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ADVANCEMENTS IN 3D PRINTING TECHNIQUES FOR LOW-SPEED AERODYNAMICS IN VEHICLE VENTILATION – PART 1

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Abstract: *This scientific study focuses on the comparison of various 3D printing techniques for the fabrication of air diffusers used in HVAC systems for vehicles. Specifically, the superiority of the Stereolithography (SLA) technique over other methods such as Digital Light Processing (DLP), Selective Laser Sintering (SLS), and Fused Deposition Modelling (FDM) is investigated. The goal was to determine the most effective and efficient approach for producing air diffusers prototypes that optimize indoor environmental quality and thermal comfort within vehicles. Through a comprehensive analysis and evaluation of the different 3D printing techniques, it is conclusively demonstrated that the SLA technique has advantages for this specific application. The accuracy of SLA enables the production of intricate geometries and fine details crucial for efficient air distribution and diffusion. The complexity of design features, including the unique geometry of lobed air diffusers that allows for increased air induction compared to conventional diffusers needed for the specific application, contributes to enhanced indoor environmental quality. In conclusion, this study confirms that the SLA technique surpasses DLP, SLS, and FDM in producing sensitive aerodynamics related components. The combination of accuracy, material versatility, complex design capabilities, dimensional stability, and efficient production make SLA the preferred choice for achieving optimal indoor environmental quality and thermal comfort. The findings provide insights for researchers, engineers, and manufacturers in the field of automotive ventilation systems, paving the way for advancements and using 3D printing technology in aerodynamics related applications.*

Keywords*: 3D printing, Air diffusers vehicles, HVAC, SLA, SLS, DLP, FDM*

1. INTRODUCTION

In recent years, 3D printing has revolutionized the manufacturing industry, offering new possibilities for producing complex and customized components. This technology has found applications in various fields, including aerospace, medicine, and automotive engineering. In the automotive sector, 3D printing has emerged as a promising tool for enhancing the design and performance of vehicle systems, particularly in the realm of low-speed aerodynamics and ventilation [1].

Ventilation plays a critical role in ensuring occupant comfort and maintaining a healthy environment within the vehicle cabin. Effective ventilation systems can efficiently control airflow, regulate temperature, and remove pollutants, providing an optimal driving experience. However, traditional manufacturing methods often face challenges in fabricating intricate components that facilitate efficient airflow and precise control.

Proper air distribution inside a vehicle plays a crucial role in ensuring optimal indoor environmental quality (IEQ) in vehicles, including automobiles, trains, buses, and airplanes [2-4] or even more enclosed spaces as cabin crew on international Space Station [5, 6]. As these spaces are enclosed and the quality of air has a significant impact on the comfort and well-being of both passengers and crew members. Insufficient IEQ (Indoor Environmental Quality) can give rise to health issues and discomfort, leading to increased fatigue among users. This, in turn, can impair their ability to respond promptly to stimuli, resulting in longer reaction times and potentially giving rise to undesirable and unpleasant incidents.

The vehicle HVAC (Heating, Ventilation and Air Conditioning) system plays a crucial role in ensuring a continuous flow of fresh air while effectively removing pollutants from the surrounding environment through dilution. High induction air diffusers with lobed orifices have emerged as a promising solution for enhancing indoor environmental quality (IEQ) in vehicles [7]. This finding is also supported by Bode et al.[8], who highlight the effectiveness of these air diffusers in supplying fresh air to the enclosed space and promoting its mixing with the ambient air. As a result, the concentration of pollutants is reduced, leading to an overall improvement in IEQ. The concept of utilizing lobed orifices in ventilation systems for high induction purposes is not a novel idea. In fact, previous research by Bragança et al. [9] demonstrated significant enhancements in thermal comfort when comparing lobed diffusers to conventional ones without any adverse effects on pressure drop or sound pressure levels.

An innovative geometric design, aimed at achieving passive airflow induction, was initially developed at the University of La Rochelle, France [10, 11], as well as the University of Rennes [7]. Building upon this foundation, further research was conducted at the Technical University of Civil Engineering of Bucharest [12-16].

In [17], the numerical analysis conducted by the authors involved a comparison of four air diffuser geometries, all of them having lobed forms, including the original air diffuser found in the Dacia/Renault Duster vehicle. Among the various cases examined, the most extensively studied configuration was characterized by three concentric circles featuring lobes, accompanied by guide blades positioned at different angles. In this design, the lobes were located on the outer portion of the air diffuser. The findings revealed that this particular configuration demonstrated the highest effectiveness in terms of entraining ambient air, exhibiting a remarkable 35% increase in air induction when compared to the reference air diffuser. A few months later, the same authors, after more research related to this field discovered a new shape capable of inducing the highest ambient air entrainment, with a 41% greater air induction rate than the reference air diffuser [18].

The main difficulty in producing the innovative shapes for the air diffusers is directly linked with the complexity of the geometry. This is where 3D printing techniques offer a compelling solution [19]. By harnessing the power of additive manufacturing, engineers can create intricate geometries, lightweight structures, and functional prototypes with unprecedented precision. The ability to print components with complex internal channels, customized shapes, and optimized designs has immense potential for improving low-speed aerodynamics and ventilation systems in vehicles.

Several 3D printing techniques have emerged as prominent tools for fabricating components related to vehicle ventilation. Stereolithography (SLA), Digital Light Processing (DLP), and Selective Laser Sintering (SLS) are some of the leading techniques that have gained significant attention due to their capabilities and versatility.

SLA, known for its exceptional resolution and surface finish, enables the production of high-quality, detailed parts. By utilizing SLA, engineers can create intricate ventilation ducts, optimized diffusers, and precisely designed grilles that facilitate smooth and controlled airflow. The precise control over shape and dimensions achieved through SLA allows for tailored ventilation solutions, reducing air resistance and minimizing noise.

DLP, an alternative to SLA, offers faster printing speeds by curing entire layers at once. This technique excels in creating components with good resolution, although not always as precise as SLA due to potential light bleeding. Nonetheless, DLP-based 3D printing enables the production of complex geometries and functional prototypes, making it a viable option for rapid prototyping and iterative design optimization in vehicle ventilation systems.

SLS, on the other hand, leverages the power of laser sintering to fuse powdered materials together. This technique allows for the creation of functional prototypes and end-use parts with a wide range of materials, including those with excellent mechanical properties. By employing SLS, engineers can develop durable ventilation components with intricate internal structures, maximizing airflow efficiency while maintaining structural integrity. Nevertheless, SLS can be quite prohibitive in terms of costs.

In this article, we delve into the advancements in 3D printing techniques for low-speed aerodynamics in vehicle ventilation. We explore the capabilities and limitations of SLA, DLP, and other emerging techniques in achieving optimal airflow control, noise reduction, and energy efficiency in automotive ventilation systems. Furthermore, we discuss the design considerations, material selection, and post-processing techniques associated with each printing method to facilitate the integration of 3D-printed components into real-world automotive applications.

By harnessing the potential of 3D printing technologies, researchers and engineers can unlock new avenues for designing and fabricating efficient ventilation systems in vehicles. The following sections of this article will provide an in-depth analysis of the advancements, challenges, and future prospects of utilizing 3D printing techniques for low-speed aerodynamics and ventilation in the automotive industry.

2. MATERIAL AND METHOD

2.1. General context

This article presents the implementation of numerical studies conducted as part of a collaborative research project between the Technical University of Civil Engineering Bucharest (TUCEB) and Renault Technologie Roumanie (Renault Group Romania - RTR). The primary objective of these studies was to investigate and analyse various aspects concerning the ventilation system of the Renault Duster vehicle. Within the scope of the research project, an in-depth examination of the Renault Duster was carried out using advanced numerical techniques, specifically Computational Fluid Dynamics (CFD).

These numerical studies encompassed simulations and analyses that aimed to explore different aspects associated with the utilization of high induction air diffusers in the Renault Duster vehicle. The results of the numerical studies emerged in pointing out few shapes to be used as air diffusers for the HVAC system in Dacia/Renault Duster vehicle. The lobed shape, previously studied, was specifically adapted to suit the Duster dashboard. The construction of the analysed geometries was accomplished using SolidWorks software, and subsequently, these models were imported into the 3D printer software under *.stl format, to prepare them for the 3D print.

In Fig.1 is presented the geometry of the air diffuser that has resulted from the numerical simulation approach from [17], in which the induction rate of the ambient air into the stream of fresh air of these air diffusers is 35%.

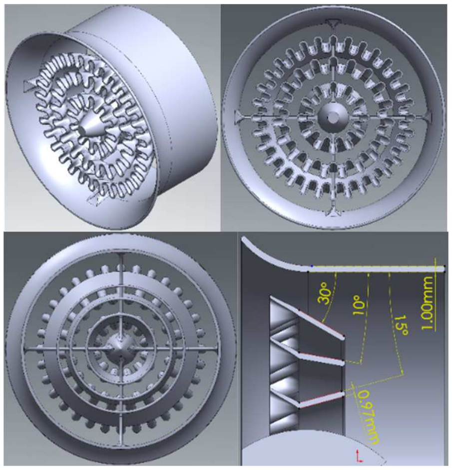

Fig. 1. Air diffuser with 35% induction rate used for 3D printing technologies evaluation.

2.2. 3D printing techniques

In the first phase, the air diffuser presented in Fig. *1* was 3D printed with various techniques with the purpose to find the best technology for this specific application in terms of the airflow through the air diffuser. For this, 4 different 3D printing technologies were approached, each of them having a number of advantages and disadvantages compared to the other technologies.

2.2.1. FDM technique

Thus, in this first phase, 3D model was printed using the FDM (Fused Deposition Modelling) technique: This is the most widespread 3D printing technology. FDM involves the extrusion of a thermoplastic material, by means of a printing head moving in the X, Y and Z coordinates for cartesian setups. The material is melted and deposited in successive thin layers, which cool and solidify quickly, forming the printed object. Some of the main capabilities for the FDM technique can be found in the Table 1.

Table 1

Main capabilities for the FDM technique

Subtypes of Material Extrusion	Fused deposition modelling (FDM), Construction 3D Printing, Micro 3D Printing, Bio 3D Printing
Materials	Plastics, metals, foods, concrete, and many others
Dimensional Accuracy	±0.5% (lower limit ±0.5 mm)
Common Applications	Prototypes, electrical housings, form and fit testing, jigs and fixtures, investment casting patterns, houses, etc.
Strengths	Lowest cost 3D printing method, a wide range of materials
Weaknesses	Often lower material properties (strength, durability, etc.) and generally not as dimensional accurate

The 3D printers used for the 3D printing of the air diffusers is the one presented in Fig.2 (Anycubic Vyper).

Fig. 2. 3D printer used for FDM technique.

The most important technical specifications of the used 3D printer are printing resolution ±0.1mm, positioning accuracy: X/Y 0.0125mm; Z 0.002mm, nozzle diameter: 0.4 mm, printing speed: ≤ 180mm/s (recommended 80mm/s), support filaments: PLA, TPU, ABS, PETG, Wood.

2.2.2. SLS technique

The SLS (Selective Laser Sintering) technique uses a laser to selectively melt and synthesize a granular material, such as polyamide powder (nylon), to form the printed object. The laser heats and "sinters" (unites/bond) the powder particles in thin layers to create the desired object. Some of the main capabilities for the SLS technique can be found in the Table 2.

Table 2

Main capabilities for the SLS technique

Types of 3D Printing Technology	Selective laser sintering (SLS), laser powder bed fusion (LPBF), electron beam melting (EBM)
Materials	Plastic powders, metal powders, ceramic powders
Dimensional Accuracy	±0.3% (lower limit ±0.3 mm)
Common Applications	Functional parts, complex ducting (hollow designs), low-run part production
Strengths	Functional parts, excellent mechanical properties, complex geometries
Weaknesses	Higher cost for machines, often high-cost materials, slower build rates

2.2.3. DLP technique

DLP (Digital Light Processing) technique uses a light source, such as a digital projector, to strengthen successive layers of photosensitive resin. Instead of a laser like in the next technology we used, a 2D model of the layer is projected onto the resin, solidifying it and building the object into thin layers. The platform on which the object is located is gradually lifted from the resin to create new layers. Some of the main capabilities for the DLP and SLA techniques can be found in the Table 3.

Table 3

Main capabilities for the DLP and SLA techniques

Types of 3D Printing Technology	Stereolithography (SLA), liquid crystal display (LCD), digital light processing (DLP), micro-stereolithography (µSLA), and more.
Materials	Photopolymer resins (castable, transparent, industrial, biocompatable, etc.)

Dimensional Accuracy	±0.5% (lower limit ±0.15 mm or 5 nanometers with µSLA)
Common Applications	Injection mold-like polymer prototypes and end-use parts,
Strengths	jewellery casting, dental applications, consumer products
Weaknesses	Smooth surface finish, fine feature details

The 3D printer that was used for DLP techniques was 3D Creality Halot-one printer (Fig.3).

Fig. 3. 3D printer used for DLP technique.

Some of the 3D printer specifications are: Printing Speed: 60mm / h; Max Printing Size: 127 * 80 * 60MM; Machine Size: 221 * 221 * 404mm; Curing Speed: 1-10 S / layer, XY Axis Accuracy: 0.01-0.05mm.

2.2.4. SLA technique

SLA (Stereolithography) technique uses a liquid photosensitive resin that hardens under the action of an ultraviolet laser. A laser is focused on the surface of the resin to polymerize and solidify the successive layers of the object. The platform on which the object is located is gradually lifted from the resin to create new layers.

SLA technique is quite similar to the DLP technique in terms of principle of operation, but the main difference lies in the fact that SLA is using a laser for resin hardening while DLP is using a light source.

Nevertheless, there are some advantages and disadvantages between these techniques.

In terms of resolution SLA 3D printers typically offer excellent resolution and produce high-detail prints with smooth surface finishes while DLP printers can achieve good resolution, but the quality may not always be as precise as SLA due to light bleeding and the layer-by-layer curing process.

In terms of printing speed, SLA printers cure each layer individually, resulting in longer print times compared to DLP, while DLP printers cure entire layers at once, leading to faster print times compared to SLA. When speaking about materials: SLA printers are compatible with a wide range of resin materials, including engineering-grade and specialty resins, providing versatility for various applications while DLP printers may have a more limited selection of compatible resins compared to SLA printers, although this can vary depending on the specific printer model.

In terms of accuracy, SLA technology often provides higher accuracy, making it suitable for applications that require fine details and intricate geometries, while DLP can achieve good resolution, it may have slightly less accuracy in the vertical (Z-axis) direction due to the curing of entire layers at once. The 3D printer that was used for DLP techniques was 3D SLA Anycubic Photon M3 Max (Fig. 4).

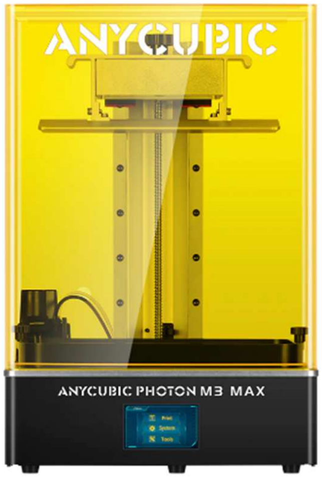

Fig. 4. 3D SLA Anycubic Photon M3 Max.

Relevant technical specifications: Printing accuracy: 6,480 x 3,600 px (7K), Light source:

Parallel matrix (LED lights x 84), Printing speed: ≤ 60 mm/hr, Print size: 300 x 298 x 164 mm / 11.8 x 11.7 x 6.46 in. (HWD), Printing volume: 14.7 L / 498.5 oz.

3. RESULTS AND DISCUSSIONS

All the technologies presented in the previous chapter were used to print the complex shapes of the resulted air diffusers from the numerical simulation studies.

3.1. FDM technique

The material used for the 3D print was PLA (polylactic acid). However, due to the successive deposition of the layers and due to the limited resolution, the parts do not correspond in terms of quality. As can be seen in the following images the quality of the walls is not good enough and the lobes were not represented as accurately as desired.

The following properties were used to print the geometry (Table 4):

Table 4

Printing properties

Layer height [mm]	0.06
Wall thickness [mm]	8
Top/bottom thickness [mm]	0.8
Infill density [%]	20
Material printing temp. [°C]	200
Build plate temp. [°C]	60
Print speed [mm/s]	60

The 3D printed part can be observed in Figure 5. The roughness of the walls is also quite high for aerodynamic applications.

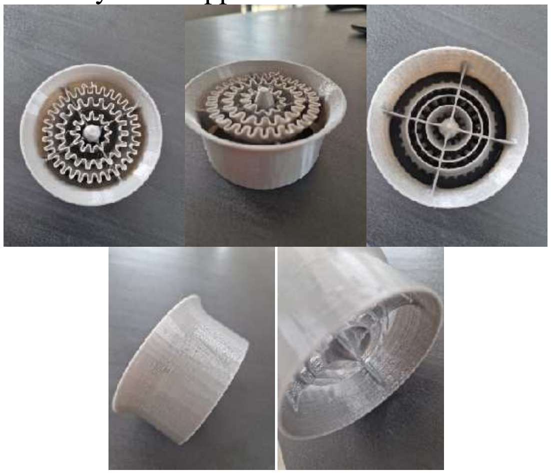

Fig. 5. The air diffuser 3D printed with FDM technique.

3.2. SLS technique

The part printed by this technique had a higher quality than those printed by the FDM technique.

The following tolerances were used to print the part using the SLS technique: Z axis: 0,15 mm, XY axis: 0.1-0.2mm.The parts were printed at a layer height of 0.1 mm using Nylon PA12 upper gray.

However, in the area of the lobes, the arc was executed in certain areas in increments, which can affect the flow of air through those areas. Given the fact that the shape of the lobe is responsible for the apparition of the flow structures that have the property to entertain more air from the ambient air into the flow stream, we considered the try unsatisfactory (Fig. 6).

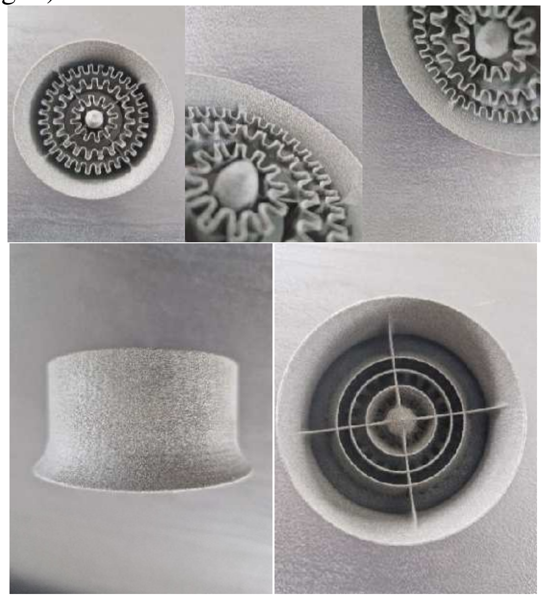

Fig. 6. The air diffuser 3D printed with SLS technique.

3.3. DLP technique

The following setup was used for the present 3D print of the air diffuser. Anycubic Standard Resin (Gray) was used with a layer thickness of 50 μm. The following printing parameters were used (Table 5):

Table 5

Printing parameters for DLP technique

Bottom Exposure Time	Light Off Delay	Exposure Time	Bottom Lifting Distance	Motor Speed
50s	5s	3.5s	6 mm	1 mm/s

The diffuser was printed with the upstream part set on the printer's build plate. The results were satisfactory in terms of quality, however because of the diffuser geometry, the aerodynamic cone of the stator was not printed accurately (it was cut off).

Rotating the part so that the downstream end is fixed to the build plate is not an option, as the ends fixed to the build plate are always the lowest in terms of print quality and the downstream side is the essential part of the diffuser in terms of aerodynamics and thus, needs to be of the highest possible quality.

The solution envisaged was to keep the diffuser with its upstream side on the build plate and use supports in an attempt to sustain the weight of the stator's upstream end. Two attempts were made, one using automatic supports generated by the slicing software, one using manually placed supports.

The supports were conical supports with a diameter of 1.5 mm, a tip length of 3 mm and a tip diameter of 0.6 mm.

The automatic supports were too dense and were difficult to break off, leading to the diffuser being damaged during support removal. The stator was not printed accurately and more defects to its upstream end were found than in the case without any supports.

The manual supports yielded a slightly improved upstream stator end; however, the stator's conical shape was not captured. Manual support placement also had the highest rate of errors due to the difficulty of placing supports in precise locations such as the edges and tip of the stator's upstream end.

The only remaining solution is to print the diffuser as two halves and glue them together. The diffuser was sliced through the middle with each half containing a part of the stator structure. It was this central part of the stator that was attached to the build plate during printing.

The results in terms of print quality were accurate and the geometry was nicely captured, however the increased surface area of the diffuser halves stuck to the build plate and proved hard to remove resulting is some attempt where the diffuser's outer walls were damaged during removal of the part from the build plate.

After a successful print, the part was washed in a bath of isopropyl alcohol for 8 minutes and subsequently cured in UV light for 20 minutes while placed on a spinning plate in a washing and curing station.

The quality produced was superior in terms of its aerodynamics but due to the details at a high resolution some of them were not represented correctly. Also, the circles were not represented very well, having a large tolerance (Fig. 7).

The supports executed using the 3D printer software were not very accurate and the cone from the upstream was not represented at all. Therefore, the next setup consisted of the use of manual supports but also in this situation the cone was not represented correctly (Fig. 8).

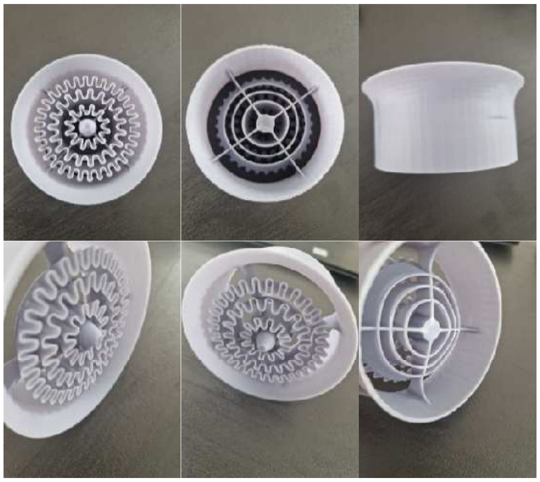

Fig. 7. The air diffuser 3D printed with DLP technique.

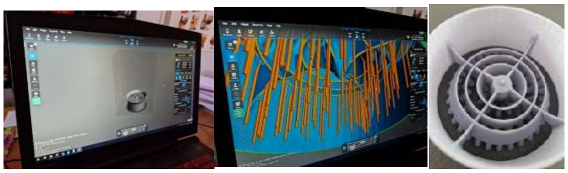

Fig. 8. The used software for printing as well as the manual supports.

The next stage consists in splitting the part in half, to represent as correctly as possible the two halves, at the end they will be stuck together to have a geometry as correct as possible (Fig. 9).

3.4. SLA technique

The quality of the part was superior from all the above-mentioned points of view, compared to the other technologies used, thus, the final air diffuser was executed by 3D printing with this technique (Table 6).

Fig. 9. The air diffuser 3D printed with DLP technique – second iteration.

Table 6

Printing properties for SLA technique

Slice parameters:		Bottom layers control steps		Normal layers control steps	
Layer thickness [mm]	0.05	Z lift height [mm]	7.5	Z lift height [mm]	2.7
Normal exposure time [s]	4	Z lift step speed [mm/s]	4	Z lift step speed [mm/s]	2
Off time [s]	2	Z retract step speed [mm/s]	4	Z retract step speed [mm/s]	2
Bottom exposure time [s]	30				
Bottom layers	6				

In Figure 10, we can observe the 3D printed air diffuser part created using the SLA technique. It is evident that all the geometric features have been faithfully reproduced in three dimensions, including the cone on the inner side.

Fig. 10. The air diffuser 3D printed with SLA technique.

FDM, which builds objects layer by layer using melted thermoplastic filaments, struggled to achieve the desired level of detail. Its limitations in resolution and surface quality resulted in a grille that lacked the refined aesthetics and accuracy required for automotive applications.

SLS, which employs a laser to sinter powdered material layer by layer, demonstrated better detail reproduction than FDM but still struggled to fully capture the intricate lobes of the grille. The nature of the powder-based process limited the resolution, resulting in some loss of definition in the final print.

DLP, utilizing a digital projector to cure liquid resin layer by layer, showcased improved resolution and surface finish compared to FDM and SLS. However, it still faced challenges in reproducing the finer details, especially in complex areas where accessibility was limited.

In contrast, SLA emerged as the standout technique for accuracy and detail. Its utilization of a liquid resin cured by a UV laser allowed for exceptional accuracy, enabling the reproduction of intricate features, including the rounded lobes of the grille. The resulting print boasted smooth surfaces, well-defined edges, and a level of detail that surpassed the other techniques.

4. CONCLUSIONS

Based on the findings of this study, it can be affirmed that the SLA (Stereolithography) technique surpasses other 3D printing methods such as DLP (Digital Light Processing), SLS (Selective Laser Sintering), and FDM (Fused Deposition Modelling) for the fabrication of air diffusers for HVAC systems in vehicles. The findings are based on several key factors that contribute to the superiority of SLA in this specific application.

Firstly, SLA offers superior accuracy in producing complex geometries and very fine details, which is essential for the efficient and optimized performance of air diffusers. The high-resolution capability of SLA ensures the production of smooth surfaces, precise dimensions, and intricate features necessary for effective air distribution so needed for aerodynamic applications.

Furthermore, the SLA process allows for the production of air diffusers with a high level of complexity, including the lobes so necessary for the entrainment phenomenon of the ambient air into the air stream. These design features contribute to enhanced air induction, improved mixing of fresh and ambient air, and superior distribution of the conditioned air within the vehicle cabin, thereby maximizing indoor environmental quality.

Moreover, the SLA technique provides a relatively faster printing speed compared to other 3D printing methods, allowing for efficient production of air diffusers for HVAC systems in vehicles. This faster turnaround time is advantageous for industries that require rapid prototyping and production of customized air diffusers for different vehicle models.

Overall, the results of this study strongly support the notion that the SLA technique stands as the superior choice for 3D printing air diffusers for HVAC systems in vehicles. The combination of accuracy, material versatility, complex design capabilities, dimensional stability, and efficient production make SLA the ideal solution for achieving optimal indoor environmental quality and thermal comfort in vehicles.

Thus, this study demonstrates that choosing the appropriate 3D printing technique is crucial in achieving high-quality automotive components related with fluid flow. Stereolithography (SLA) represents a superior option for attaining the desired accuracy and detail. The continued development of SLA technology and its application in various areas of the automotive industry will open new possibilities and contribute to advancing the production of complex and precise components.

5. ACKNOWLEDGEMENTS

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TEHNICI AVANSATE DE IMPRIMARE 3D PENTRU AERODINAMICA LA VITEZĂ REDUSĂ ÎN VENTILAȚIA VEHICULELOR. PARTEA I-A.

Rezumat: Acest studiu se concentrează pe compararea diferitelor tehnici de imprimare 3D pentru fabricarea difuzoarelor de aer utilizate în sistemele HVAC pentru vehicule. În mod specific, este investigată superioritatea tehnicii stereolitografiei (SLA) față de alte metode, cum ar fi Digital Light Processing (DLP), sinterizarea selectivă cu laser (SLS) și Fused Deposition Modeling (FDM). Scopul a fost de a determina cea mai eficientă abordare pentru producerea prototipurilor de difuzoare de aer care optimizează calitatea mediului interior și confortul termic în vehicule. Printr-o analiză și evaluare cuprinzătoare a diferitelor tehnici de imprimare 3D, se demonstrează în mod concludent că tehnica SLA oferă avantaje pentru această aplicație specifică. Acuratețea superioară a SLA permite producerea de geometrii complexe și detalii fine cruciale pentru distribuția și difuzarea eficientă a aerului prin geometrii complexe. Complexitatea caracteristicilor de proiectare, inclusiv geometria unică a difuzoarelor de aer lobat permit o inducție crescută a aerului în comparație cu difuzoarele de aer convenționale. În concluzie, acest studiu confirmă faptul că tehnica SLA e superioară DLP, SLS și FDM în producerea difuzoarelor de aer pentru sistemele HVAC din vehicule. Combinația de precizie, versatilitate a materialelor, capacități complexe de proiectare, stabilitate dimensională și producție eficientă fac din SLA alegerea potrivită pentru obținerea unei calități optime a difuzoarelor de aer. Constatările oferă informații cercetătorilor, inginerilor și producătorilor din domeniul sistemelor de ventilație auto, deschizând calea pentru progrese în tehnologia de imprimare 3D pentru aplicațiile legate de aerodinamică.

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