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Alternative polymer separation technology by centrifugal force in a melted state

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ABSTRACT

In order to upgrade polymer waste during recycling, separation should take place at high purity. The present research was aimed to develop a novel, alternative separation opportunity, where the polymer fractions were separated by centrifugal force in melted state. The efficiency of the constructed separation equipment was verified by two immiscible plastics (polyethylene terephthalate, PET; low density polyethylene, LDPE), which have a high difference of density, and of which large quantities can also be found in the municipal solid waste. The results show that the developed equipment is suitable not only for separating dry blended mixtures of PET/LDPE into pure components again, but also for separating prefabricated polymer blends. By this process it becomes possible to recover pure polymer substances from multi-component products during the recycling process. The adequacy of results was verified by differential scanning calorimetry (DSC) measurement as well as optical microscopy and Raman spectroscopy.

1. Introduction

Several options of separating materials from each other have gained new impulses of development, due to their adequacy for a more pronounced way of recycling. In the past three decades, the use of polymers has been increased continuously. The production of plastic materials has been increasing by about 5% annually. As a consequence, the polymer waste stream has been rising too, especially that of municipal solid waste. By processing only low-quality products it can be realized if the whole waste stream is used at the same time, which is called ‘downcycling’. More than half of polymer materials are discarded every year despite their durability, so it is necessary to separate and recycle polymers because of social pressure and environmental aspects (Alter, 2005; Bezati et al., 2011; Wu et al., 2013). Thus, it would be desirable to establish a new, alternative separation method, which enables the sorting of assorted waste products into individual substances from the waste stream possible in one step, regardless of the materials (Zhang et al., 2012). The processing temperature, density, and molecular and physical characteristics are different for all polymer materials, so they are usually not compatible with each other. Therefore, it would be desirable to separate the waste component with high effectiveness. Separating the fine purity of the waste component is the most important precondition for producing good quality products. When the polymers are washed and separated from each other, and further additives are added at manufacturing – such as fibre reinforcement or chemical agents – it could be possible to produce higher quality products than virgin materials. This process is called ‘upgrading’ or ‘upcycling’ (Vermeulen et al., 2011).

The management of post-consumer plastic waste is complicated since the greater part of it is placed into communal rubbish. The separated polymer waste from post-consumers is typically: (i) polyethylene terephthalate (PET) from soft drink bottles; (ii) polypropylene (PP); (iii) polyethylene (PE) with high (HDPE) or low density (LDPE) from packaging and bottles; (iv) polystyrene (PS) from drinking cups and pots; and (v) polyvinyl chloride (PVC) from pipes and interior furnishings (Bezati et al., 2011; Pongstabodee et al., 2008). Given that the content of the post-consumed polymer waste is heterogeneous it is necessary to separate it into pure polymer component. The recycling process can be more complicated if the polymers contain fibre reinforcement or other additives, or if the material is foamed. These components modify the density, thus it is not possible to assign a fixed density value to the polymer. A density range can only be established where the individual component can be found. In addition, splitting polymer blends into neat substances is not solved yet with the current sorting equipment. These polymer blend parts are present as contaminants in the separation process, and impair the quality of the recycling process.

As is currently known, it is difficult to achieve the required purity of mixed polymer waste in just one step. Indeed, the grade of PP and PE from waste should be higher than 97%, in order to be suitable for manufacturing at high level (Bakker et al., 2009).

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Multi-step separation methods are usually applied to industrial processes. By simple, common density-based separation technologies, it is difficult to separate mixed plastic waste constituents from each other, when there are slight differences in density, such as PET and PVC mixtures (Burat et al., 2009; Sadat-Shojai and Bakhshandeh, 2011; Takoungsakdakun and Pongstabodee, 2007).

The simplest separation method is hand-sorting. The pickers separate the materials from each other, while the hazardous waste, metal parts and non-polymer waste is removed. The disadvantage of this process is the low output and errors made by humans, so it is suitable as an option of pre-sorting (Super et al., 1993). The same principle applies to optical sorting, which can be automated, and is another way of pre-sorting, whereby an optical light, infrared or X-ray source can be used. The absorbed light can be exploited in this way and is reflected differently by the polymers owing to the specific state of electrons which characterize every polymer substance (Arvanitoyannis and Bosnea, 2001; Bodzay et al., 2009; Serranti et al., 2011). With optical methods, polymers can only be sorted by colour, except for black painted materials. Near-infrared technology is also unsuitable for dark objects. However, with mid-infrared ranges dark-coloured polymers can be identified. X-ray spectroscopy is only used to isolate PVC materials (Alter, 2005; Zhang et al., 2012). Another possibility for pre-separation is the density-based separation method. In this case, separation is feasible with dry particles, using air classifiers, or water-based solutions or suspensions as separating media. The particles sink or float in the fluid depending on the force of buoyancy (Gent et al., 2011). One simple way of separation is the water separation method as an intermediate density medium, where the municipal solid plastic waste can be separated into less than 1 g/cm^3 polyolefin and other polymers of higher density.

Standard industrial solutions for polymer waste separation of individual components are: (i) integrated spectral imaging analysis (Bodzay et al., 2009; Serranti et al., 2011); (ii) gravity separation of density-based of polymers; (iii) froth flotation; (iv) electrostatic separation; and (v) magnetic separation (Bakker et al., 2009; Burat et al., 2009; Carvalho et al., 2007; Pongstabodee et al., 2008; Sadat-Shojai and Bakhshandeh, 2011; Takoungsakdakun and Pongstabodee, 2007). The literature also mentions centrifugal force separation (Gent et al., 2009), separation in a melted state and chemical solving (Bakker et al., 2009), which are used rather within laboratory conditions.

Surveying separation by spectral signs, Gondal and Siddiqui (2007) found that laser-induced breakdown spectroscopy is suitable for detecting PE, PP and ABS molecules. Fourier transform infrared spectroscopy (FTIR) and Raman spectroscopy are widely used for detecting the purity of the separated final polymer waste, after the measurement of the spectral signals for pure substances (Fávaro et al., 2013; Giancola et al., 2012; Ramesh et al., 2007; Serranti et al., 2011; Vajna et al., 2012).

Triboelectrostatic separation can be a solution for post-consumer waste management. With different materials touching each other they have a different charge in opposite polarities. It is well-known that two particles with different surface properties, in contact with each other, may be charged, and electron transfer happens until equality of the Fermi levels of the touching materials. This phenomenon is called triboelectric charging effect or tribocharging (Matsusaka et al., 2010). After this step, charged particles are fed into an electric field to separate the fractions into homogeneous parts, because the trajectories of particles are deflected, according to the polarities and the quantity of the charge.

Density-based separation can be accomplished either with dry particles and separation medium, or by water-based suspensions. The division of polymers is based on the effects of sinking or floating of the particles in the separation medium. The process is driven by the force of buoyancy (Gent et al., 2009). Super et al. (1993) used a mixture of near-supercritical fluids – sulphur hexafluoride (SF_6) and carbon dioxide (CO_2) – to separate post-consumer plastic waste. The density of the separation media was changeable, depending on the ratio of the gases. The results showed a pollution grade of 3–5% in the neat separated polyolefin fractions, and less than 1% of cross-contamination in PET/PVC mixtures. A wet shaking table is a wet waste separation method, where the relative movement responds to gravity and other forces. To separate plastic waste from one another a minimum difference of density of the materials is needed, which has been determined by Wills (1997). Carvalho et al. (2007) investigated the efficiency of wet shaking table separation of PS/PET/PVC mixtures. The results showed that it was possible to separate whole amounts of PC from a PET/PVC waste stream in one step. They found if a higher grade of PET purity was needed a lower recovery was obtained, and vice versa.

The separation of plastic mixture is not possible because of the slight differences in density. Therefore, it is necessary to also use a frothing and wetting agent, to achieve acceptable purity of the substances. Pongstabodee et al. (2008) developed a three-stage sink-float method with selective flotation, to separate post-consumer plastic waste into pure fragments. Burat et al. (2009) used also froth flotation to separate virgin and recycled PET and PVC. They found that strong alkaline solutions are able to destroy the hydrophobicity of PET more than PVC. So PET was rendered to hydrophilic, while the PVC remained in a hydrophobic state. It can be concluded that separating post-consumer waste is more difficult because of the degradation and dirtiness of the waste.

Bakker et al. (2009) developed an alternative method of separating polyolefin fractions. They used inverse magnetic density separator (IMDS), where a lower apparent density than water could be achieved by the separation medium, because of the combination of the gradient magnetic field and the magnetic liquids, where the latter contains nanoscale ferrite particles. So it is possible to make the suspension artificially lighter or heavier. They used a splitter, with which the height of the separation line could be adjusted in the liquid after the mixing zone. PE particles were flown under, while PP flown over the splitter (Fig. 1). The results of the research of Bakker showed a 98% purity and 72% recovery rate for PP. A higher grade of purity of PE can be achieved with a second splitter to separate fractions into three groups.

Taking advantage of the centrifugal force field is another opportunity to separate materials, which is exploited in many other areas. Centrifugation is a density-based separation technology, based on the density differences of the particles. Centrifugal separators can exert huge forces on the liquid and particles, so the contamination can be isolated from the other fraction or the fractions can be separated from each other. Eq. (1) shows that the separation force depends on the density of the particle and the spinning speed, in 1D case at small Reynolds number ($Re < 1$).

$$F_{cf} = m \cdot a_{cf} = \rho_a \cdot V_a \cdot r \cdot (2 \cdot \pi \cdot n_{c,m} \cdot 60)^2 \quad (1)$$

where F_{cf} is the fictitious centrifugal force, m is the mass of the particles, a_{cf} is the centripetal acceleration, r is the distance between the axis of rotation and the particle, $n_{c,m}$ is the speed of the equipment in minutes, ρ_a and V_a are the density and the volume of the particle a, respectively.

This procedure is used for the fabrication of biodegradable polymer fibres (Wang et al., 2011), in mineral processing at classification and separation, dewatering or waste-water treatment (Batalović, 2011), producing highly integrated biodiesel fuels (Kraai et al., 2009) and particle classification (Yamamoto et al., 2009). This technology is also significant as it is used in the field of medical technology (Kim et al., 2013) and in the food industry