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Reduction of the carbon footprint through polystyrene recycling: Economical evaluation

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ABSTRACT

The incorporation of CO_2 into new processes is one of the most important strategies for gas emissions mitigation that also would help to decrease the *Carbon footprint*. Recycling of wastes is also considered as a route to prevent greenhouse emissions as well as a source of interesting raw material. The process of recycling of polystyrene (PS) wastes using high-pressure CO_2 as antisolvent and blowing agent in order to produce microcellular foams with enhanced properties was proposed, because the process could combine the benefits of both strategies for CO_2 mitigation while high value-added materials were achieved.

The technical, environmental and economical advantages of the recycling of polystyrene wastes were evaluated in an industrial and pilot-scale plant considering that CO_2 could be recirculated during the process in several cycles in order to minimise its consumption while the economical profit is maximised.

1. Introduction

Global warming has become one of the most important threats to human life since it could modify health of living beings and environment steadiness (Jacobson, 2009). It is believed that greenhouse gases produced by human activities are mainly responsible for global warming. In the past years, *Carbon footprint* term has attracted an increasing attention in the context of the climate policy negotiations despite being a generic concept (Minx et al., 2009; Wiedmann, 2009). Although a generally accepted definition of *Carbon footprint* is not achieved, it could be established that the total sets of direct and indirect greenhouse gas emissions are produced directly or indirectly by organisations, events, products or people and are measured in tonnes of CO_2 equivalent (Fuglestvedt et al., 2003) .

Industrial manufacture of new products (steel, cement, plastics, paper, etc.) could be considered as the main source of CO_2 emissions, and also fossil fuel burning, transportation or wastes disposal and treatment (Raupach et al., 2007). Carbon capture and storage, reduction of materials, design of light-weighting products, extension of their life span, recycling of components or conceiving new and more innovative process are some of the main strategies for the mitigation of CO_2 emissions (Allwood et al., 2010). Although a wide attention is being paid to carbon capture and storage (Jiménez et al., 2012; Li et al., 2011; Markewitz et al., 2012; Pires et al., 2011; Rabbani and El-Kaderi, 2011; Wang et al., 2011), the use of CO_2 as raw material is shown as an almost unexplored alternative that could have several advantages. In this way, carbon dioxide is not considered an issue but a key element for the feasible development of environmentally friendly chemical processes (de Falco et al., 2013).

Carbon dioxide could be incorporated in several processes as a carbon source, as a solvent or as a processing fluid due to its interesting physicochemical properties (Cooper, 2000; de Falco et al., 2013; Hearon et al., 2014; Peters et al., 2011; Song, 2006). Particularly, supercritical carbon dioxide ($scCO_2$) offers numerous advantages from an economical, chemical and environmental point of view, since it is non-toxic, non-flammable and inexpensive, and it presents an adjustable

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solvent strength and moderate critical temperature and pressure (Beckman, 2004; Davies et al., 2008; Kikic, 2009; Pantoula and Panayiotou, 2006; Woods et al., 2004; Yeo and Kiran, 1999). Besides the above-mentioned benefits, the use of $scCO_2$ as a feedstock yielding high value-added products greatly increases the interest of new processes.

However, increasing amounts of wastes are accumulated in landfills, which could lead to higher emissions of greenhouse gases (Jeswani et al., 2013) together with the disposal of high economic value materials (Gutiérrez et al., 2015). European authorities are focused on the design of new waste management strategies in order to prevent greenhouse emissions, reduce environmental impacts and take advantage of wastes, mostly from plastic residues due to their potential value (Da Cruz et al., 2014; Ferrão et al., 2014). The design of a process for plastic recycling, incorporating CO_2 as feedstock to get high value-added products, ideally combines different strategies to achieve *Carbon footprint* reduction.

Recycling of polystyrene (PS) wastes is shown as a current challenge since it is a non-renewable polymer, whose disposal creates environmental pollution (Hearon et al., 2014; Mwashaa et al., 2013). With the aim of recycling plastics residues through an environmentally friendly process using CO_2 and producing microcellular foams of PS, the process schematised in Fig. 1 was proposed. It consists of two steps: dissolution of polymer wastes in natural terpenes and separation of the solution components using high-pressure CO_2 (García et al., 2008; Gutiérrez et al., 2012). According to Fig. 1, very small amount of residue would be produced since CO_2 and terpenes streams could be recovered during the process in several cycles.

Limonene was selected to dissolve PS since it can be obtained from natural sources (García et al., 2009a,b; Noguchi et al., 1998), is non toxic, is relatively low cost and is fully miscible with CO_2 (Gutiérrez et al., 2013b; Sovová et al., 2001). Besides, high-pressure CO_2 was incorporated as antisolvent of PS, allowing the polymer precipitation, and as blowing agent, allowing the polymer foaming in order to achieve higher value product from wastes (Dixon and Johnston, 1993; Gutiérrez et al., 2014; Luna-Bárcenas et al., 1995). Microcellular foams typically exhibit high impact strength, toughness and thermal stability, as well as low dielectric constant and thermal conductivity (Bao et al., 2012), which make them suitable for non-weight-bearing architectural structures due to its rigid nature and enhanced properties.

The described process would be economically feasible if the microcellular foams present improved properties; it means that higher value-added products should be obtained to balance the costs of recycling while *Carbon footprint* is reduced. The right choice of operating conditions, the optimal design of plant facilities and the decision about CO_2 regeneration were selected as key parameters to determine the environmental, technical and economical feasibility of the process. The aim of this work is to establish the range of conditions where the recovery of CO_2 to the process provides financial benefits while reducing the *Carbon footprint*.

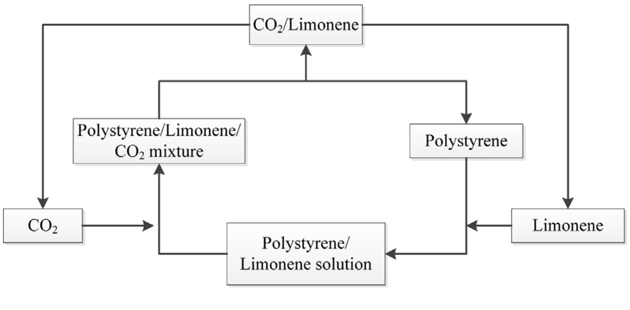

Fig. 1 – Schematic diagram for recycling of polystyrene wastes using limonene and high-pressure CO_2 as antisolvent.

2. Experimental

2.1. Materials

Atactic polystyrene in pellets and R-(+)-limonene (97% purity) were supplied by Sigma-Aldrich (Spain) and used without further purification. Carbon dioxide with a purity of 99.8% was selected as the supercritical solvent and was supplied by Carburos Metálicos S.A. (Spain).

3. Foaming setup

The experiments for recycling polystyrene were performed at laboratory scale, as shown in Fig. 2. The polymer solution was placed in the vessel (E-2) under the working temperature. Next, liquid CO_2 from a stainless-steel cylinder was cooled (E-1), filtered (F-1) and compressed using a positive-displacement pump (P-1). The pressure was regulated by a back-pressure regulator and checked by a manometer (PI) before got into the 350 ml stainless-steel vessel (C-1) through a regulation valve (V-4). The temperature was kept constant through a digital controller (TIC) which regulated the electric current by means of a resistance placed around the vessel (±0.1 °C). Foaming experiments were performed for 4 h in order to assure that saturation conditions were reached. Finally, the vessel was depressurised opening a discharge valve and a regulator valve (V-5 and V-6, respectively), which were controlled manually by the measurement of the flow in a turbine flow meter (I-1). The flow was regulated in order to induce and control the cell nucleation.

4. Characterisation

Microcellular foams were characterised using a Quanta 250 scan electron microscope (SEM) to determine size and structure of the cells. Motic Images 2.0 and Minitab 16 (Minitab Inc, State College, Pennsylvania, EE.UU.) software were used to determine diameter distributions and density of the cells.

5. Methodology

A plant for recycling polystyrene wastes in order to produce microcellular foams was designed. The general scheme of the plant consists of a main vessel, where the foaming of PS is performed with several tanks containing solutions and raw materials. In addition, there are pumps and compressor for the feeding of polymeric solution and CO_2.

The profitability of CO_2 recovery related to economical criteria was studied in two different scenarios, which were fixed according to the population of the region and the rates of the polystyrene wastes produced per habitant in Spain (ANAPE, 2014). Scenario 1 (Fig. 3) was based on building and operating a new plant for the recycling of 10 ton PS wastes/day. The industrial plant consisted of one CO_2 reservoir (C-7), one solvent reservoir (C-0), five foaming vessels (C-1 to C-5), one separation vessel (C-6), heat exchangers (E-1 to E-3), two compressors (K-1 and K-3) and one expander (K-2). Five vessels for