



An on demand chilling system: Activated carbon based desorptive cooling

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ABSTRACT

Every year in Europe refrigerant gases with a greenhouse-warming equivalent of more than 30 Mt CO₂ are emitted from retail refrigerators. Furthermore, the effective efficiency of such refrigerators is far below that achievable under ideal (e.g. optimal-load; minimum access) operation. In this work the design of an alternative on-demand cooling unit is presented. The unit is based on the cooling effect provided by desorption of carbon dioxide previously adsorbed onto a bed of graphite-bonded activated carbon: in this paper, a case study of a self-chilling beverage can is used to demonstrate the technology. The high compaction of the activated carbon, and the presence of graphite, enhances the heat transfer properties of the adsorbent, thus enhancing the efficiency of cooling. Furthermore, potential exists for the use of activated carbon and CO₂ from waste sources. This paper provides an overview of the design basis and environmental advantages of the unit, and experimental and simulation studies on the thermal dynamics of the cooling process. Particular attention is given to the effective thermal conductivity of the activated carbon bed. The results indicate that adequate on-demand cooling can be achieved within a portable unit. However, scope exists for enhancing the heat transfer within the cooling chamber through design and bed composition alterations. Recommendations for improved unit design are presented.

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1. Introduction

Every year in Europe, refrigerant gases with an equivalent global warming impact of 30MT_{CO₂e} are emitted from retail refrigerators (Cowan et al., 2010). In the Kyoto Protocol, the most commonly used group of refrigerants, – hydrofluorocarbons (HFCs), are in the list of the seven worst significant greenhouse gases, commonly referred as the *basket* of greenhouse gases (Bovea et al., 2007; UNFCCC, 1997; Wakefield, 2016). Leakages of HFCs and hydrochlorofluorocarbons (HCFCs) have adverse impacts on climate change not only because they are powerful greenhouse gases, but also because leaking systems are less energy efficient (Bovea et al., 2007; Cowan et al., 2010). Therefore, worldwide energy consumption has directed more attention on alternatives to conventional refrigeration systems (Halder and Sarkar, 2007; Neveu and

Castaing, 1993; Wang and Oliveira, 2006) already highlighted in the Montreal Protocol of 1987.

Desorptive cooling using activated carbon and carbon dioxide has emerged as one of the possible alternatives with zero ozone-depletion potential (Chan, 1981; Goetz and Guillot, 2001; Halder and Sarkar, 2007; Wang and Oliveira, 2006). Adsorption technology is commonly used for gas separation processes in which a gas is adsorbed on a packed column of microporous-mesoporous adsorbent at high pressure. Depressurising the column then leads to endothermic desorption of the adsorbed components from the solid (Alpay, 1992; Halder and Sarkar, 2007; Sircar, 2002), thus providing a cooling effect. The adsorbent can be then reused. Based on this simple desorptive cooling process, a new technology to provide cooled products on demand has been designed. This *chill-on-demand system* avoids any requirement for chilled storage. It uses the cooling effect provided by desorption of carbon dioxide previously adsorbed onto a bed of activated carbon contained in an inner chamber of the self-chilling product. This technology has the potential to be applied to any type of product that needs to be cooled at the point of consumption or service that requires rapid cooling on demand.

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List of acronyms

AC	Activated Carbon
CCU	Carbon Capture and Utilization
CENG	Consolidated Expanded Natural Graphite
CVA	Constant Volume Adsorber
DEA	Diethanolamine
ENG	Expanded Natural Graphite
HCFC	Hydrochlorofluorocarbons
HEU	Heat Exchange Unit
HFC	Hydrofluorocarbon
IGA	Intelligent Gravimetric Analyser
LCA	Life Cycle Assessment
MOF	Metal Organic Framework
PSA	Pressure Swing Adsorption

This paper reports on the design and evaluation of a self-chilling unit for one possible application of this technology: a self-chilling beverage can. The system consists of an outer steel can containing the beverage and an inner aluminium can, called the Heat Exchange Unit (HEU), which contains activated carbon (AC) mixed with graphite to increase the thermal conductivity and loaded with carbon dioxide. The beverage has no contact with the activated carbon; a vent located at the bottom of the container allows the carbon dioxide to be released to the atmosphere, releasing the pressure inside the HEU. The desorption of carbon dioxide from the activated carbon is endothermic, thereby providing a cooling effect that should ideally decrease the temperature of the beverage by about 15 K. Specific consideration is given here to CO₂ desorption from activated carbon obtained from coconut shells. In previous work (Arena et al., 2016a, 2016b) the potential environmental benefits of such a carbon source, compared to coal based activated carbon, has been reported.

A Life Cycle Assessment (LCA) has previously been developed for this product system considering all the life cycle stages of a self-chilling can: manufacture of each part of the beverage container, its utilization, collection of the used can, and management of the waste by reuse, recycling and landfilling (Arena et al., 2016b). The most significant environmental impact categories were found to be Global Warming Potential, Human Toxicity Potential and Acidification Potential. These arise primarily from production of the activated carbon granules. The LCA showed that the sustainability of AC production, and consequently that of the whole self-chilling system, can be improved by reducing electrical energy consumption in the process units of crushing and tumbling, by using an efficient integrated process, and by locating the production where the carbon intensity of the electricity supply is low or by using energy produced *in situ* from renewable sources such as biomass. Offsetting the additional impacts of producing the additional components to make the impacts of the self-chilling can comparable with those of a conventional can would require unrealistically high rates of recovery and re-use, particularly of the HEUs. (Arena et al., 2016b).

In this work, attention is given to an experimental investigation of the thermal dynamics of the process, supported by a transient heat exchange model.

2. Theoretical background

2.1. CO₂ – activated carbon combination

Some studies have been reported on solid sorption cooling using

carbon dioxide as refrigerant and activated carbon as adsorbent (Goetz and Guillot, 2001; Zhong et al., 2006). This solute-sorbent combination appears to be the best for several reasons (Ku wagaki et al., 2003). First of all, the CO₂ is neither toxic nor flammable; it is inexpensive and widely available. Because it is a waste product from some industrial processes, any subsequent use has low impact on the global environment (Arena, 2016; Arena et al., 2016b; Zhong et al., 2006). The thermodynamic properties of the gas are also particularly attractive because its heat of desorption is high and the adsorption pressures needed are acceptable (Goetz and Guillot, 2001; Halder and Sarkar, 2007).

Furthermore, the adsorbent structure fits the carbon dioxide molecule particularly well. From a theoretical point of view, zeolites are considered the sorbents with the best adsorption efficiencies at low pressure and ambient temperature. They have an ordered, continuous and predictable structure due to the equal distribution of silicon and aluminium which provides a uniform pore size distribution. For a known molecular size, this allows the adsorption efficiency to be predicted for most physical conditions. The adsorption efficiency of a zeolite is affected by its size and charge density and the chemical composition of cations in the porous structure. However, as reported in several studies (Martin et al., 2010; Yu et al., 2012), the use of activated carbons is preferred due to their wide availability, low cost, ease of regeneration, lower sensitivity to moisture and larger capacities at high pressure. They are also characterized by more rapid mass transfer, stable adsorption performance and also absence of the corrosion concerns that can arise with metal containers and chemical absorbents (Wang et al., 2013). In particular, the manufacture of the chilling HEU requires the sorbent to have a high capacity to limit the pressure at which the carbon dioxide is adsorbed. There is a potential for moisture to be present in the HEU, particularly if it is re-used, and this would render a zeolite-based HEU less efficient and less reusable than one filled with activated carbon. These characteristics all suggest that activated carbons are preferred over zeolites for application in self-chilling drink cans.

Yu et al. (2012), also reported the use of MOFs (Metal Organic Frameworks) sorbent materials, which have the advantages of high surface area, controllable pore structures and tunable pore surface properties while the preparation cost is lower than for microporous carbons (Wickramaratne and Jaroniec, 2014). However, resistance to water contamination, thermal stability, ease and consistency of preparation, and cost and energy requirements for regeneration all indicate activated carbon as a superior material for the application of interest here.

2.2. Heat transfer in activated carbon

Poor heat and mass transfer in adsorption systems is one of the factors that prevent widespread application of adsorption refrigeration systems (Li et al., 2015) and represents a potential negative aspect for the chill-on-demand system. To function efficiently, the self-chilling system needs to cool the beverage quickly and keep it chilled, while not losing too much of the potential cooling by overcooling the HEU itself and the vented carbon dioxide. Therefore, along with adequate cooling on desorption with a sufficient quantity of adsorbed carbon dioxide to achieve the desired cooling, good heat transfer is important between the HEU and beverage.

Beds of granular activated carbon have low thermal conductivity, typically in the range 0.17–0.28 W m⁻¹ K⁻¹ (Ku wagaki et al., 2003; Li et al., 2015; Py et al., 2002; Tamainot-Telto and Critoph, 2001; Wang et al., 2003, 2013). Ku wagaki et al. (2003), classified activated carbon as “a non-thermally conductive material”, and found that combining the activated carbon with a suitable additive can increase the conductivity. One of the most common approaches

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