Figure 1: comfort pyramid according to Bubb [1]

Furthermore the HVAC is a car's biggest auxiliary energy consumer. Rising gas prices and the coming of electric vehicles demand a significant increase in energy efficiency. Heating and cooling have a very notable effect on the overall energy consumption by reducing the vehicle range significantly. Heating or cooling the whole cabin is an unnecessary waste of energy. This can be prevented by conditioning the air zonally and localized.

In chapter II, the fundamentals necessary for the layout and design of the system are explained. Basis is thermal sensation, that is to say the perception of warm and cold. It is important to know the body's static and dynamic response on local and global temperature changes. Based on the thermal sensation a person will feel thermal comfort or discomfort globally as well as locally. A zone of thermal comfort is defined that sets the basic aspired state of the cabin conditions. The basics of heat and mass flow are used to set the parameters needed to achieve and maintain these conditions. Fundamentals of pipe flow are essential to dimension the air ducts geometry.

Chapter III addresses relevant state of the art regarding the HVAC system and chapters IV through VIII describe the system as it is implemented in EVA.

Finally Chapter IX gives a conclusion and lessons learned as well as a future outlook on ongoing and planned work.

II. FUNDAMENTALS

A. Thermal Sensation

Thermo receptors in the skin are responsible for the registration of hot and cold environments. The distribution of both receptor types over the body is inhomogeneous as seen in Figure 2 for the case of cold receptors. The intensity of the response and with it the tolerance of cold is dependent on the density of receptors on the affected body part. Chin, mouth, nose and neck are the most sensitive areas, hand and fingers the least perceptible to cold and can thus endure lower temperatures.

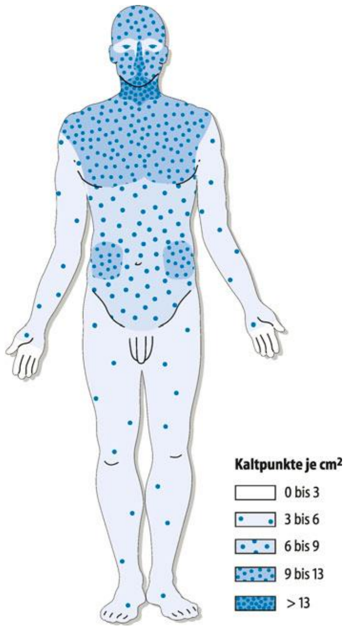

Figure 2: Distribution of cold receptors [5]

Figure 3 shows the response of cold and warm receptors over the mean skin temperature. Cold receptors are activated by cooling down and warm receptors by heating up.

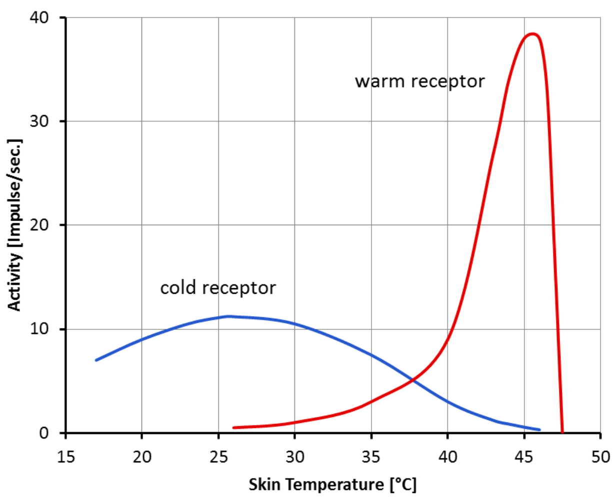

Figure 3: Static esponse of cold and warm receptors [6]

Skin temperatures between about 31°C and 36°C lie inside the zone of indifference and are percieved neutral. Everything above and below is perceived as permanently warm and respectively permanently cold.. Figure 4 shows the change in thermal perception depending on the initial skin temperature. A change in temperature that crosses the threshold will trigger a dynamic receptor response.

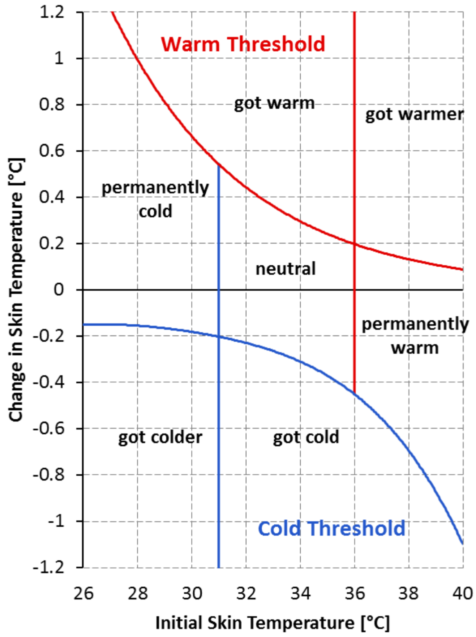

Figure 4: Warm and cold thresholds depeding on initial skin temperature [5]

B. Thermal Comfort

The expression thermal comfort is described in the DIN EN ISO 7730 as “that condition of mind, which expresses satisfaction with the thermal environment” [2]. It is affected by various environmental and human factors such as temperature, humidity, air flow, radiation, metabolic rate, clothing, sex, age and more.

To evaluate thermal comfort, FANGER [3] introduced the predicted mean vote (PMV) and the predicted percentage dissatisfied (PPD). The PMV gives a notion of user acceptance in terms of thermal sensation. It is expressed on a seven-point comfort scale which ranges sensations from hot to cold. The PMV is calculated by complex equations regarding the values of heat conduction, convection and radiation, the metabolic rate, clothing factor, ambient temperature and humidity and air movement. The PPD is consecutively giving information about how many people are experiencing the given conditions as too hot or too cold.

The PMV requires very detailed input about ambient conditions and state of the affected person. The definition of comfort zones describes an easier method for rough estimations of comfortable climate. The comfort zone is defined as the “range of environmental conditions within which the average person would feel comfortable” [8]. While there are multiple approaches to define the comfort zone, this paper is in line with the approach of Auliciems & Szolokolay [13]. The comfort zone is herein drawn with equal-comfort-lines using the new effective temperature ET*. It is defined as the "temperature of a uniform enclosure at 50% relative humidity, which would produce the same net heat exchange by radiation, convection and evaporation as the environment in question". For Singapore the mean temperature of $\vartheta_m = 28°C$ leads to a neutral temperature of

$$\vartheta_n = 21.5K + 0.11\ \vartheta_m = 24.6°C. \qquad (1)$$

This temperature marks ET* at a relative humidity of $\varphi = 0.5$ and a condition of PMV = 0. The calculation of the comfort lines can be found in [14] and is done by iteration with the algorithm

$$\vartheta_{ET^*,\ \varphi=0} = ET^* + 0.023\ (ET^* - 14K)\ x_{ET^*,\ \varphi=0.5} \qquad (2)$$

with the relative humidity φ and the dry globe temperature ϑ. To create a comfort zone of 90% acceptability the equal-comfort-lines are expanded with an ET* range of ±1.2K.

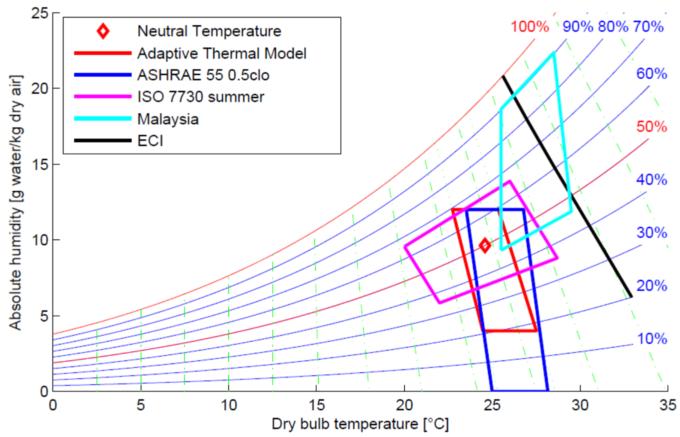

Figure 5: Psychometric chart and comfort zones

The limits of humidity are given at absolute humidity $x_{low} = 4^{g}/_{kg}$ and $x_{high} = 12^{g}/_{kg}$. The upper limit marks the vapor pressure above which sweat will not evaporate. The lower limit is due to non-thermal reasons to prevent drying out of the skin or irritation of the eyes. The AC control in EVA aims to condition the air to stay within these limits close to the neutral temperature. Figure 5 shows the resulting comfort zone for 80% acceptability (Adaptive Thermal Model) compared to a selection of different comfort zones.

TABLE 1: COMPARISON OF RESIDENTIAL AND AUTOMOTIVE A/C [7]

parameter	***residential air conditioning***	***automotive air conditioning***
Volume of structure	≈ 30 m³	≈ 3 m³
Volume per person	≥ 10 m³	≈ 0.6 m³
Air velocity from outlets	≈ 0.2 m/s	≤ 5 m/s
Air exchange number	2 – 8 h^{-1}	10 – 200 h^{-1}
Distance to surrounding surfaces	≥ 1 m	≈ 0.2 m
Temperature field	almost homogeneous	inhomogeneous
Current field	almost homogeneous	inhomogeneous

Predictions of thermal comfort by the above mentioned methods are applicable for uniform conditions as might occur in open surroundings or buildings. Conditions in a car however differ significantly to that. As seen in Table 1, thermal conditioning will mostly be localized with high gradients in temperature and air speed. Thus the thermal perception has to be assessed locally as well as globally. Thermal comfort is consecutively also divided in local and global perception.

C. Local Thermal Comfort

Local thermal comfort phenomena are manifold and still subject to ongoing research. At the institute of ergonomics (LfE) studies were conducted that evaluate the influence of local conditioning on the overall comfort. It was shown, that the dynamic receptor response in one body part could have significant impact on the global thermal comfort. The strongest effect for cooling was noted at the head, followed by the upper and lower torso.

D. Heat and mass flow

To establish a climate inside the thermal comfort zone, an evaluation of heat and mass flow balance will give information about the input parameters temperature, mass flow and humidity. The control volume is defined to enclose the interior of the passenger cabin as well as the pipework as seen in Figure 6. Thus heating up of the air flow inside the ducts is neglected.

Two scenarios for Singapore are calculated: a worst case scenario assuming a sunny day and four passengers in the car, and a best case scenario with one passenger on a cloudy day. The derivation is too extensive to be presented in this paper. The mass flow is taken from Grossmann [7] and represents a typical air flow required for cooling and ventilating. For the two cases the temperature after the HVAC unit is then derived as $\vartheta_{in\ worst\ case} = 8.5°C$ and $\vartheta_{in\ best\ case} = 22.3°C$. These values are calculated to condition the whole passenger zone and have to be adapted with local comfort studies.

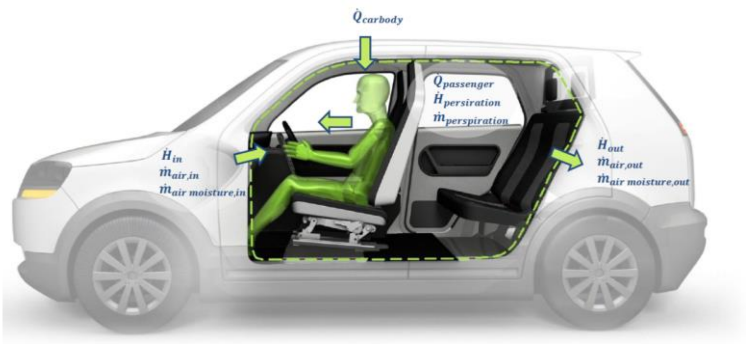

Figure 6: Heat and mass flow balance of the control volume passenger cabin

E. Pipe flow

Air inside ducts of the air conditioning system undergoes pressure losses due to turbulence and stall like any kind of flow streaming in pipework. These pressure losses define the possible maximum mass flow and the distribution of mass flow in different branches.

Pressure losses in pipe flow by wall friction are described as

$$\delta p = \lambda \cdot l / d \cdot \rho / 2 \cdot q^2 \quad (3)$$

with the coefficient of pipe friction λ, length of the pipe section l, the pipe diameter d, the fluid density ρ and the mean fluid velocity q. In case of a non-circular cross section, the hydraulic diameter is used

$$d_{hydr} = 4 \cdot A_f / l_f \quad (4)$$

A_f denotes the cross section passed by the fluid and l_f the wetted perimeter.

The pipe friction λ is calculated according to the degree of turbulence in a pipe. This is determined by the dimensionless Reynolds number Re and the pipe roughness k_s. According to Grossmann [7], air flow in cabin air ducts can be regarded as rough and turbulent. Thus pipe friction is calculated with

$$\lambda = (1.14 - 2 \cdot \log_{10} (k_s / d))-2 \quad (5)$$

This method does not take all hydrodynamic effects into account. It is however a reasonable approach for estimation of occurring pressure losses. To obtain exact results numerical simulation is inevitable.

III. State of the Art

HVAC systems follow the same pattern. Figure 7 shows one HVAC unit and air distribution on the example of a VW Touareg. A centralized HVAC unit located under the dashboard manages all functions needed for providing conditioned air in the car's interior. Air is usually drawn from the outside. Most modern systems feature a recirculation flap to reduce energy consumption by reusing the cabins air. The air passes a blower and a filter and is then directed through the evaporator where it can be cooled. After that it can be heated or re-heated and is then distributed to the air outlets.

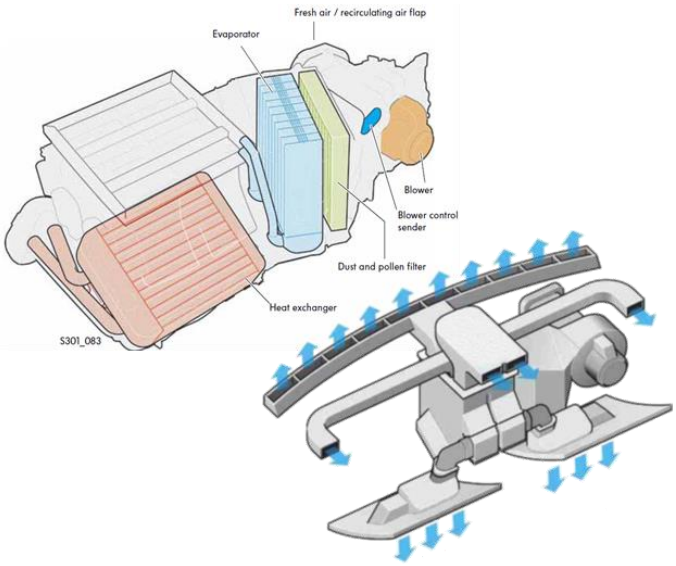

Figure 7: HVAC unit and air distribution of a VW Touareg [9]

A. Air Cooling

Core of modern so called "air conditioning" (AC) units is a standard refrigeration cycle. By switching between a high and low pressure side, the condensation enthalpy of the refrigerant is used to transport thermal energy from a colder to a warmer environment. Standard refrigeration cycles use the hydrofluorocarbon R-134a or the highly disputed hydrofluoroolefin R-1234yf [10] [11]. An alternative can be found in CO_2 which requires an adapted cycle running on higher pressure levels [12].

B. Air Heating

In standard combustion engine cars heating is provided by the waste heat of the motor. A heat exchanger in the HVAC module is linked to the engine cooling cycle. Vehicles with a diesel engine face the problem of a slow motor heat-up. They often feature an additional electric positive temperature coefficient (PTC) heater to provide heating from the start.

C. Air Distribution

Simple HVAC units are only able to regulate air temperature for the whole cabin. The air is distributed by air flow flaps, via air ducts in the dashboard and through outlets which often feature manual flow direction air foils.

D. Automatic Control

Thermal comfort is ensured by setting the cabin's temperature to a globally satisfying value. Locally discretised comfort phenomena are often not or only vaguely taken into account. AC automatics are based on settings of test drivers and medical common knowledge ("head cool, feet warm"). Some advanced HVAC systems feature a dual-zone control by separating the air flow after the evaporator in left and right side. In some premium class cars a second HVAC unit can be found in the rear to achieve a four zone control.

E. Roof Outlets

While most vehicles spot a horizontal air distribution (from dashboard outlet directed at feet, torso and head), there is only a small number that is outfitted with roof outlets to support a vertical air flow. These are most often located in the B-pillar and seldom in the ceiling. Several U.S. patents held by Mazda Motor Corporation [16] are concerned with a roof cooling located between sunroof and sunshade which target similar goals as the concept described here.

F. Seat ventilation and cooling

Automotive seats with active or passive cooling are not a new development. The first active seat climate control in series production cars was introduced in the late 1990s. The most common implementation is built-in fans in or under the seat cushion. Air is blown through perforated leather or fabric covers to the passenger's body. Moisture and heat accumulations are reduced significantly.

IV. CONCEPT IN EVA

Every passenger inside the car has to be able to have climate conditions that meet his expectations of comfortable climate. To achieve this, the car is divided into four zones. The air for each zone is conditioned individually to the requirements of the passenger. The idea to include a second HVAC unit for the rear passengers was discarded due to weight, package and effort reasons. A new air distribution box is engineered to provide individual air flow to four zones.

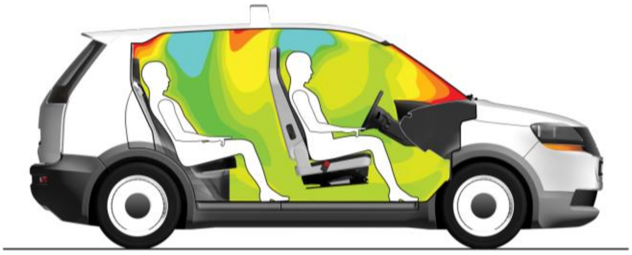

Figure 8: Temperature layering in individual climate zones inside the cabin

While standard air distribution into a car's interior is provided from front to back (horizontal), the approach in EVA is an air distribution for cooling from top to bottom (vertical, Figure 9). Large area overhead outlets provide a uniform, draught-free "cold air shower". This aims to create a temperature layering inside each zone. Cooling the head and upper torso supports the goal of creating global thermal comfort by conditioning locally where needed.

To support the vertical air movement, air is drawn into the seat and away from the passenger. Outlets in the dashboard directed at the passengers' torso are built in to cover thermal peak loads. The basic HVAC unit is a take-over part from a donor vehicle. It includes the recirculation flap, the filter and the evaporator. The pressure outlet is located under the rear bench.

Figure 9: Air distribution in EVA interior

V. AIR DISTRIBUTION BOX

The electric taxi prototype EVA is outfitted with only one HVAC unit located under the dashboard. To be able to control four passenger zones individually the air flow is divided in four branches after the condenser (Figure 10).

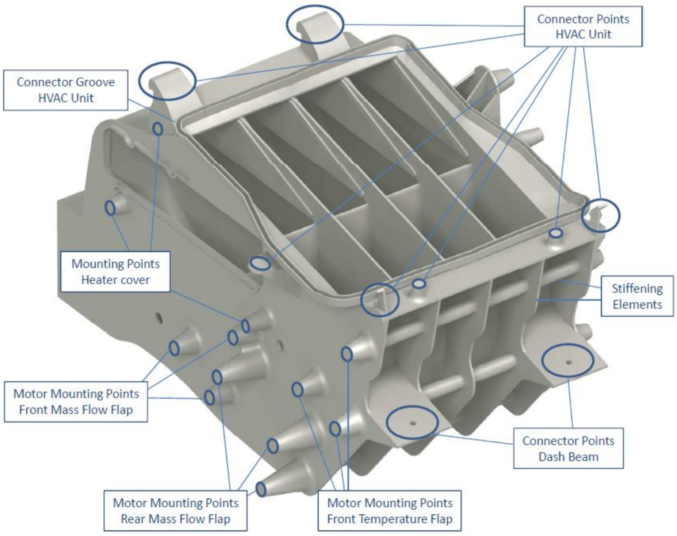

Figure 10: Air distribution box with four air paths

The air flow inside the distribution box is shown figuratively in Figure 11. In each branch the air flow is then guided by the temperature flap either through the heater or past it. The mass flow ration between the branches is regulated by four mass flow flaps.

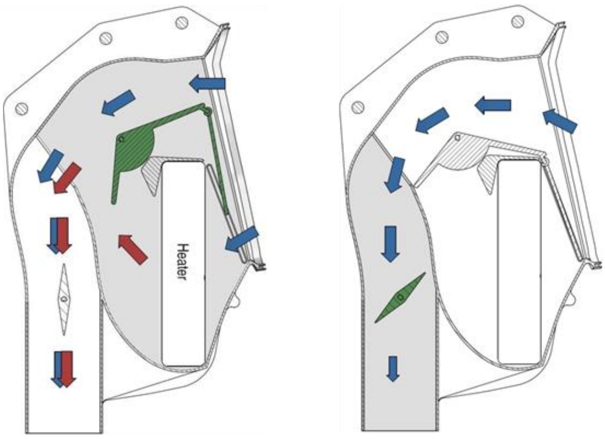

Figure 11: functionality of temperature flap (left) and mass flow flap (right)

Each flap is driven by its own servomotor. Since all flaps are parallel on the same rotational axis, the flap for the inner branch is rotated via a shaft inside the hollow shaft for the outer flap (Figure 12).

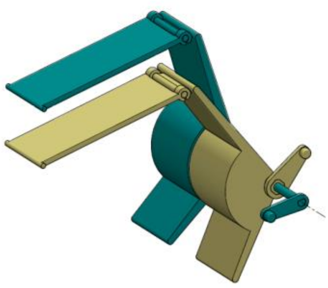

Figure 12: Assembly of the temperature flaps

To manufacture the housing of the air distribution box it is sectioned in multiple segments (Figure 13). Each segment is CNC milled out of acrylonitrile butadiene styrene (ABS) and glued together.

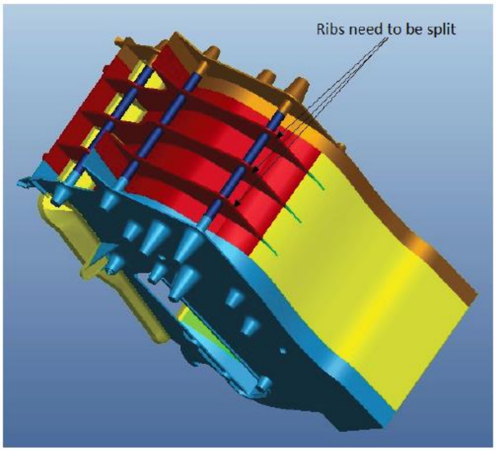

Figure 13: sectioning of the housing

VI. Ducting

As there is no need for defrosting in Singapore, the conventional outlets at the windshield are discarded. The same applies for outlets in the footwell as heating is not required and ergonomic studies at the LfE have shown that cooling the legs can have a contra productive effect on global comfort.

A. Layout and dimensioning

To prevent annoying noise the air flow inside the air ducts should not exceed a velocity of $v_{max} = 5^{m}/_{s}$ [15]. Since this information was not available for air conditioning in cars it is adapted from air conditioning in buildings. With an assumed maximum air flow of $\dot{m}_{air} = 5^{kg}/_{min}$ and the density of the air flow $\rho = 1.2^{kg}/_{m^3}$ the minimum pipe cross section is calculated for all cabin air ducts in total.

$$A_{min} = \dot{m}_{air} / (\rho \cdot v_{max}) = 0.014m^2 \quad (6)$$

The air path is however split up to feed four zones which in turn are also divided into torso and overhead cooling outlets. The cross-sections are calculated linear to the desired mass flow at the respective outlet. Due to package reasons the air ducts have to be designed in complicated shapes at space critical points. However, to minimize pressure losses, the cross-sections are aimed to be if not square at least quasi-quadratic. Critical areas are below the drivers' box in the central console, close to the HVAC unit in the dashboard and inside the b-pillar. The pressure loss has to be the same in each of the four branches to provide the same mass flow for each zone.

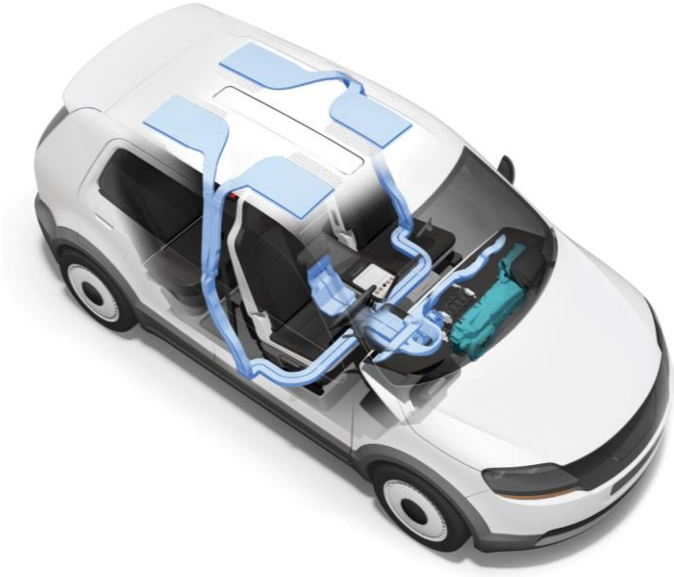

Figure 14: Pipework inside EVA

B. Implementation and manufacturing

As can be seen in Figure 14 and Figure 15, the inner branches are providing the rear passengers with air and the two outer branches supply the zones for driver and co-driver. The air ducts for the torso outlets are straightforward: The outlets for driver and co-driver and the ducts connecting them are under the dashboard. The outlets for the rear bench passengers and the ducts connecting them are in the centre console.

The piping up to the roof outlet is comparably more difficult. To reach the roof, the air ducts have to be guided along the A-, B- or C-pillar. This can make them unnecessarily thick and may lead to obstructed visibility, especially at the A-pillar. Since the B-pillar has to have a certain thickness to meet side crash requirements the idea was to guide the air ducts inside the structure. The ducts to the roof are split of the main branches inside the middle console, are then guided under the front seat structure into the side sill, from there into and up the structure of the B-pillar and leave it again after splitting up into the sandwich between roof structure and ceiling.

As can be seen in Figure 15, the ducts are sectioned in 42 parts to ensure assembly in the vehicle. For easy connectivity, the ducts are equipped with flanges and simply have to be stuck together. The geometrically simple parts of the air ducts are produced by thermoforming polyethylene (PE). More complex parts are produced by selective laser sintering (SLS) of nylon plastic.

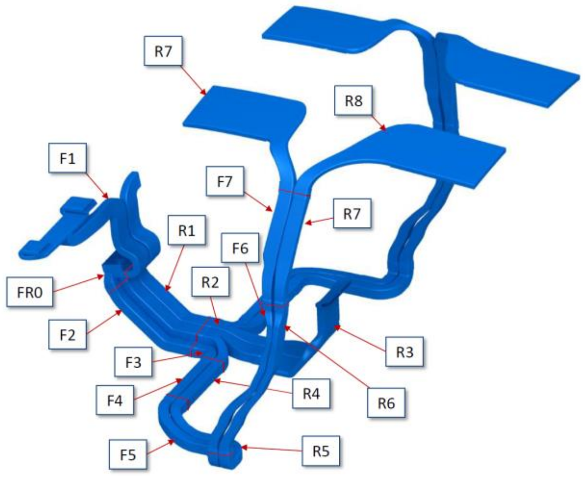

Figure 15: Pipework assembly with sectioning

C. Air Outlets

The outlets directed at the torso are simple directed air ducts with an air foil grille to guide the flow and prevent objects or fingers to access the duct. At the roof outlet, the air passes through small holes in the ceiling (Figure 16). To achieve an air flow like a "cold-air-shower" at the roof outlet, the area of the outlet has to be wide. A cross-section of 300mm x 350mm was chosen to cover the head and the shoulders for all passengers. This also has to cover the position of drivers with different anthropometrics and therefore the adjusted seat positions. The area and hole sizes are furthermore defined according to the draught limits [17]. Even if a person is sitting very close to the outlet, the draught limit at the defined maximum air flow is not exceeded.

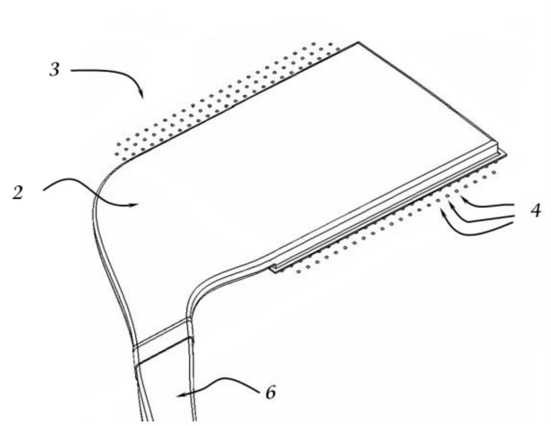

Figure 16: Roof outlet (2), ceiling (3) perforated with holes (4), air duct from B-pillar (6)

D. Flow simulation

To verify and adapt the design before manufacturing a numerical simulation is inevitable. The Simulation is conducted in ANSYS Fluent. The simulations for the air flow through the duct show a satisfying result. Air speed is kept below $5^{m}/_{s}$ at all places. The air flow at the outlets is below the critical draught limit of $0.15^{m}/_{s}$ [17]. Flow direction at the outlet is vertical as intended and velocity distribution is uniform. The pressure losses in the branches are identical and thus the air distribution will be uniform at equal mass flow flap positions.

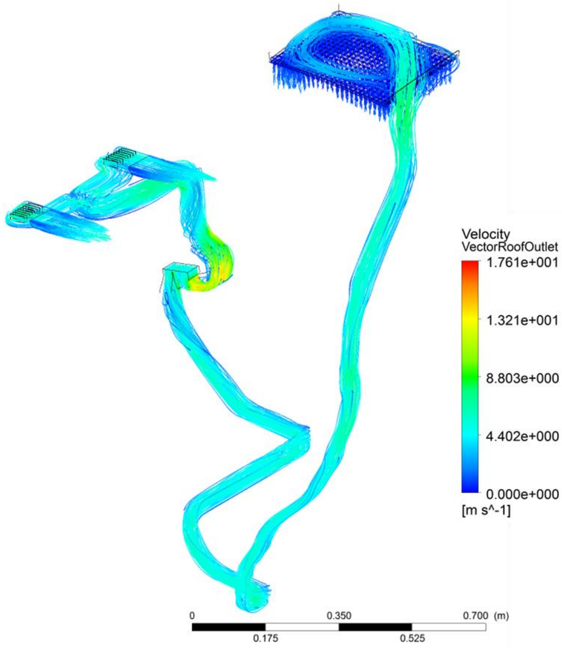

Figure 17: Simulation of flow velocity inside the front ducts

VII. SEAT VENTILATION

At very hot and humid conditions in Singapore, passengers are likely to enter the car overheated and transpiring. Sitting down on a car seat, especially a leather or fake leather seat can result in high levels of discomfort. Thus the seats feature built in ventilation. The blowers are located under the seat and draw the air away from the heat spots of the seating surface and the backrest. The decision of drawing air away rather than blowing cool air out of the seat is due to the effect of evaporative cooling. If the degree of transpiration cannot be measured, the cooling effect by evaporating sweat is difficult to control. By drawing air and moisture away, this effect is diminished and unwanted overcooling causing high discomfort is prevented.

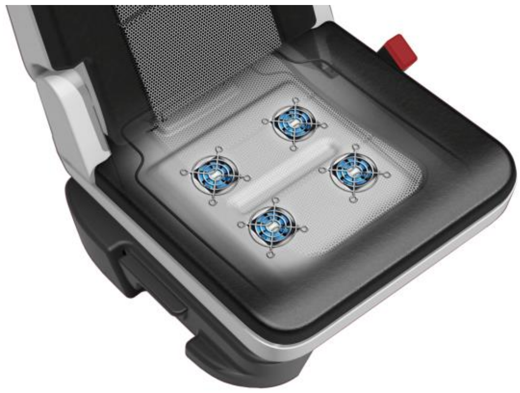

Figure 18: Ventilated front seat

Each seat sports four blowers in the seating surface (Figure 18). Two more blowers draw air away in each back rest of the rear bench seats. The front seats do not yet have active back rest ventilation due to difficulties in the development process. This is a feature that can easily be integrated in a revised version. The fan speed can be adjusted in three levels to suit individual needs: high, medium and off. The values were determined in mock-up tests and have to be validated in a full vehicle test setup.

To ensure a comfortable microclimate, the cushion material should be as highly vapour-permeable as possible [18].Instead of foam, the seat is equipped with a warp-knitted 3D spacer fabric. It is composed of two reticular top and bottom layers that are kept apart by polyester microfilaments. It acts as an air distribution layer to ensure that the relatively punctually extracted air is distributed over the entire seat surface. Even if the blowers are not operating, passive convection will allow a comfortable microclimate at the contact areas between passenger and seat.

VIII. Control Strategy

Advanced AC automatics are able to calculate the most energy saving operation mode for the given settings [19]. In this matter, it is important to ask the question: How well can a passenger target the optimal settings manually? How much freedom of control should then be given to the passenger?

In EVA the controls for air conditioning are kept at a minimum. The AC automatic calculates the optimum settings according to ambient and interior conditions. The default setting is the calculated "neutral comfort" state. The only manual possibility to influence the system is a scale inspired by Fangers PMV: The passenger can state his thermal sensation (too warm/hot, too cool/cold) and the system is adapting the output accordingly inside the calculated comfort range.

The controls are implemented on a display located in the center console, the central information screen (CIS), as well as in the passengers smartphone. The passenger can activate, adapt and deactivate the climate control for his/her seat. The driver has the possibility to change the settings for each seat via the CIS. Figure 19 shows two versions of the control visualization for CIS and smartphone.

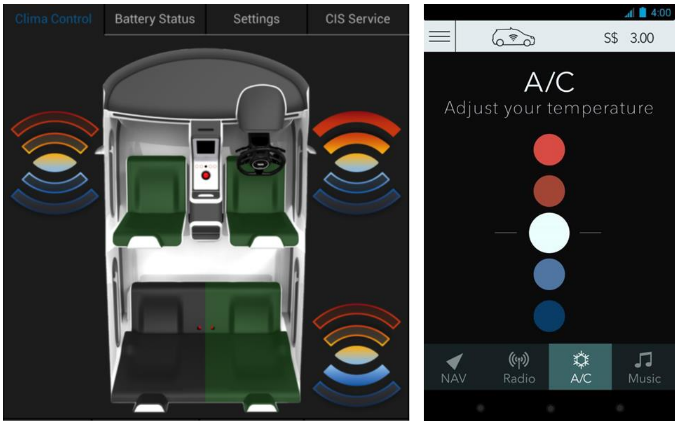

Figure 19: AC control on the CIS (left) and the passengers smartphone (right)

IX. Conclusion and Outlook

Based on the initial concept a coherent system has been developed. This system has been built up and integrated into a working prototype which was showcased at the Tokyo Motor Show in November/December 2013. Still some drawbacks occurred. Since a timespan of two years to develop a car from scratch is very short and the team only consisted of about 30 people plus around 40 students, a lot of good ideas had to be discarded. Also many steps had to be taken based on engineering practice to fulfil deadlines that would have been worth to be considered more closely and thoroughly. As an example the numeric flow simulation was only conducted for vital sections. A closer look at local phenomena e.g. at the outlets or inside the mixing chamber could be of interest. Also a lot of time was lost on the production process. Early order of test pieces is vital to discover design flaws and develop a valid time plan.

Alongside the main system a number of mock-ups were set up. A scientific evaluation was often not possible due to the progress of the project. Small principle studies were undertaken to get the necessary input for the engineering process. The mock-ups are currently adapted and will be tested in a climate chamber to get more detailed information. One example is a seat mock-up with relocatable fans and adaptable fan speed as well as temperature. With the obtained findings the parameters can be adjusted and the respective sub-system can be refined. With the collected results, the system in EVA will be fine-tuned and tests will be conducted with the vehicle on the road as well as in a climate chamber.

Acknowledgment

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References

[1] Bubb, H. Komfort und Diskomfort. Ergonomie Aktuell Ausgabe 4. 2003

[2] DIN EN ISO 7730, Ergonomics of the thermal environment.

[3] Fanger, P.O., Thermal Comfort: Analysis and Applications in Environmental Engineering, New York: McGraw-Hill, 1972.

[4] BMW GROUP. Der neue BMW 7er. Entwicklung und Technik. 1st ed. Wiesbaden: Vieweg + Teubner 2009. ISBN: 3-8348-0773-1.

[5] Schmidt, R. F. Lang, F. Heckmann, M. Physiologie des Menschen. 31. Auflage. Heidelberg: Springer. 2010. ISBN-13: 978-3-642-01650-9

[6] Klinke, R. Baumann, R. Physiologie. 6. Auflage. Stuttgart. Thieme. 2010. ISBN: 978-3-13-796006-5

[7] Grossmann, H. Pkw-Klimatisierung. Physikalische Grundlagen und technische Umsetzung. Heidelberg: Springer. 2010. ISBN: 3-642-05494-5.

[8] Olgyay, V. Design with climate. Princeton Uni. Press, Princeton, N.J. 1963

[9] Volkswagen AG. Touareg Heating/air-conditioning system. Design and function. Self-Study Programme 301. Wolfsburg. 2002.

[10] 2006/40/EG Richtlinie des europäischen Parlaments und des Rates vom 17. Mai 2006 über Emissionen aus Klimaanlagen in Kraftfahrzeugen und zur Änderung der Richtlinie 70/156/EWG des Rates

[11] BAM (2010) Ignition behaviour of HFO1234yf. Berlin www.umweltbundesamt.de/sites/default/files/medien/419/dokumente/test_report_hfo1234yf_2010_06.pdf

[12] Burger R (2000) Das Kältemittel CO2 im Vergleich zu R134a. In: Reichelt J (Hrsg) Grundlagen der Pkw-Kälte-Klima-Anlagen. Lehrgang im Test- und Weiterbildungszentrum Wärmepumpen und Kältetechnik, Karlsruhe

[13] Auliciems, A.; Szolokolay, S. V. Thermal comfort. 2nd ed. Brisbane, Qld: PLEA in association with Dept. of Architecture. 2007. ISBN: 0-86776-729-4.

[14] Rohles, F. H.; Hayter, R.B.; Milliken, G. Effective Temperature (ET*) as a predictor of thermal comfort. ASHRAE Trans. 81 (pt.2): 18-156 1975.

[15] SBZ Monteur. Hydraulischer Durchmesser. Kanäle für die kontrollierte Wohnraumlüftung. <http://www.gentner.de/gentner.dll/14-17-sbz-m-2011-10-1017-Kanaele-Wohnraumlueftung_MzMxODEw.PDF> - 13.04.2013.

[16] Masaya, W.; Takako, I. Air conditioning system for automotive vehicle. U.S. Patetnt 6,282,911 B1 filed January 14, 2000, and issued September 4, 2001.

[17] Fanger, P. O. Christensen, N. K. Perception of draught in ventilated spaces. Ergonomics. Volume 29:2. London: Taylor & Francis. 1986.

[18] Mecheels, J. Körper, Klima, Kleidung: Grundzüge der Bekleidungsphysiologie. Berlin. Schiele & Schön. 1991.

[19] Khayyam, H., Kouzani, A. Z., Hu, E. J., Nahavandi, S., Coordinated energy management of vehicle air conditioning system, Applied Thermal Engineering, Vol. 31, Iss. 5, 2011: 750-764.