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## Article

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# Innovative polymeric air–air heat recovery system — Life cycle assessment

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## Abstract

The energy consumption of conventional HVAC systems in cold climates is strongly influenced by the ventilation thermal loads required to keep adequate levels of indoor air quality. The improvement of the energy efficiency of such systems may be achieved using heat recovery systems consisting of heat exchangers used to heat cold outdoor air using as heat source hot discharge air. Today, heat recovery systems are mostly made of metallic materials, namely aluminium alloys. The present paper assesses the technical viability of an alternative concept using polymeric materials. A set of functional requirements have been defined taking into account the operating conditions of the heat recovery system in order to select a polymer that is considered an alternative to the current metals. Polystyrene was the polymer selected. It is also reported a cradle to grave life cycle assessment for polystyrene and aluminium establishing a comparative analysis of environmental impact between both. The indicators considered are: emission of greenhouse gases and energy consumed.

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*Keywords:* Heat recovery; IAQ; Life cycle assessment; Polymer integration; Ventilaqtion

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## 1. Introduction

Energy consumption plays a key role in global economic development. However, the environmental impacts associated with the production of electricity are a concern in achieving a sustainable economy. In 2016, the production of electricity worldwide with the use of fossil fuels represented about 67% [1]. In OECD countries, electricity consumption in the residential sector accounts for about 31% of final energy consumption. The indoor air heating is the most representative in what concerns energy consumption in residential buildings with about 50% [2].

In order to mitigate pollutant emissions resulting from excessive electrical consumption, it is imperative to reduce thermal load losses with the construction of airtight houses [3]. In residences of high thermal insulation, air tightness

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**Nomenclature**

ASTM	American Society for Testing and Materials
HDT	Heat Distortion Temperature
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
OECD	Organisation for Economic Co-Operation and Development

is quite high and the adoption of ventilation systems is mandatory to guarantee IAQ [4]. However, in compact envelope buildings, mechanical ventilation systems account for 50% of the total thermal losses in cold climates [5]. Heat recovery systems are an alternative to minimize those losses. These systems are characterized by recovering heat from the exhaust air to heat the new air from the outside. Energy can be recovered in the form of sensible heat or latent heat [6].

Currently, heat exchangers used in HVAC applications are manufactured mainly from metallic materials, namely aluminium alloys, due to their recognized better mechanical and thermal properties. It is also a fact that metallic alloy products have heavy energy demands thought out its life cycle and high environmental impact, whereas, for example, polymeric material products tend to detain a few advantages concerning these variables, due to their weight and volume reduction, production versatility and easy recyclability. Moreover, the literature also highlights a few advantages concerning the use of some polymeric materials when considering fouling and corrosion resistance, specially when dealing with gases as exchange fluids if dehumidification processes are considered [7].

An alternative concept based on a multi-functional modular design in polymeric material is here proposed as an air–air heat recovery system. The modularity of the design is exploited to allow the integration of modules within the system to attain the desired functionalities, such as the elimination of pollutants and odours. The present article focuses on the study of the technical feasibility of polymeric materials in the development of a heat recovery system. Moreover, the environmental impact of the production of a heat exchanger unit in polystyrene is assessed through a life cycle assessment, by analysing two different production scenarios.

## 2. Selection of polymers for air–air heat recovery

The technical feasibility analysis of the polymeric materials in the development of the air–air heat recovery is composed of several stages. Initially, the operating conditions that characterize the heat recover are defined. The next step is to associate the operational requirements with the thermomechanical properties that differentiate the polymers. Finally, polymers that can be used in air–air heat recovery according to the established criteria are selected.

### 2.1. Operational requirements

In the development of the air-to-air heat exchanger, the selected polymer must have a reduced water absorption capacity. The non-absorption of water prevents the biodegradation of the polymer by the formation of microorganisms. Humid environments have a high tendency to create bacteria that pose a high risk to health. Thus, the absorption of water should be avoided in order to guarantee indoor air quality [8].

Dimensional stability must be ensured for the temperature range of operation of the air–air heat recovery. The short-term and long-term effect of temperature and pressure are critical in the mechanical behaviour of the polymer.

The intended life for the heat recovery system is ten years. This means that the fatigue resistance that comes from the different thermal demands must be considered [9].

## 2.2. Definition of criteria

In this section, the operational requirements of the air–air heat recovery will be associated with the thermo-mechanical properties of the polymers. The polymer should be non-hygroscopic. According to ASTM D570, the dimensional stability of a polymer is ensured when the water absorption does not exceed 1% by weight [10].

Dimensional stability must be ensured for a temperature range between  $-20\text{ }^{\circ}\text{C}$  and  $50\text{ }^{\circ}\text{C}$ . The mechanical performance of the polymer at high temperatures is determined by the glass transition temperature, heat distortion temperature in the short term and maximum service temperature and thermal index in the long term, in order to achieve a lifetime as long as possible [10–12]. The glass transition temperature should not be in the operating temperature range. Above the glass transition temperature limit, the polymer acquires a rubbery structure. Below the glass temperature limit, the polymer becomes hard. The heat distortion (or heat deflection) temperature indicates at what temperature the material starts to “soften” when exposed to a fixed load at elevated temperatures (i.e. temperature at which a sample deflects by 0.25 mm under a centred standard flexural load of 455 kPa). The HDT is a useful indicator of the temperature limit above which the material cannot be used for structural applications [13]. The long-term maximum service temperature corresponds to the temperature above which the polymer properties degrade significantly [11]. The thermal index is an indicator of long-term material behaviour. The thermal index indicates the maximum working temperature at which the tensile strength decomposes by 50% after 50,000 h [12]. The temperature limit for all properties listed must be greater than  $50\text{ }^{\circ}\text{C}$ , except for the glass transition temperature.

## 2.3. Thermal and mechanical properties

A set of polymers that could be used in the application envisaged were therefore selected. Since the development of a new air–air heat recovery system was under analysis and having into account the pre-defined system specification, both material thermal and mechanical properties considered relevant were taken into consideration. The properties were compiled from the open literature database Matweb ([www.matweb.com](http://www.matweb.com)) and are listed in Table 1.

**Table 1.** Mechanical performance properties for polymers at high temperatures.

Material	Thermal index ( $^{\circ}\text{C}$ )	Heat distortion temperature ( $^{\circ}\text{C}$ )	Glass transition temperature ( $^{\circ}\text{C}$ )	Water absorption (%)	Minimum service temperature ( $^{\circ}\text{C}$ )	Maximum service temperature ( $^{\circ}\text{C}$ )
PC	75–130	78–187	142–152	0.015–0.7	–40	116–135
PEEK	180	140–260	143–155	0.05–0.5	–100(–20)	180–310
PPS	–	75–270	88–90	0.02–0.05	–	200–260
PPSU	–	182–218	220–230	0.2–1.2	–	160–210
PP	65–221	37–172	–	0–1	–30	65–125
PS	–	62–98	83–100	0–0.15	–	70–80
PSU	–	80–260	185–266	0.003–1.7	–	141–220
PTFE	–	50–93	–	0–0.1	–268(–200)	93–316
PVDF	–	40–168	–50(–18)	0–0.2	–60(–40)	100–160
PET	–	60–115	70–78	0.05–0.8	–50(–20)	60–225
HDPE	–	42–47	–120	0–0.2	–269(–70)	70–135
LPDE	–	38–101	–	0.01	–	–

From the analysis of Table 1, it can be verified that PPSU and PSU are highly hygroscopic materials and should be avoided in this type of systems. Moreover, PP, PTFE, PVDF, HDPE and LPDE detain thermal distortion temperatures below or very close to the required  $50\text{ }^{\circ}\text{C}$  and PEEK and PET do not comply with the minimum service temperature.

From the data presented in Table 1, only PC, PS and PPS comply with the minimum limits established concerning the thermal criteria and will, therefore, be further analysed concerning thermomechanical property data. Table 2 summarizes the relevant thermomechanical properties data for those selected polymers.

Having into account the system pressure requirements and the thermomechanical properties listed in Table 2, it can be seen that all polymers guarantee dimensional stability. Furthermore, the thermal conductivity is similar in all polymers listed. It could, therefore, be said that cost seems to be the last parameter to take into account to issue a decision. All polymers listed in Table 2 correspond to different polymer categories: high-performance

**Table 2.** Thermomechanical properties of polymers.

Material	Young modulus (GPa)	Yield strength (MPa)	Flexural modulus (GPa)	Yield flexural (MPa)	Thermal conductivity (W/m K)
PPS	4.34–17	–	3–21	52–230	0.255–0.3
PC	1.8–6.0	40–154	0.228–10	27.6–200	0.163–2
PS	0.3–3.35	11–59	0.9–3.54	28–206	0.17

polymers (PPS), engineering polymers (PC) and commodity polymer (PS), where the latter are considerably cheaper. According to the established criterion, the polystyrene seems to be the polymer to use in the development of the air–air heat recovery.

### 3. Life cycle assessment

The life cycle concept consists of assessing the environmental impact of a product throughout its useful life. The life cycle analysis evaluates the carbon footprint of a product from the extraction of the raw material to the recycling of the product, in a cradle to grave perspective. The elaborated life cycle follows ISO 14040 and ISO 14044 [14,15].

#### 3.1. Goal and scope definition

The goal of the LCA is to evaluate and compare the environmental impact of a heat exchanger developed on polymer material and metallic material. Moreover, when considering and assessing the polymeric product life cycle two manufacturing technologies (extrusion and injection moulding) will be addressed and compared. The latter is here considered to assist the heat exchanger design convergence criteria. The scope of the study covers the different stages of the air–air heat recovery, from the extraction of the raw material, followed by the production process of the materials and the product, until the recycling. The functional unit of the life cycle is defined by the production of a heat recovery unit. This means that the inputs and outputs of the system are relative to the requirement required to produce a drive.

#### 3.2. System boundaries

Fig. 1 illustrates the air–air heat recovery analysis of the heat exchanger for aluminium and polystyrene including the production process of polystyrene and aluminium. The input of the system corresponds to the energy consumed in the various steps throughout the life cycle, while the outputs are agents responsible for the environmental impacts such as the emission of greenhouse gases as well as the consumption of fossil fuels.

#### 3.3. Inventory analysis

The life cycle analysis begins with the extraction of the raw materials required to produce the material. For aluminium only, primary production is considered. Thus, aluminium is produced from the extraction of bauxite, which by the Bayer process is converted to alumina. This process is widely used by the industry in the primary production of aluminium. The molten aluminium is obtained through the electrolysis of alumina by the Hall–Heroult process. The anodes used in this process, for the passage of electric current, result from coke extraction. Finally, smelting is reheated to eliminate impurities resulting in ingots casting. Aluminium sheets are the result of the hot rolling mill process [16–18].

The production of polystyrene is based on the extraction of crude oil and natural gas. Ethylene is produced by cracking between the combination of naphtha and natural gas. Naphtha results from the refinement of crude oil [19]. By the reaction between benzene and ethylene is formed ethyl-benzene, which upon suffering dehydration becomes styrene. Polymerization, in solution, of styrene free radicals produces polystyrene [20].

The manufacturing methods of the air–air heat recovery in study vary depending on the material. For the air–air heat recovery of aluminium were considered technologies of laser cutting and mechanical conformation. For the polymeric air–air heat recovery the injection and extrusion processes were studied.

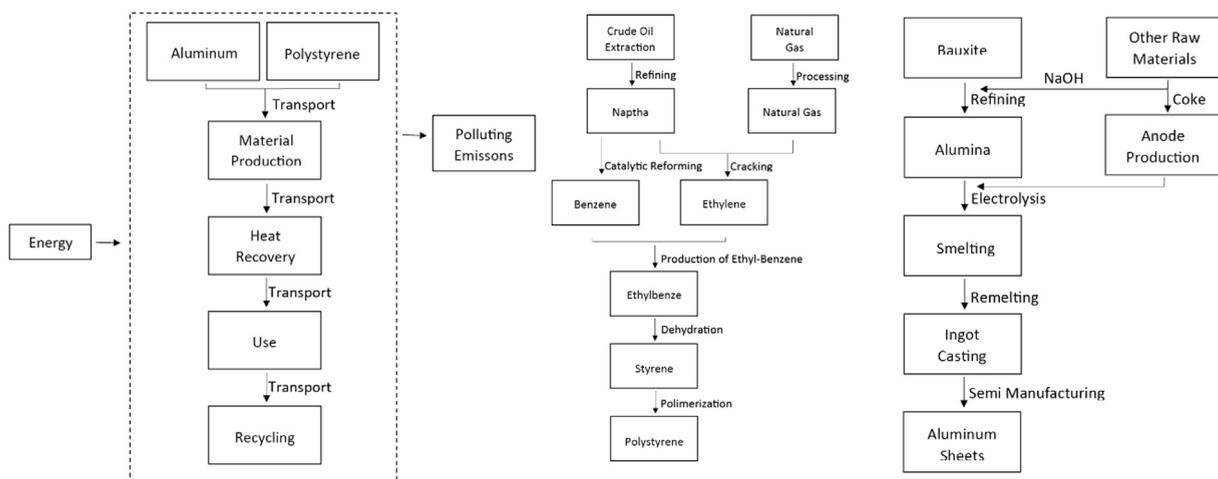


Fig. 1. Considered life cycle scheme for a heat recovery system (including raw materials processing).

In the course of the use phase, no processes or energy consumptions were analysed. The heat transfer between air fluxes only depends on the geometry of the air–air heat recovery. The recycling does not consider the manufacture of recycled material nor the reintegration of this in the productive cycle.

Transport operations contemplate various types of transport such as railway and truck in the interior of Europe and barge and boat in the transport of the raw material. The production of the air–air heat recovery was assumed in Europe and therefore the distances are defined accordingly. Also, the electric consumption is based on the European average values.

### 3.4. Impact assessment

The method used to assess the environmental impact was IMPACT 2002+ with SimaPro software. This method consists of the combination of the IMPACT 2002, Eco-Indicator 99, CML and IPCC methods. The IMPACT 2002+ method assesses environmental impact by converting LCI data into midpoint impact categories. Impact categories are converted into damage categories [21]. The environmental impact analysis is based on the categories of global warming potential, namely CO<sub>2</sub> and non-renewable energy. Fig. 2 presents the obtained results.

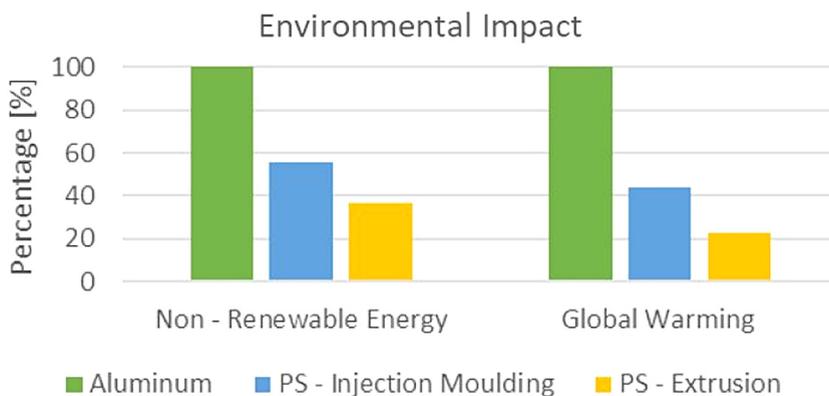


Fig. 2. Environmental impacts related to life cycle analysis of aluminium and polystyrene.

Non-renewable energy is characterized by energy consumption at different stages of the life cycle, from fossil fuels. The aluminium air–air heat recovery consumes about 9380 MJ, the HR - injection moulding 5040 MJ and the HR - extrusion 3330 MJ. Global warming is defined by the amount of CO<sub>2</sub> emitted during the life cycle. Thus, the

HR in aluminium emits about 572 kg CO<sub>2</sub> eq, the HR - injection moulding 244 kg CO<sub>2</sub> eq and the HR - extrusion 128 kg CO<sub>2</sub> eq.

#### 4. Heat recovery

The life According to the environmental and mechanical assumptions evidenced here, a polystyrene air–air heat recovery was developed. The air–air heat recovery has a quasi-counter flow configuration and a parallel flat plate. This means that it combines a counterflow arrangement with crossflow arrangement. The cold airflow alternately fills the channels formed by the stacking of the plates. The same rationale applies to the flow of hot air. For a plate thickness and channel height of 2 mm, the achieved efficiency for the air–air heat recovery is 80%. Efficiency only considers the transfer of sensible heat.

#### 5. Conclusion

The present study evaluates the technical feasibility of a new design heat recovery system in a polymeric material. Having into account the criteria specified for product compliance, only PPS, PC and PS, were observed to meet the minimum requirements for the established operating conditions. A further analysis enabled to verify that all three selected polymers would guarantee dimensional stability for the operating pressures range specified and that the three material thermal conductivities were very close, therefore, the selection of the polystyrene is based on the cost of the material. A life cycle analysis of a polymer air–air heat recovery is also evaluated in comparison with an aluminium heat exchanger. LCA demonstrates that the greatest environmental impact belongs to the aluminium heat exchanger, as it emits more CO<sub>2</sub> into the atmosphere and consumes more energy from fossil sources. In turn, the extrusion of PS proves to be more environmentally friendly when compared to the injection moulding manufacture, as it emits about half the amount of CO<sub>2</sub>. In addition, injection moulding consumes more energy from fossil fuels. It can, therefore, be concluded that the development of polymeric heat exchangers still has a number of interesting issues worthing further research.

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