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Journal of the European Ceramic Society 32 (2012) 2087–2094
www.elsevier.com/locate/jeurceramsoc

The carbon footprint and energy consumption of a commercially produced earthenware ceramic piece

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Received 2 December 2011; received in revised form 7 February 2012; accepted 12 February 2012
Available online 7 March 2012

Abstract

The product carbon footprint quantifies the greenhouse gas (GHG) emissions during the life cycle of a product, from the extraction of raw materials, through the production, use and recycling, to the disposal of the used product.

In this study, the carbon footprint of an ornamental earthenware ceramic piece has been estimated following the PAS 2050:2011 methodology, and the energy and GHG hotspots have been identified.

The carbon footprint and the total energy consumption of the selected ceramic piece is 1.22 kg CO_2e per piece and 8.19 kWh, respectively.

The manufacture represents almost 90% of the carbon footprint of the piece.

The energy hotspots are natural gas production, biscuit firing and condensing boiler. Some measures to reduce the consumption of natural gas and electricity have been applied, such as the implementation of a gas pressure control system in the kilns and the mill lighting system optimization, respectively.

Keywords: Carbon; Product carbon footprint; Firing; Slip casting

1. Introduction

The issues related with energy requirements, greenhouse gas (GHG) emissions and sustainable development have become a major concern for many companies and business councils, as they are increasingly being incorporated into governmental policies.

The Brundtland report, published in 1987 by the World Commission on Environment and Development (WCED), defined sustainable development as development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs.[1] The sustainable development considers three main components: environment, economy and society. These pillars should be equally developed in order to achieve a sustainable development. They are related with each other so as to reduce the exploitation and use of natural resources, the consumption of energy and fuels and to decrease the emissions, maintaining the economic competitiveness and social cohesion.

The energy mix in the European ceramic industry is typically 80% of natural gas and 20% of electricity.[2] In 2003, the average specific energy consumption of the European ornamental earthenware sector was 45.18 GJ/t, whereas the brick sector presented the lowest average specific energy consumption (2.31 GJ/t).[3]

Between 2003 and 2007, the ornamental earthenware sector has been strongly affected by either the economic downturn and by the strong competition from the new emerging markets.[4] Therefore, to ensure the competiveness this sector highlights the need of reduction of the energy consumption across the life cycle of the product, and the quantification and reduction of the GHG emissions.

The ornamental earthenware ceramic manufacturing is typically a multifunctional system because several pieces with different dimensions and geometries are produced in the same mill, at the same time, involving multiple firing cycles for the same ceramic piece. Therefore, to estimate the energy

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doi:10.1016/j.jeurceramsoc.2012.02.018

consumption and the CO_2 emissions, per piece, in the manufacture stage, an allocation procedure is needed. Different allocation methods based on mass, volume, energy content or market price criteria may be used for solving multifunctionality.[5,6] The choice of the most appropriate method depends, among others, on the available data and the characteristics of the multifunctional system.[6] Therefore, to estimate the energy consumption and the CO_2 emissions, per piece, an allocation hybrid approach has been applied, based on the mass, volume or number of pieces, depending on the type of energy and stage of manufacturing.[7]

Although there are some published studies that quantify energy requirements and emissions for ceramic products,[8–12] none of them deals with ornamental earthenware ceramic pieces. Furthermore, the application of allocation procedures is not commonly referred in those studies.

The product carbon footprint quantifies the GHG emissions over the whole life cycle of a product, from the extraction of raw materials, through the manufacture, use and recycling, to the disposal of the used product (cradle-to-grave approach).[13] The product carbon footprint enables the:

- communication, by labelling, to customers and consumers of the quantified GHG emissions;[14]
- identification of hotspots, i.e. main unit processes where peak energy consumption and/or GHG emissions occur;
- establishment of opportunities measures to reduce the GHG emissions;
- establishment of opportunities measures to promote the energy efficiency and the economic sustainability of the mill; and
- establishment of an opportunity for product differentiation and/or market penetration.

These GHG emissions are converted to their carbon dioxide equivalent (CO_2e) on the basis of their per unit radiative forcing using 100-year global warming potentials defined by the Intergovernmental Panel on Climate Change (IPCC).[15]

Several methodologies are being developed and tested in order to establish an international standard for the product carbon footprint quantification.

In 2011, the second version of PAS 2050 – Specification for the assessment of the life cycle greenhouse gas emissions of goods and services was published by the British Standard Institution (BSI).[16]

In 2008, two parallel initiatives have been launched, both with the aim of to draw up an international standard for measuring the product carbon footprint. One initiative consists on the ISO standards 14067-1 (Carbon footprint of products – part 1: quantification) and ISO 14067-2 (Carbon footprint of products – part 2: communication).[17,18] The first drafts of these standards have been released in 2010 by the ISO Technical Committee for Environmental Management (TC 207) and the final versions are expected for 2012. The other initiative is the product accounting and reporting standard developed by the GHG Protocol of the World Resource Institute and World Business Council on Sustainable Development.[19] The second draft of this standard has been released in 2010 and a final version has been published in October 2011.

In this study, the carbon footprint of an ornamental earthenware ceramic piece (a cubic vessel), has been estimated following the PAS 2050:2011 methodology. This analysis enables the identification of hotspots and proposes improvement measures to reduce the energy consumption and the inherent GHG emissions, promoting thereby the energy efficiency of the mill under study.

2. Methodology

2.1. Aim of the study

This study intends to quantify the carbon footprint of an ornamental earthenware ceramic piece, produced and consumed in Portugal, following the PAS 2050:2011 methodology, and using the GaBi 4.3 life cycle software system. The piece is a cubic vessel with a mass of 0.417 kg and the dimensions of 10 cm × 10 cm × 10 cm.

Further, this study seeks to identify the hotspots across the life cycle of the ceramic piece and to propose measures to reduce the energy consumption and the GHG emissions, promoting, thereby, the energy efficiency of the mill under study.

2.2. Cradle-to-grave system boundary

Fig. 1 shows the detailed process map of the ornamental earthenware ceramic piece life cycle, which illustrates all materials and unit processes belonging to the identified system boundary. This process map provides a graphical reference to conduct both data collection and quantification of the carbon footprint of the ceramic piece. The system boundary identifies the life cycle stages of the piece that should be included in the study of the carbon footprint.

According to PAS 2050:2011 methodology, when the supplementary requirements (e.g. Product Category Rule as outlined in ISO 14025:2006,[20] product rules, product carbon footprint rules or sector-specific standards) specifying a system boundary have been developed for the product under study, they should be used. As the analysed earthenware piece is not covered by any supplementary requirement, the system boundary has been defined by considering the following stages:

- raw and ancillary materials – includes cradle-to-gate GHG emissions (from the raw materials extraction through production stage until the gate of the company) for the production of the raw materials – white and black clays, calcite, kaolin, silica sand and sodium silicate – consumed in the manufacture of the ceramic piece, namely in the proportioning and mixing unit process. This stage also includes cradle-to-gate GHG emissions for the production of the gypsum plaster needed to produce the piece mould, cradle-to-gate GHG emissions associated with the production of cartonboard used to pack the ceramic piece, cradle-to-gate GHG emissions from the production of the diesel necessary to the transport of the raw

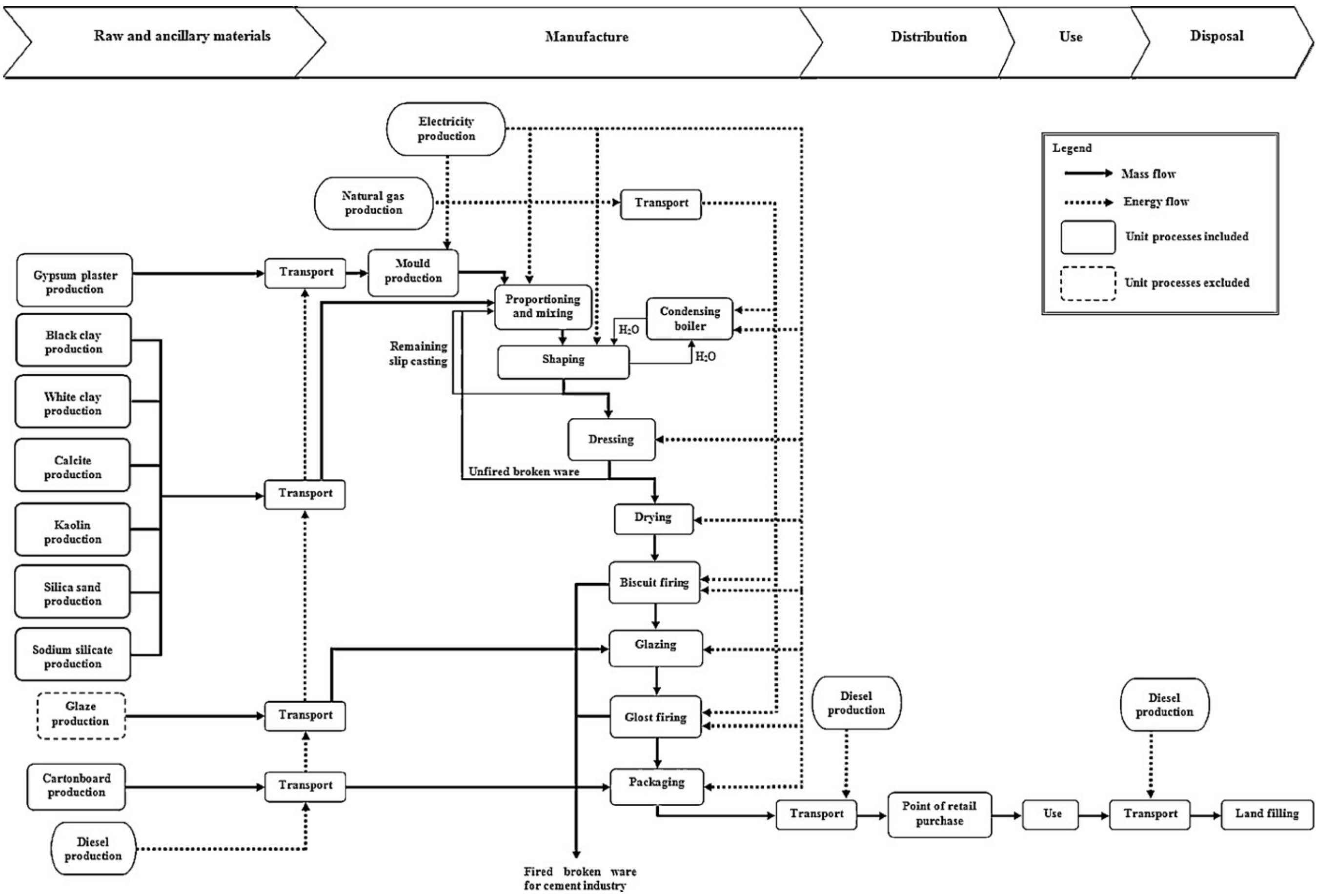

Fig. 1. Process map of the ornamental earthenware ceramic piece.

materials to the ceramic mill and GHG emissions released during this transport by truck;

- manufacture – includes GHG emissions by the industrial production of the ceramic piece and by the operational activities such as lighting, administrative activities, heating, ventilation and air conditioning. This stage also includes cradle-to-gate GHG emissions from the auxiliary unit process mould production, from the production of electricity and natural gas consumed in the production of the ceramic piece and from the transport of the natural gas to the ceramic mill;
- distribution – includes GHG emissions by the transport by truck of the ceramic piece to the point of retail purchase and by the production of diesel used by the truck;
- use – it has been assumed that there is no energy consumption and/or GHG emissions during the usage of the ceramic piece;
- final disposal – the piece has been assumed to be landfilled at the end of its life cycle; this stage includes GHG emissions of the landfill, the transport of the piece by truck to the landfill and by the production of diesel used by the truck.

In this study, all energy consumptions and GHG emissions within the defined system boundary have been taken into account, except those from the production of glaze. For this process, primary data (direct measurements) are confidential and secondary data (external measurements that are not specific to the product but represent an average or general measurement of similar processes or materials) are lacking.

As specified by the PAS 2050:2011, the system boundary also excludes the transport of consumers to and from the point of retail purchase and the transport of employees to and from the manufacturing mill, as well as the production of capital goods (machinery and equipment).

2.3. Functional unit

The functional unit provides a reference unit to which the collecting data are normalized. In this study, the functional unit was defined as one ceramic piece ready to be sold, with a mass of 0.417 kg and dimensions 10 cm × 10 cm × 10 cm.

2.4. Data collection

All data from each unit process comprised in the manufacturing of the ceramic piece have been collected at the ceramic mill that produces the analysed piece and refer to the year 2008. This year has been chosen because the production was not yet affected by market recession and it could be assumed as a typical year from the production point of view.

In the manufacture stage of the ceramic piece, the natural gas is consumed in the condensing boiler to heat the water used

Table 1
Data sources used in the secondary data collection.

Unit process	Data source
Kaolin production	GaBi 4.3. software database[26]
Silica sand production	GaBi 4.3. software database[26]
Calcite production	European Industrial Minerals Association LCA Project – IMA Europe[27]
Black clay production	European Industrial Minerals Association LCA Project – IMA Europe[27]
White clay production	European Industrial Minerals Association LCA Project – IMA Europe[27]
Sodium silicate production	Fawer et al.[28]
Cartonboard production	Pro Carton – European Association of Carton and Cartonboard Manufactures[29]
Gypsum plaster production	European Reference Life Cycle Data System database[30]
Land filling	European Reference Life Cycle Data System database[30]
Electricity production (Portuguese mix)	GaBi 4.3. software database[26]
Natural gas production	GaBi 4.3. software database[26]
Diesel production	European Reference Life Cycle Data System database[30]
Transport	All transport unit processes correspond to transport by truck and the corresponding GHG emissions have been based on the distances travelled provided by the mill under study (including the return journey of the empty truck) and on GHG emission factors from the GaBi 4.3 software database[26]

in shaping and during the biscuit and glost firing. Electricity is consumed in all the unit processes and has two components: the non-permanent component that occurs directly due to the production of the piece and the permanent component that represents the electricity consumed in the absence of production. This last component refers to the existence of equipment permanently in operation (e.g. stove fans) and to the lighting system of the mill.

The CO_2 emissions arise from the consumption of energy (natural gas and electricity) and from the decomposition of the calcium carbonate ($CaCO_3$) contained in the piece during the biscuit firing.[21,22]

As the ornamental earthenware ceramic manufacturing is typically a multifunctional system, to estimate the energy consumption (electricity and natural gas) and the CO_2 emissions, per piece, an allocation hybrid approach has been applied, based on the mass, volume or number of pieces, depending on the type of energy and stage of manufacturing. Experimental tests have been carried out in the biscuit and glost firing cycles in order to quantify the mass of fired ceramic pieces within the biscuit firing cycle, the volume of fired ceramic pieces within the glost firing cycle and the natural gas consumption in the biscuit and glost firing cycles.

The mass of the pieces is used to estimate the non-permanent component of the electricity consumption and natural gas consumption in the biscuit firing cycle. The volume occupied by the pieces (including hollow spaces inside) is considered to determine natural gas consumption in the glost firing cycle, whereas the number of pieces is used in the calculation of the permanent component of electricity consumption.

As referred above, different criteria have been applied to allocate natural gas consumption in the biscuit and glost firing cycles. In the glost firing cycle the pieces cannot touch each other since they would vitrify together. However, in the biscuit firing cycle the pieces can touch each other and smaller pieces can be placed inside larger ones. Hence, for the biscuit firing cycle, a linear relationship has been assumed between natural gas consumption and the mass of the green ceramic pieces, while for the glost firing cycle, a linear relationship has been assumed between natural gas consumption and the volume of the fired glazed pieces.[7]

The approaches suggested by PAS 2050:2011 to avoid allocation (unit process division and system expansion) are not feasible to apply due to the absence of data. When these approaches cannot be performed and applicable supplementary requirements are not available, the PAS 2050:2011 methodology recommends economic allocation. However, in this study this allocation criterion has been disregarded because the market price of the pieces changes with the market demand. This allocation criterion would result in a poor time-related representativeness for the GHG emissions of the ceramic piece, as market prices change over a short time, being necessary to reformulate the study whenever the market price of the pieces changes.

For the remaining unit processes belonging to the process map, secondary data were collected from literature, industry reports and databases (Table 1).

3. Results and discussion

3.1. Carbon footprint of the ornamental earthenware ceramic piece and GHG hotspots identification

The carbon footprint of the selected ornamental earthenware ceramic piece is 1.22 kg CO_2e per piece. This figure is liable to be communicated to the customer by means of a carbon label on the piece, which should indicate all stages of the life cycle of the piece, and should be assigned by Carbon Trust. Therefore, consumers can make more informed purchasing decisions in relation to the environmental burdens of products.

Fig. 2 presents the relative contribution of each life cycle stage of the ornamental earthenware ceramic piece to the total carbon footprint. The major contributor is the manufacture stage that represents 88% of the total carbon footprint. The raw and ancillary materials, the distribution and the final disposal stages are responsible for about, 10, 1 and 1% of the total carbon footprint, respectively.

The unit processes that contribute with more than 1% to the total carbon footprint of the ornamental earthenware ceramic

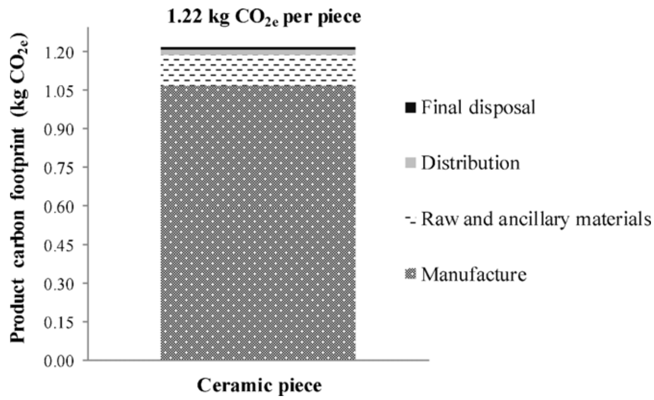

Fig. 2. Relative contribution of each stage to the total carbon footprint of the ornamental earthenware ceramic piece.

piece are shown in Fig. 3. The biscuit firing, condensing boiler, glost firing and natural gas production contribute, each one, with more than 10% to the total carbon footprint of the ceramic piece and therefore are considered to be the hotspots. They are responsible for 30, 18, 13 and 12% of the total carbon footprint of the ceramic piece, respectively.

The emissions of the biscuit and glost firing result from the electricity consumption, from the natural gas combustion and from the decomposition of $CaCO_3$ during the biscuit firing. The $CaCO_3$ decomposition emits 0.12 kg CO_2e per piece (process emissions).

About 90% of the total carbon footprint of the ceramic piece comes from the energy consumption and only 10% arises from the process emissions. Therefore, the major responsible for the quantified carbon footprint of the piece is the energy consumption.

3.2. Total energy consumption and hotspots identification

The total energy consumption during the life cycle of the ceramic piece is 8.19 kWh, and the manufacture stage represents almost 90% of the total energy consumption across the life cycle of the ceramic piece.

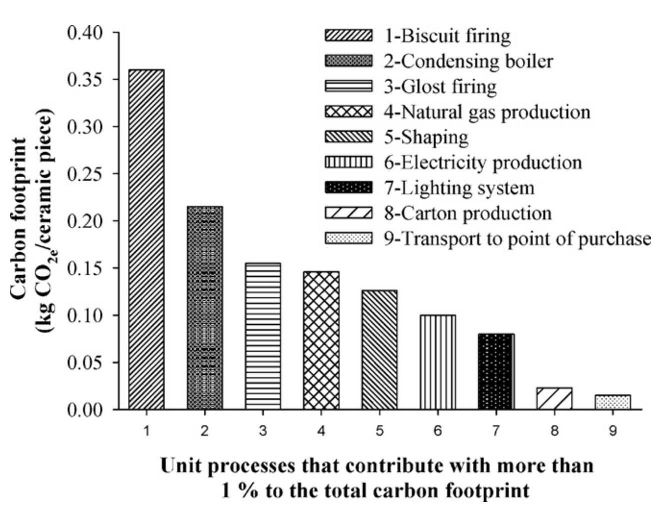

Fig. 3. Unit processes that contribute with more than 1% to the total carbon footprint of the ornamental earthenware ceramic piece.

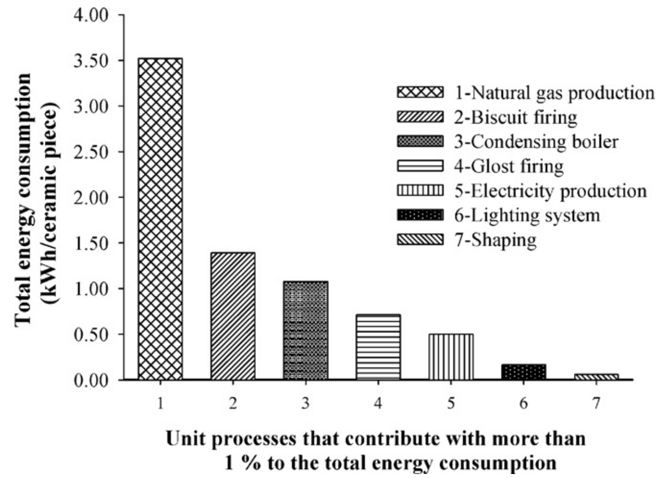

Fig. 4. Unit processes that contribute with more than 1% to the total energy consumption of the ornamental earthenware ceramic piece.

The unit processes that contribute with more than 1% to the total energy consumption of the ornamental earthenware ceramic piece are shown in Fig. 4. The natural gas production, biscuit firing and the condensing boiler are the hotspots, as they contribute each one, with more than 10% of the total energy consumption of the ceramic piece. They are responsible for 43, 17 and 13% of the total energy consumption of the ceramic piece, respectively.

The production of the ceramic piece consumes 85% of natural gas and 15% of electricity. Other studies focusing on specific ceramic products report a lower share of natural gas than the 85% above mentioned, although none of those studies deal with ornamental earthenware ceramic pieces.

According to Nicoletti et al.,[8] the manufacturing process of an Italian flooring ceramic tile consumes 69% of natural gas and 31% of electricity. Goldoni et al.[9] estimated that the natural gas consumption in the manufacturing process of an Italian ceramic *gres porcellanato* is responsible for about 50% of the total energy consumption (natural gas and electricity). Bovea et al.[23] found that the energy consumed during the manufacturing process of a Spanish ceramic tile consisted of 78% of natural gas and 22% of electricity.

On the opposite, Almeida et al.[11] reported an higher share of natural gas than to the one obtained in this study. These authors estimated that the natural gas consumption represents 98% of the total energy consumption (natural gas and electricity) during the manufacturing process of a Portuguese brick.

There are also studies reporting fuels other than natural gas. For instance, Koroneos and Dompros[10] calculated the energy consumption in a Greek brick manufacturing process and found that pet-coke is the main energy source with almost 100% of the total energy consumption. The electricity represents a residual percentage (0.3%) of the total energy consumption. According to Tikul and Srichandr[12] the manufacturing process of a Thai

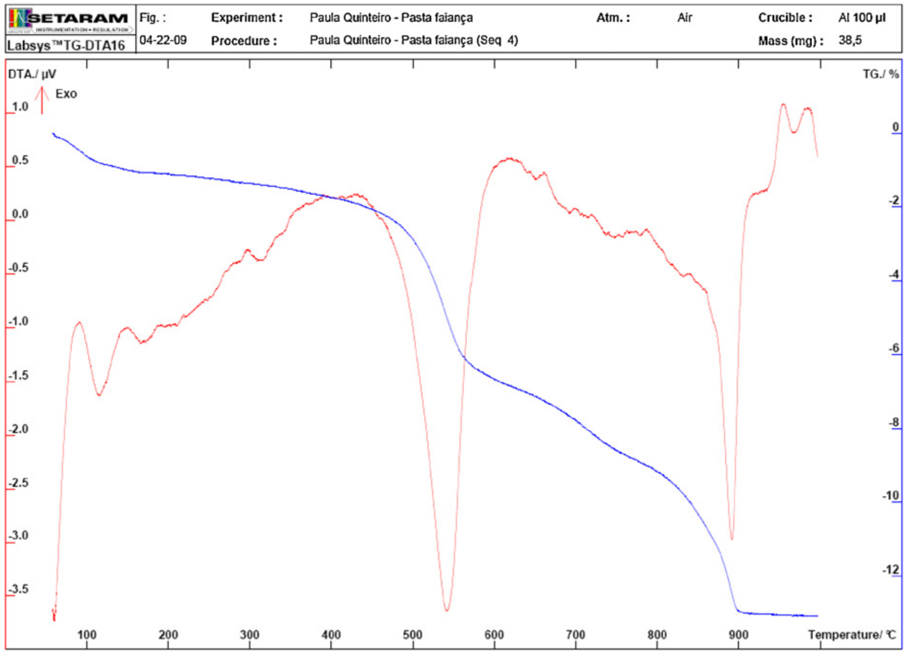

Fig. 5. Thermogravimetric analysis (TGA) and differential thermal analysis (DTA) of the slip casting.

ceramic tile consumes 62% of liquefied petroleum gas (propane and butane), 24% of electricity and 14% of furnace oil.

These results show that the used energy sources and share vary depending on the ceramic product, manufacturing process and location of the mill.

3.3. Improvement measures

Although the natural gas production is the major energy consumption hotspot, this process has not direct influence on the studied mill. Therefore, the efforts to implement energy efficiency measures have been focused on the biscuit and glost firing, and condensing boiler unit process.

To reduce the total energy consumption of the piece and the inherent GHG emissions, some measures have been identified. First, a gas pressure control system in the kilns (shuttle kilns) has been implemented at the studied mill. The gas pressure control system creates an air curtain that prevents the release of the combustion gases to the atmosphere. Once secured that the residual moisture content and interstitial water are driven out of the slip casting, the gas pressure control system goes into operation at a temperature of 550 °C. In practice, the back-pressure inside the kiln is achieved by four tubes with small holes placed around the kiln chimney. These small holes have a slope of 5° and release cold air, which throttling the release of the combustion gases because this cold air “pushes” them into the kiln. For safety reasons, a maximum pressure of 0.8 mm H_2O is applied. Therefore, a constant pressure inside the kiln is created, leading to a decrease of the natural gas consumption. This improvement measure have been resulted in the decrease of 10% of natural gas consumption and CO_2 emissions in each one of the biscuit and glost firing unit processes, and, therefore, in the decrease of 3% of the total carbon footprint of the ceramic piece.

Another improvement measure to promote the energy efficiency in the mill is changing the temperature profile in the biscuit firing. To characterize the transformations of the slip casting, which occur during a firing cycle, a thermogravimetric analysis (TGA) and a differential thermal analysis (DTA) were performed, as shown in Fig. 5. The TGA shows the mass loss of the ceramic body during the allotropic transformation of the quartz at around 573 °C, and then during the $CaCO_3$ decomposition in calcium oxide (CaO) and CO_2 to the range from 800 to 900 °C, resulting in a total loss of mass of the ceramic body of 13%. The DTA detect the thermodynamic nature of the occurred transformations during the firing cycle. For instance, DTA shows that both allotropic transformation of the quartz and $CaCO_3$ decomposition are strongly endothermic.

This information allowed (together with a dilatometry analysis done by the company, which measures volume changes during the firing and the technical characteristics of the kilns) to set a time reduction of the peak of the biscuit firing of 20 min. In an attempt to ensure that the peak temperature penetrate into the cooler parts of all load of pieces, i.e. to ensure that all chemical and physical reactions occurs without compromising the porosity and the mechanical strength of the ceramic pieces, the peak temperature has been increased to 1100 °C. Before and after this change in the temperature profile, measurements of the average temperature of the kiln atmosphere have been performed. For that it has been used the Buller rings, which has been positioned on the kiln cars in accordance with a predetermined plan of the mill[24].

The change of the temperature profile resulted in a decrease of 2% of natural gas consumption in the biscuit firing unit process. However, the Buller rings measurements revealed that the average temperature in the kiln atmosphere had been decrease 11 °C, which caused the increase of broken ware and the decrease of the mechanical strength of the ceramic pieces. Therefore, this measure has been disregarded.

To reduce the natural gas consumption, and consequently the CO_2 emissions, in the condensing boiler unit process, the insulation of the warm water closed pipe system should be improved. The effects of this measure were not yet completely evaluated.

Although the lighting of the mill is not an energy consumption hotspot, it was decided to optimize it, by replacing the conventional ballasts by electronic ones as suggested by Sá[25]. Therefore, a decrease, on average, of 20% of annual electricity consumption of the mill, and a reduction of 2% of the total carbon footprint of the ceramic piece has been obtained.

Concerning to the electricity production unit process, this is also not an energy consumption hotspot and it is not of the direct responsibility of the studied mill. Therefore, no improvement measure was identified.

4. Conclusions

The main conclusions drawn from this study are as follows:

- the product carbon footprint is a strong tool to companies better understand the energy consumption of their products, and to identify and apply measures to reduce the energy consumption and the GHG emissions, promoting, thereby, the energy efficiency and the competitiveness of the ornamental earthenware ceramic mills;
- about 90% of the total carbon footprint comes from the energy consumption and only 10% arises from the process emissions. Therefore, the major responsible for the quantified carbon footprint of the selected ceramic piece is the energy consumption;
- the major contribution both to the total carbon footprint and to the total energy consumption of the ceramic piece is the manufacture stage that represents almost 90%;
- the carbon footprint and the total energy consumption of the selected ornamental earthenware ceramic piece is 1.22 kg CO_2e per piece and 8.19 kWh, respectively;
- the GHG hotspots are the biscuit firing, condensing boiler, glost firing and natural gas production being responsible for, respectively, 30, 18, 13 and 12% of the total carbon footprint of the ceramic piece;
- the total energy consumption hotspots are the natural gas production, biscuit firing and the condensing boiler, as they are responsible for 43, 17 and 13% of the total energy consumption over the life cycle of the ceramic piece, respectively;
- the application of the gas pressure control system in the kilns resulted in a decrease of 10% of natural gas consumption in each one of the biscuit and glost firing unit processes, and in a reduction of 3% of the total carbon footprint of the selected ceramic piece.
- the optimization of the lighting system of the ceramic mill has been resulted, on average, in a reduction of 20% of annual electricity consumption of the mill, and of 2% of the total carbon footprint of the ceramic piece.

Acknowledgements

The authors would like to thank Faianças J. Barreiro, Lda. for the collaboration in providing first-hand information and data and also the availability of all the resources to perform this study. The authors also gratefully acknowledge FCT (Science and Technology Foundation – Portugal) for the scholarship granted to Ana Cláudia Dias (SFRH/BPD/20363/2004).

This work was presented in the Fourth Portuguese-Spanish Congress on Ceramics and Glasses IV held at the University of Aveiro, November 16–18, 2011 and supported by the Journal of European Ceramic Society Trust.

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