IMPROVING ENERGY EFFICIENCY OF CAR CLIMATE CONTROL WITH SLS

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Abstract

In Europe, passenger cars are responsible for 12% of CO_2 emissions. The European Commission established new regulations to drastically reduce the emissions from 130g to 95g CO_2 per km between 2015 and 2021. While the automobile industry is looking at different ways to meet those criteria, the presented industry-driven project aims at reducing energy consumption by up to 30% of air-conditioning (AC) in passenger cars with the introduction of a novel system. The current systems reduce the fuel economy to up to 20% for gas motors and even more for electric cars. Through Selective Laser Sintering (SLS) design freedom and short production cycles; the design of the AC casing was drastically optimized to increase its contact area with incoming air. To further increase the heat exchange throughout the system, the thermal conductivity of SLS material was improved by incorporation of mineral fillers. The successful implementation of both optimizations led to a CO_2 emission reduction of around 50% for the climate control of passenger cars.

Introduction

The emission of greenhouse gases into the atmosphere is believed to be one of the key reasons for the steady increase of temperature throughout the globe provoking an increase in climatic catastrophes. In 2012 within the European Union, the overall emission of carbon dioxide, the main greenhouse gas, attained a value of 3.8 billion tonnes from which 12% originated from passenger cars [1]. To tackle this problem, the European union has set emission reduction targets of 130g CO_2/km by 2015, lowering even further to 95 g CO_2/km in 2021 [2]. The automotive industry investigates different ways of increasing the energy efficiency of their fleet like weight reduction, optimization of combustion engine or develops viable electric/hybrid cars concepts. Farrington [3] showed that using air conditioning could reduce the fuel economy of mid-size passenger cars by 20% and even limited the autonomy range of an electric Mitsubishi iMiev by 46% [4]. The potential energy savings are important when improving AC in passenger cars; the herein presented project combines thermodynamics with SLS to achieve this goal.

Conventional air conditioning systems take outside air in at the front window before being cooled down by the AC system and flood the passenger cabin. During summer, the sun radiation on the hood leads to increase in temperature of the air taken in as showed in Figure 1. This temperature difference decreases with increasing driving speed, however for "STOP and GO" situations, especially in cities, the energy increase of incoming air is important and directly affects the amount of energy needed by the AC to cool down the air taken in. The narrower the air intake, the less area will be affected by the radiations and the less the temperature difference will be. The current project aims at using cool air from the passenger cabin to counter the uptake of additional energy during suction before being brought to the AC evaporator and thus diminish the AC energy consumption as simulated in Figure 1.

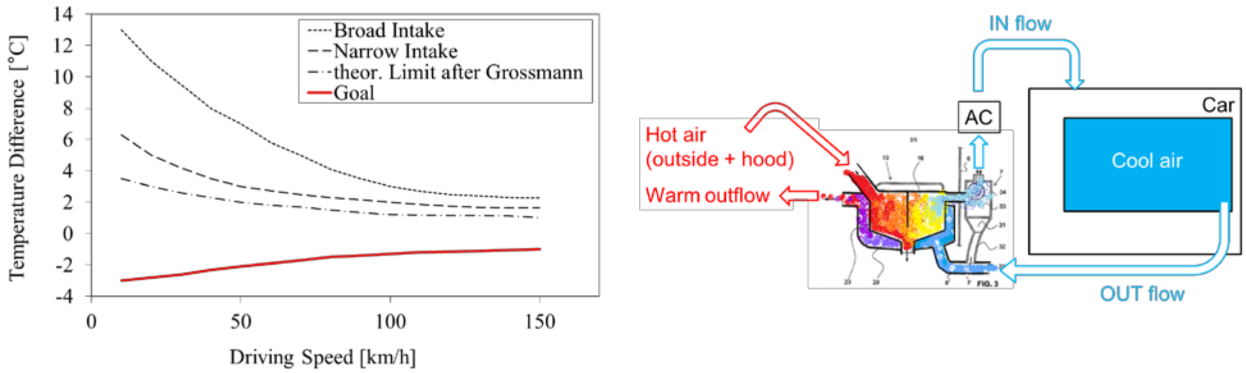

Figure 1 Left: Effect of air intake geometry on temperature difference between ambient outside air and air at partition wall depending on the driving speed adapted from Grossmann [5]; Right: Graphical representation of box configuration for pre-conditioning of air taken in at the front windshield.

The new AC concept is composed of an outer and an inner box as shown in Figure 1. The incoming air is suctioned through a narrow air intake at the front window, directed to the inner box and finally to the AC condensator. At the same time, recycled air from the passenger cabin, with comparatively much lower energy content, is expelled through the outer box surrounding the inner box. The inner box wall acts as "heat exchanger" and must therefore conduct heat well enough to optimize the exchange between the air fluxes. In comparison to the “air recirculation” option in cars, this novel system would hinder the need of removing of odours/exhalations of passengers as well as controlling humidity levels [6].

With help of design freedom enabled by SLS as well as its rapid implementation, different designs for the AC box are investigated to optimize its configuration for improving heat exchange between incoming and outgoing streams. The conventional injection moulded material to produce air ducts and air-water separation units for the climate control system used by the industrial partner is a talcum-filled polypropylene (PP). Therefore, the thermal properties of the SLS material should present similar values to this widely used material. For this purpose and due to the rather limited portfolio of available SLS materials, the development of potential novel SLS materials based on a novel SLS polyolefin, iCoPP presented by Schmid [7], is investigated. The resulting AC box will be tested in real conditions in a premium car and compared to conventional AC systems during standardized driving cycles. The tests will be conducted in a climate chamber rendering the conditions of a sunny summer day of Western Europe.

Methods

SLS Materials Development

The automobile industry uses polypropylene (PP) in combination with mineral fillers to increase different material properties. The injection moulding polypropylene of the industrial partner is filled with talcum and presents a thermal conductivity of 0.35 W/mK. Due to the low thermal conductivity of polyamide 12 (0.2 W/mK), the most used polymer for SLS, it will not be taken into account. To obtain an SLS material presenting such thermal conductivity, different mineral fillers have been considered for reinforcing iCoPP, a novel polyolefin suitable for the SLS process. The iCoPP is a polypropylene copolymer and currently the only SLS polymer on the market to present a combination of high elongation at break (~200%) and reasonable stiffness (800-1000 MPa). It was dry blended with the fillers to increase its thermal conductivity. Moreover, some other promising SLS materials available in the market were investigated and compared with the in-house developments. Table 1 summarizes the materials investigated for this project. The material TPP is a talcum reinforced PP produced by extrusion. Talcum is widely used to increase thermal properties in polymers. For this reason the optimal type of talcum to use, fine or coarse, for the SLS process was determined in a pre-screening round with fine Luzenac, with a D_{95} diameter of 7.7 μm, and Luzenac 1445, D_{95} of 49.2 μm. The impact on thermal properties and flowing behaviour of both types with iCoPP were determined. The finer talcum proved to worsen the flowability so much that it could not be measured on the RPA as well as shrink even further the sintering window; only the coarser talcum could thus be considered.

Table 1 List of the assessed materials during the project.

Obtained	Polymer	Type	Comments
Development	iCoPP	A1	polypropylene copolymer, $D_{50,vol}$ 47.3 µm
		A2	20wt% calcium carbonate ($CaCO_3$) surface treated (Omyafilm 753 – FL, Supplier: Omya, with $D_{50,vol}$ 3.2 μm)
		A3	20wt% talcum (Luzenac 1445,Supplier: Imerys, with $D_{50,vol}$ 15.6 μm)
	TPP	B	polypropylene reinforced by talcum, obtained by coextrusion, $D_{50,vol}$ 46.2 µm
Commercial	Microfol Sinterplast	C	polypropylene reinforced by glass beads, dry blend, $D_{50,vol}$ 68.1 µm
	Duraform HST	D	Polyamide 12 reinforced by mineral fibers, dry blend, $D_{50,vol}$ 60.5 µm

The characterization of a material suitable for SLS must not only take into account the powder properties but properties of the processed material as well; for the project the methods used to determine the powder and the processed material are presented in Table 2. The flowability of a powder is essential to help predict its processability while the DSC gives indications about the sintering window. The sintering window is the temperature range in which the semi-crystalline polymer is molten and has not yet begun its crystallization as detailed by Schmid [8]. This value is calculated by the difference between the onset melting and crystallization temperatures obtained during the DSC experiment ($(T_m-T_c)_{onset}$). The presence of foreign bodies inside the molten polymer leads to heterogeneous nucleation due to the diminution of the free surface energy at the interface filler-polymer and starts the crystallization at higher temperature [9].

Table 2 Characterization methods implemented during the project

State	Name	Method description	Measurement Conditions
Powder	Revolution Powder Analyser (RPA)	Backlit rotating drum to investigate the powder flowing behaviour [10]	25 ml powder, counting 128 avalanches at a rotation speed of 0.6 rpm
	Differential Scanning Calorimetry (DSC)	Determination of thermal and heat transition behaviour during heating and cooling	1st heating: 25 - 200°C, 10°C/min Cooling: 200-25°C, -10°C 2nd heating: 25-200°C, 10°C Nitrogen flow 50 ml/min.
Processed	Heat Conductivity	Modulated DSC determines the heat conductivity through a solid body	ASTM E1952-11
	Heat Deflection Temperature (HDT)	Temperature at which a material shows a certain deformation under a certain load	DIN EN ISO 75-2:2013-08/A (1.8 MPa).

The heat deflection temperature (HDT) is the temperature at which a slab, loaded with a defined charge, undergoes a given deformation. The HDT value of the industrial PP lies around 80°C. However, because the AC casing is not mechanically solicited and the comparatively short duration of the tests to a whole lifecycle of car components, the HDT values of the investigated materials should at least withstand temperatures of 50°C. The commercial materials (A1, C, and D) and the TPP (B) were produced on a DTM Sinterstation 2000 with optimized process parameters. The development materials A2 and A3 were extruded on a laboratory extruder at a temperature of 150°C using a rectangular die with an opening of 10x8 mm. This extrusion process was used in order to obtain a homogeneous distribution of the fillers inside the composites and therefore solely determine their effect on the thermal conductivity of iCoPP composites.

<u>Design Optimization</u>

The AC box was subject to design optimization in order to further increase the heat exchange between the air fluxes. Its design was modified using the software Solidworks and MAGICS. It was subject to certain restrictions to achieve its successful implementation under the car's hood. The dimensions had to show an optimal balance between the available place under the hood and the minimal volume to avoid a pressure drop within the aeration system. Secondly, there are only few SLS machines able to produce high volume parts and these machines generally process only the conventional PA12. This was the reason why multimaterial designs were investigated to optimize not only the volume and structure of the box but as well the heat exchange part. Finally the inner box should present the maximum contact area between the incoming and out coming air fluxes. Those optimization steps will be assessed by mounting the boxes in the car and measuring the fuel consumption and compressor voltage under real driving conditions.

<u>Test Cycles Measurements</u>

The energy consumption tests were conducted in real conditions with a Mercedes C-class during which the following parameters were measured: the fuel consumption, the temperature at partition wall as well as the compressor voltage. They took place in the climatic chamber at the

EMPA in Dübendorf that reproduced a summer sunny day in Western Europe with a temperature of 30°C and a relative humidity of 65%. The front window of the car was irradiated with halogen lamps at a power of 1000 W/m^2 to mimic the solar radiation. Three different standardized driving test cycles were run (ECE15 1970, NEFZ 1990 and WLTP 2017).The "**W**orldwide Harmonized **L**ight Duty **T**est **P**rocedure" is the closest to real driving conditions [11]. The successful materials were processed on an SLS machine in the optimized design of the AC box and compared to reference AC configurations to determine the decrease in energy consumption. The conventional reference configurations are given hereunder:

- Premium vehicle with narrow air inlet (PV1)
- Premium vehicle with broad air inlet (PV2)
- AC system of a Mercedes C-Class Series

While the developed boxes (WP standing for **W**eid**P**las) configurations will be described below.

Results & Discussion

SLS Material Development

Table 3 Summary of results for the material development

Type	Powder			Processed	
	Avalanche Angle [°]	Surface Fractal [-]	Sintering Window $(T_m\text{-}Tc)_{onset}$ [°C]	Heat Conductivity @ 27°C [W/mK]	Heat Deflection Temperature [°C]
A1	42.6 ± 4.9	1.6 ± 0.2	11	0.29	51.20 ± 0.10
A2	55.0 ± 6.9	3.8 ± 0.8	11	0.32	48.85 ± 0.05
A3	57.4 ± 7.3	4.2 ± 1.6	9	0.44	50.25 ± 0.95
B	39.2 ± 3.1	1.5 ± 0.2	21	0.57	54.55 ± 0.35
C	48.0 ± 10	3.3 ± 0.9	16	0.31	63.35 ± 1.15
D	52.8 ± 5.8	2.5 ± 0.8	20	0.25	135.80 ± 1.30

Table 3 provides the results obtained during the investigations and unveils important behaviour difference between the materials. The powder properties show a clear dependency on the type of filler used. A powder is considered as flowing homogeneously and in a repeatable manner when the mean avalanche angle and surface fractal are low and show narrow standard deviations [10]. The way the powder flows is affected by the filler form, spherical fillers like for $CaCO_3$ (type A2) or glass beads for type C hinder less the movement of particles relative to each other than lamellar structures like talcum (type A3) or needles in the case of D. This fact is here confirmed by the avalanche angles as well as the surface fractals of all the investigated powders. Here, the best flowing material is the type B, the particles are not only ellipsoidal but their increased weight compared to pure PP help stabilizing the flowing behaviour. The homogeneity of the powder particles is a key factor as can be observed in Figure 2 and it can be observed that fillers inside the particles will be less likely to hinder the powder flow than dry blended fillers. The width of the sintering window is a very sensible parameter and good comparison basis for the processing of the material on the machine. For the developed materials and depending on the morphology of the filler, the sintering window is either not affected, as for type A2, or diminished due to the nucleating effect of the filler, as for type A3. The type B presents the widest sintering window and fulfils thus the most important characteristics of an SLS powder.

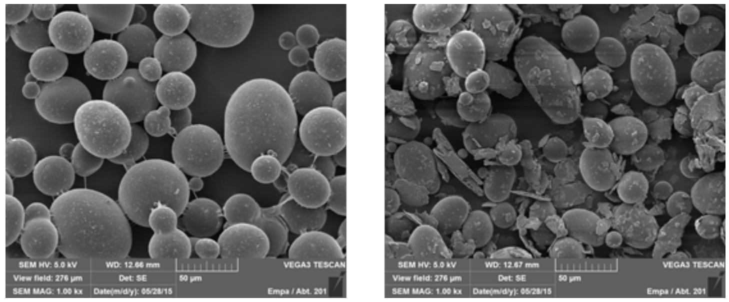

Figure 2 SEM pictures at 1000 magnification; Left type B, polypropylene extruded with talcum; Right type A3 obtained by dry blending of coarse talcum and iCoPP

The thermal conductivity is highest for the talcum filled materials A3 and B even though they have a significant difference of 0.13 W/mK. The more intimate contact of PP with talcum obtained as well as its homogeneous distribution during the extrusion process in type B leads to a better conduction of heat through the material than for the dry blending case. The other materials present all better conductivity than plain polyamide but are still half as good conductors as the type B. Type C and D show the highest HDT values but due to their flowing behaviour coupled with thermal conductivity, they are less interesting for SLS processing than type B. Type B with its good powder properties combined to high heat conductivity is definitely the material of choice for the casing of the AC box.

<u>Design Optimization</u>

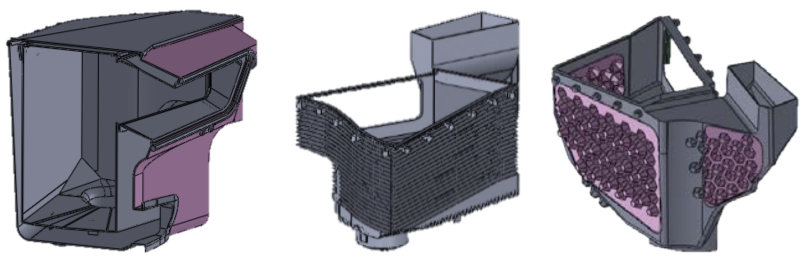

Figure 3 Optimization steps of AC box designs; Left: First step; Middle: Increased surface area (2x); Right: PA12 structure and insert out of developed material (area 2.5-3x)

Figure 3 presents the evolution of the box design from basic box (left) to a more complex and combining multi-material box. For the second iteration, only the inner box was optimized to double its surface area. However, due to the big volume of the inner box, there exists few machines on the market able to process such dimensions and the ones having a large enough building platform generally only process PA12. The final version of the inner box is a structured body produced with PA12 and high surface area inserts. These pull-outs can be produced using the different SLS materials designed for and investigated in this work. Thus, the novel AC system is mainly composed of PA12 and, at the positions of desired maximum heat exchange (honeycomb structures in Figure 3 - right picture) with high conductivity optimized material. The outgoing cool cabin air flows around the inner box and heat exchange happens at the wall with the outside hot incoming air. The following WeidPlas inner box configurations are tested in real conditions:

- WP1: structure and inserts produced with PA12, tests are performed with and without evaporative cooling (EC)
- WP2: structure produced with PA12, inserts made out of material type A with EC
- WP3: structure produced with PA12, inserts made out material type B with EC

The evaporative cooling process enables to further cool down the cabin outflow by using water's high enthalpy of vaporization. The cool airflow from the cabin passes through a curtain of sprayed water, obtained by condensation of the hot outside air. By flowing through the water curtain, the cool air will lower its temperature while increasing its humidity.

Test Cycles Measurements

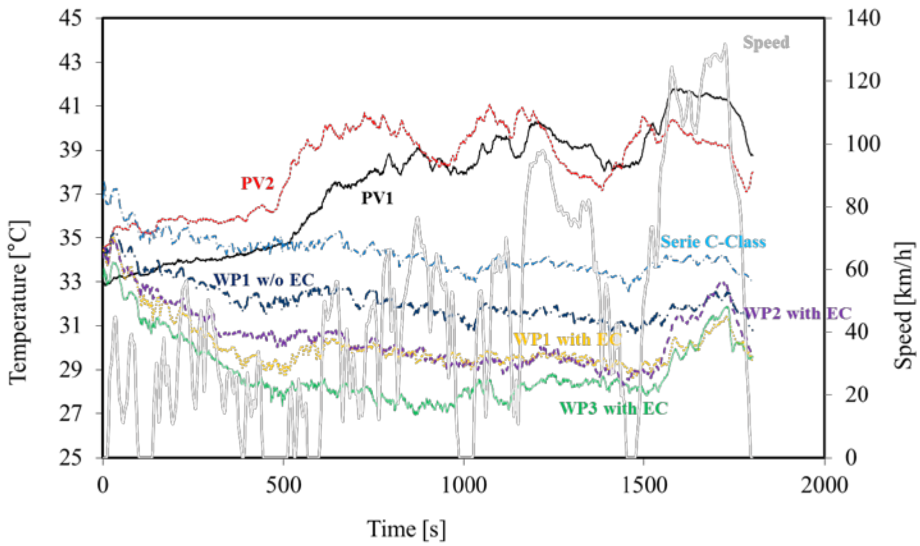

Figure 4 Air intake temperature at partition wall during the WLTP test cycles for the configurations Premium Vehicle 1 and 2 (PV1-2), the Mercedes C-Class configuration (Serie C-Class) and the developed boxes (WP1-2-3).

Figure 4 presents the temperature evolution of intake air at the partition wall during the WLTP driving test with the different AC configurations. The temperature ranges of the three Weidplas concepts (WP1-2-3) present clearly reduced temperature of the air transmitted to the AC evaporator, needing thus less energy to cool the air before flooding the passenger cabin. The behaviour presented in Figure 1 is confirmed; the prepared air with the new concept is much cooler than the conventional systems, with either broad or narrow intakes. The effect of material conductivity is clearly observed with the lowest temperature profile for the type B, the most thermally conductive SLS material. The temperature decreases with increasing thermal conductivity of the AC box; it confirms the original idea of increasing heat transfer between two fluids through a wall to cool down the air sucked into the car.

An important feature that needs to be mentioned is the surface roughness of the SLS inserts. The intrinsic roughness of SLS parts is here a decisive point for increasing the convective heat transfer at the wall interface between the two air fluxes. This effect will need to be taken into account when the AC box is produced via injection moulding where a smooth surface is standard.

Fuel Consumption of AC System

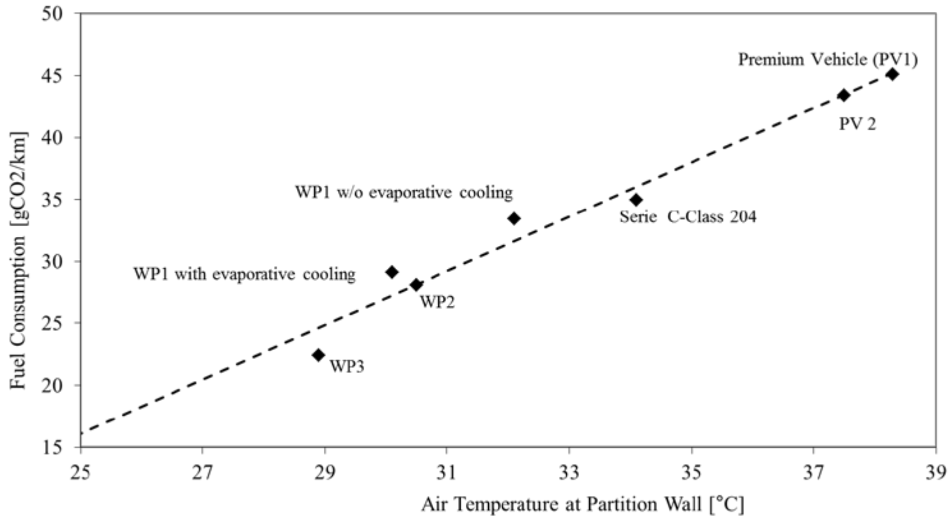

Figure 5 Fuel consumption of air conditioning system and air temperature at partition wall for the WLTP cycle at 30°C and 65% relative humidity.

Figure 5 shows the results this project aimed for; it gives the fuel consumption of the AC system in relation to the air temperature at partition wall for the different AC configurations. Just like in the case of Figure 4, the Weidplas concept box values are close together while the reference systems are scattered at high consumption values. In the optimal case, WP3 - type B, there is a reduction of 50% in fuel consumption compared to the premium vehicle solutions. The voltage of the refrigerating compressor diminished from 7.2 V in the case of the Premium Vehicle 1 to 5.2 V for the WP3, a diminution of 28% of the energy consumption of the AC system. However, even the system made entirely out of PA12 shows a drastic amelioration of the AC system on an energetic point of view. The thermal conductivity increase from PA12 (0.2 W/mK) to TPP (0.57 W/mK) enables fuel savings of up to one third. The combination between increased surface area, higher thermal conductivity of the material as well as rough surface allows the overall heat transfer to become more efficient and thus help reducing CO_2 emissions. This feature will certainly be of major interest to the automotive industry around the world.

Conclusion

The efficiency of air conditioning in private cars has been successfully increased. The effect of precooling the intake air at the front window with reused air from the passenger cabin has been found to diminish the fuel consumption of AC system to up to 50%. The novel concept was confirmed using the SLS technology advantages for the inner box design. The construction optimization enabled a drastic surface area increase to enhance the heat exchange between air fluxes while the use of inserts produced out of different thermally conductive SLS materials. To further improve the system, new SLS materials with improved thermal conductivity were identified and characterized before being implemented inside the AC box. The effect of thermal conductivity was found to give a decisive boost to the fuel savings during standardized test cycles

This novel AC system enables energy savings for cooling down cars in summer. In Europe, warm sunny days are less frequent than cold, rainy days and this is the reason why this system will be investigated under winter conditions with reuse of warm air from the passenger cabin. This feature is especially important for electric vehicles during winter. Up to now the driving range of electric cars was kept constant to the detriment of the driver's comfort. Preliminary results tend to confirm an efficiency increase for warming up as well.

Acknowledgments

The authors gratefully acknowledge the federal Commission for Technology and Innovation of Switzerland for funding the project 14793.1 PFIW-IW. This project was successfully achieved thanks to the active collaboration of all the partners based on an original idea by Stefan Harke.

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