Development of a functional prototype for recovery of recycled expanded polystyrene via extrusion

Pedro Leite [1,2,*], Carlos M. Correia [1,2], Raquel Araújo [5], João Tinoco [5], Nuno Gama [4], Paula Ferreira [3], Idalina Gonçalves [3], Victor Neto [1,2] and Tatiana Zhiltsova [1,2]

[1] TEMA - Centre for Mechanical Engineering and Automation, Mechanical Engineering Department, University of Aveiro, 3810-193 Aveiro, Portugal; leitepedro@ua.pt; carlos.correia@ua.pt; vneto@ua.pt; tvzhiltsova@ua.pt
[2] LASI—Intelligent Systems Associate Laboratory, 4800-058 Guimarães, Portugal; leitepedro@ua.pt; carlos.correia@ua.pt; vneto@ua.pt; tvzhiltsova@ua.pt
[3] CICECO – Aveiro Institute of Material, Department of Materials and Ceramic Engineering, University of Aveiro¸ 3810-193 Aveiro, Portugal; pcferreira@ua.pt; idalina@ua.pt
[4] CICECO – Aveiro Institute of Materials, Department of Chemistry, University of Aveiro¸ 3810-193 Aveiro, Portugal; nuno.gama@ua.pt
[5] Petibol - Embalagens De Plástico, S.A., 4465-592 Leça do Balio, Portugal; raquelaraujo@petibol.pt; joaotinoco@petibol.pt;
[*] Correspondence: leitepedro@ua.pt;

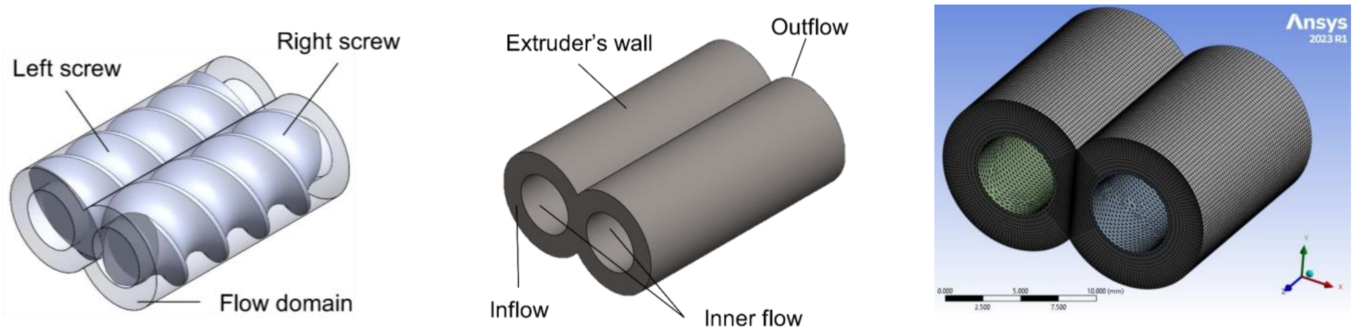
Introduction

Expanded polystyrene (EPS) is a lightweight, rigid cellular plastic comprising 98% air and 2% polystyrene (PS) [1]. EPS parts are made from expanded and melted PS beads using a blowing agent, such as pentane, which is entrapped within their structure, and originate a honeycomb-like cellular structure [1]. EPS's cellular composition provides excellent insulation properties and a superior strength-to-weight ratio compared to other rigid materials, making it highly versatile for various applications, such as protective packaging, food packaging, and insulation [1]. However, the disposal of EPS poses significant challenges due to its high volume of waste generation and relatively short-life service [2]. To address this concern, recycling is a well-known method that converts wasted materials into reusable ones, thereby decreasing the consumption of raw materials and the environmental impact of EPS waste disposal. Nonetheless, EPS's high volume and low-density result in high waste transportation costs and handling difficulties, requiring a pre-recycling volume reduction process [2]. EPS is known for its 100% recyclability; however, the predominant method for EPS bead production, suspension polymerization, must improve recycling potential. This technique relies on monomer styrene as the primary raw material, requiring chemical recycling to convert EPS waste into styrene. Unfortunately, chemical recycling is often costly and environmentally demanding. Although it is feasible to incorporate waste EPS into the process without chemical recycling, achieving high-quality beads using 100% waste EPS remains challenging [3]. Consequently, EPS waste is typically downcycled into common PS application products [2]. In light of the above, extrusion foaming emerges as an alternative method to suspension polymerization. This approach involves the use of a blowing agent into the extruder barrel, where it dissolves into the PS melted under high pressure. Upon reaching the die exit, a pressure drop induces the expansion of the blowing agent, leading to the formation of a cellular structure. Integration of a pelletizer into the process enables the production of expanded or expandable beads for molding EPS parts [4]. However, the extrusion process is complex due to the various parameters involved, particularly in the extruder's screw design, which significantly affects the extrusion process of cellular plastics [5]. Finite element method (FEM) simulations have proven to be useful for screw design analysis [6]. This study explores the feasibility of extruding recycled EPS with a blowing agent to produce recycled EPS granulates. A theoretical design for a mechanical prototype suitable for extruding recycled EPS was designed herein. Furthermore, a study is being conducted to investigate EPS compaction at various temperatures to enhance the EPS extrusion process.

Materials and methods

A parallel twin-screw extruder (Process 11, ThermoFisher Scientific) with an L/D ratio of 40 and 7 heating zones was used for the EPS extrusion. Wasted EPS parts with a 22 kg/m3 density and crushed EPS materials provided by Petibol – Embalagens de Plástico S.A are being used. The initial attempts of crushed EPS extrusion proved challenging due to the material's high air content and resulted in significantly low extrusion rates. Additionally, handling crushed EPS posed difficulties due to its susceptibility to static electricity and lightweight, causing it to adhere to surfaces. Owing to the constraints of the laboratory environment, mechanical compaction proves impractical. While the solvent approach typically produces favorable results, it is accompanied by high costs. A heat exposure method was revealed to be a suitable alternative to mechanical and solvent-based volume reduction processes. Waste EPS was cut into samples measuring approximately 108 mm in diameter and 56 mm in height (yielding a total volume of about 510 cm3). These samples were then exposed to temperatures ranging from 50 °C to 150 °C for 15 min in a digitally-controlled electric oven without convection, following a procedure similar to Kan and Demirboğa [7]. To assess the efficacy of the heat exposure method, the density increase of the samples was determined by measuring their weight and dimensions before and after the treatment, employing a caliper for precise measurements. Subsequently, the samples underwent crushing, and the extrusion performance was evaluated.

The performance of the extruder's screw was analyzed with the aid of Ansys Polyflow software. The objective of the numerical simulation was to understand the pressure distribution at the extruder's wall where the blowing agent is injected, as the physical blowing agent metering system must overcome the pressure inside the extruder's barrel. A geometric model was created to represent the section of the extruder where the introduction of the blowing agent is intended. The two screw portions were modeled based on the actual geometry of the screws used in the Process 11 extruder. In the simulation of transient flows with internal moving parts, Ansys Polyflow incorporates the mesh superposition technique, simplifying the problem by dividing it into subdomains. Each subdomain has an independent mesh, and meshes can overlap. This way, there is no need for complex intermeshing regions between parts, increasing computation speed. However, the Navier-Stokes and conservation mass equations used to solve the problem must be modified as described in the Ansys Polyflow user’s guide [8]. The polymer geometry was meshed using hexahedral elements (252000 elements) and adjusted with local sizing features. Tetrahedral elements were chosen for the screw's mesh (161000 elements for each screw), as they exhibited superior quality compared to hexahedral element mesh. The mesh quality was assessed based on the aspect ratio, skewness, and orthogonal quality of the elements, and it was validated against usual reference values [9]. The problem’s subdomains are presented in Figure 1a. The boundary conditions are shown in Figure 1b and described in Table 1. The mesh of the flow domain is shown in Figure 1c.



(a) **(b)** **(c)**

Figure 1. Subdomains of the problem (a), boundary conditions indication (b), and mesh of the flow domain (c).

Table 1. Flow boundary conditions.

Boundary Conditions	Description
Inflow	Normal and tangential forces are imposed (fn, fs) = (0, 0)
Outflow	Normal and tangential forces are imposed (f_n, f_s) = (0, 0)
Inner flow	Cartesian velocities are imposed (ω_{50rpm} = 1.047 rad/s, ω_{100rpm} = 1.047 rad/s and ω_{200rpm} = 20.943 rad/s)
Extruder’s wall	Normal and tangential velocities are imposed; Zero wall velocity (v_n, v_s) = (0, 0)
Screw (moving part)	RPM of the screw is imposed (50 rpm, 100 rpm and 200 rpm)

Results and Discussion

The density change of EPS samples after the heat treatment is shown in Figure 2. There is a positive correlation between the temperature and EPS density increase. As expected, the volume reduction of EPS begins above its glass transition temperature, typically around 95 ºC [7]. Notably, a significant degree of densification occurs for the waste EPS between 120 ºC and 140 ºC due to the collapse of its expanded structure, which stabilizes shortly after, corroborating the findings of Kan and Demirboğa [7]. While this method does not achieve densities comparable to virgin PS, it is viable for laboratory-scale experiments. The extrusion performance improved with higher extrusion rates due to the higher density of the material and reduced air content.

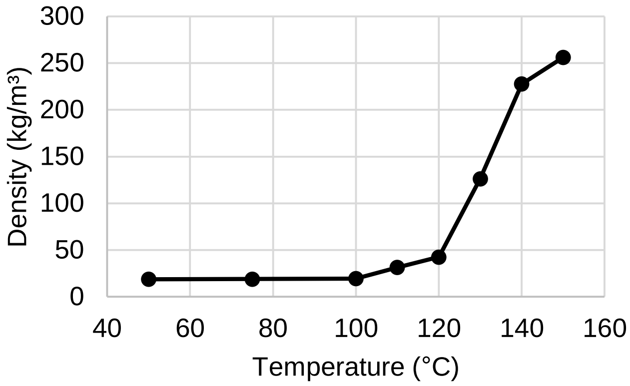
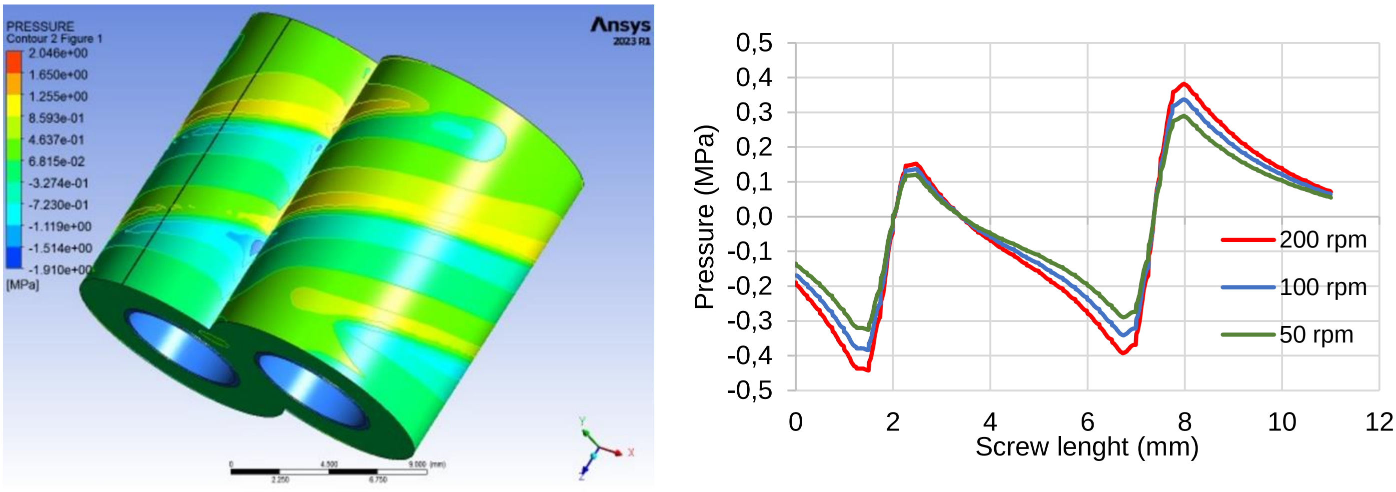


Figure 2. Waste EPS density change at different temperatures over 15 minutes.

The numerical simulation results show (Figure 3a) the pressure field along the barrel wall at the screw velocity of 200 rpm. Figure 3b shows the pressure profile at the wall of the barrel. It is evident that pressure peaks arising from melt conveying in the screw clearances are slightly more pronounced at higher screw rotations. To ensure the successful delivery of the blowing agent, the incorporation system must overcome these pressures exerted on the extruder's barrel wall. It is worth noting that despite the simulation showing negative pressures, it is not likely to occur during the extrusion process, as referred to by Goger et al. [10].



(a)

(b)

Figure 3. Pressure field along the barrel wall at 200 rpm **(a)** and pressure profile along the barrel wall for different screw rotations **(b)**.

In conventional EPS production, pentane is typically used in quantities ranging from 4 wt% to 7 wt% [1]. The used twin-extruder is capable of extrusion rates between 20 g/h and 2500 g/h. These values suggest the need for continuous addition of 0.02 mL/min to 4.66 mL/min of pentane to the extrusion process. As shown in Figure 3, the system should overcome peak pressures up to 0.4 MPa. Considering the flow and pressure requirements, a piston pump was selected. Pentane is, generally, chemically compatible with the piston pump materials. A blowing agent metering system is shown in Figure 4. The system can pump a liquid blowing agent from a source to the extruder using a positive displacement pump, typically a piston pump. This type of pump has a pulsating flow due to the pump chamber filling followed by piston actuation. This problem can be mitigated by implementing a pulsation dampener that compensates for the pulsating pressure, leading to a continuous flow. A mass flowmeter measures the exact flow being pumped and adjusts the flow to a set value via an analog signal. A bypass can be implemented as a safety measure to avoid unwanted pressure surges. Additional components like valves, filters, and pressure indicators can be implemented.

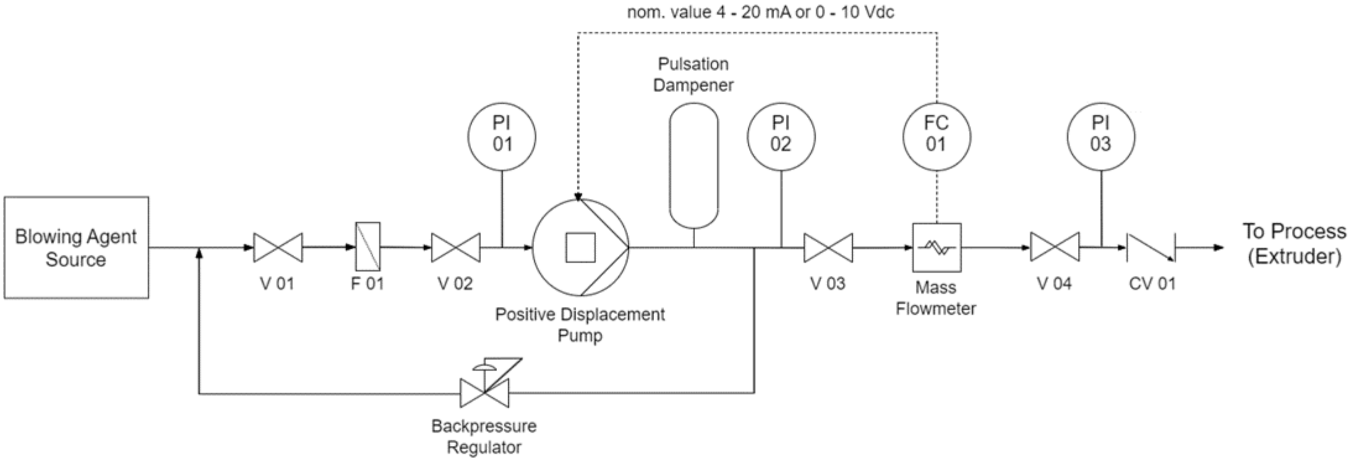


Figure 4. Blowing agent metering system.

Conclusions

This study focused on developing a prototype for incorporating a blowing agent into the extrusion of waste EPS. The heat treatment step demonstrated improvements in waste handling and extrusion performance. The Finite Element Method (FEM) analysis provided insights into the screw element's performance and pressure requirements for the blowing agent metering system. While the analysis gives general information about the pumping characteristics of the screw, a global analysis of the process is needed to determine the pressure transfer between the screw’s elements. Future research will involve conducting FEM simulations to further analyze the extruder's screw, optimizing the extrusion process, and blowing agent metering system. These insights will be valuable for the prototype’s development and production of EPS beads via extrusion. This work lays the foundation for a potential closed-loop recycling process for EPS, aligning with the European Green Deal's objectives to advance resource circularity and diminish dependence on virgin feedstocks.

Keywords: EPS; mechanical recycling; extrusion; expandable beads; blowing agent; sustainability.

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References

[1] Eaves, D. Handbook of Polymer Foams, 1st ed.; Rapra Technology Limited: Shawbury, United Kingdom, 2004; Volume 1, pp. 37-54.
[2] Raps, D.; Hossieny, N.; Park, C. B.; Altstädt, V. Past and present developments in polymer bead foams and bead foaming technology. Polymer (Guildf). 2015, vol. 56, pp. 5–19.
[3] Schyns, Z. O. G.; Shaver, M. P. Mechanical Recycling of Packaging Plastics: A Review. Macromol. Rapid Commun. 2021, vol. 42.
[4] Mumbach, G. D.; Bolzan, A.; Machado, R. A. F. A closed-loop process design for recycling expanded polystyrene waste by dissolution and polymerization. Polymer (Guildf). 2020, vol. 209.
[5] Gendron R.; Huneault, M.; Tatibouët, J.; Vachon, C.; Foam Extrusion of Polystyrene Blown with HFC-134a. Cell. Polym. 2002, vol. 21, no. 5, pp. 315–342.
[6] Hyvärinen, M.; Jabeen, R.; Kärki, T. The modelling of extrusion processes for polymers-A review. Polymers (Basel). 2020, vol. 12, no. 6.
[7] Kan A.; Demirboğa, R. A new technique of processing for waste-expanded polystyrene foams as aggregates. J. Mater. Process. Technol. 2009, vol. 209, no. 6, pp. 2994–3000.
[8] Ansys, Inc. Ansys Polyflow User’s Guide. 2019. Available from: https://ansyshelp.ansys.com/
[9] Ansys, Inc. Ansys Meshing User’s Guide. 2019. Available from: https://ansyshelp.ansys.com/
[10] Goger, A.; Vlachopoulos, J.; Thompson, M. R. Negative pressures in modelling rotating polymer processing machinery are meaningless, but they are telling something. Int. Polym. Process. 2014, vol. 29, no. 2, pp. 295–297.