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Energy consumption estimation in the scaling-up of microwave heating processes

J.M. Bermúdez [a], D. Beneroso [b], N. Rey-Raap [b], A. Arenillas [b], J.A. Menéndez [b,*]

[a] Chemical Engineering Department, Imperial College London, SW7 2AZ, London, United Kingdom
[b] Instituto Nacional del Carbón, CSIC, Apartado 73, 33080 Oviedo, Spain

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ABSTRACT

The specific energy consumption of six different microwave-driven processes and equipments has been studied and it was found that the scale used dramatically affects it. Increasing the amount of sample employed from 5 to 100 g leads to a reduction in the specific energy consumption of 90–95%. When the amount of sample is 200 g or higher, the specific energy consumption remains practically constant. This means that to assess the real energy efficiency of a microwave-driven process a minimum mass of about 200 g needs to be used. The energy results can then be easily extrapolated to larger scales. Otherwise, a correlation should be used to avoid overestimated energy values and inaccurate energy efficiencies.

1. Introduction

Microwave energy has attracted increasing interest among the scientific community since the late eighties as an alternative method of heating [1,2]. A good indicator of this interest is the evolution in the number of scientific publications in the last thirty years (Fig. 1). The increase in scientific efforts to develop microwave heating can be attributed to the several advantages that this technology offers over conventional heating technologies. These include: (i) non-contact heating; (ii) rapid heating; (iii) selective heating; (iv) a quick start/stop facility; (v) a high level of safety and automation; and (vi) heating from inside the body of the material (i.e., energy conversion instead of heat transfer) [1,3]. All of these advantages have promoted research into the application of microwave heating to a wide range of different processes including waste and biomass valorization [4], material synthesis [5,6], metallurgy and mineral processing [3,7], catalysis [8], organic synthesis [9], environmental technology [7,10], biomass extraction [11], etc.

The viability of all these processes is highly affected by their energy costs [12,13]. Lately, several authors have pointed out that the energy efficiency of microwave heating could also represent an important advantage over conventional heating technologies [10,14,15]. Yet in spite of the increasing interest in this technology, there is still very little information about its energy efficiency [16]. For example, just a few reports in the field of organic synthesis (homogeneous and heterogeneous catalysis) have assessed the energy efficiency of the microwave in comparisson with conventional heating. In these works, it has been found that a case-by-case analysis is needed, since the conclusions vary depending on the reaction studied [13,17]. Besides these works, not much studies have been published on this aspect of microwave heating (Fig. 1), and some of these are inconclusive. Factors like equipment design, the radiation frequency (915 or 2450 MHz), the mode of heating, the specific power and the scale of the process need to be carefully analyzed before conclusions that might favor or weigh against the use of microwave energy for a specific process can be drawn. A matter of great importance is the scale that is chosen to evaluate the potential of microwave heating. The results of a statistical study on this matter can be seen in Fig. 1. To collect the data, Scopus® was used as source. A search using the keyword "Microwave heating" limited to the fields of Engineering, Chemistry, Material Science, Chemical Engineering, Pharmacology, Toxicology and Pharmaceutics, Energy and Environmental Science was carried out, excluding those works that included words such as "characterization" or "dielectric properties", with the aim of narrowing the search down to those articles focused on applied microwave heating. To construct the pie graph, including the clasification of the works and their proportion by sample weight, in addition to the corresponding percentage of these proportions from which conclusions about energy consumption are drawn, a stratified probabilistic sampling was carried out. The global population of works was divided by the year of publication and 10% of the works from each year (which approximately account for

* Corresponding author. Tel.: +34 985 118972; fax: +34 985 297672.
E-mail address: angelmd@incar.csic.es (J.A. Menéndez).

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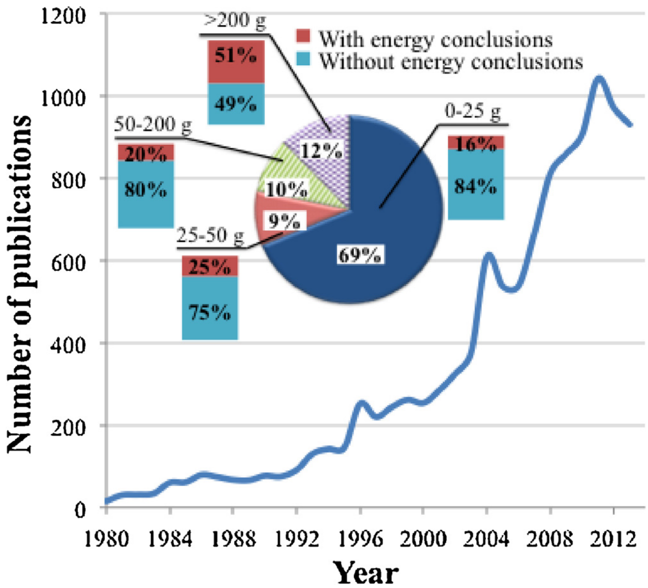

Fig. 1. Evolution of the number of scientific publications related to microwave heating. Distribution of these publications in terms of the mass used in the study and the energy conclusions drawn (Source: Scopus®).

a total of 1200 articles all randomly chosen) were reviewed. The results of this study show that most of the works published to date have been performed at lab-scale, employing only a few grams of sample (Fig. 1). However, as will be demonstrated in this paper, to draw conclusions about the viability of a process based on results obtained at such a low scale can be risky and depending on the amounts of sample used in the experiments is sometimes meaningless. Moreover, nowadays most research efforts in this field are focused on the scaling-up of microwave processes and the first encouraging results are appearing [12,13,18,19]. For these reasons it is important to determine how the energy consumption of microwave-heated processes varies depending on the scale used. This will make a valuable contribution to assessing its viability at industrial level. The energy utilization efficiency depends on the geometric characteristics of the resonant cavity and the reactor, the design and effectiveness of the impedance matching circuit to minimize the reflected power and the dielectric properties of the bulk. Actually, when changing the dimensions of the reactor, the scattering properties of the system change. Hence, the impedance matching circuit to minimize the reflected power will determine the energy efficiency. Nevertheless, when no hardware is present to reduce the reflected power, there may be regions in the attainable reactor size range, where heat generation and utilization efficiency vary non-monotonically with varying reactor size [20].

The goal of this work is to study the variation of the energy expenditure (taking into account the absorbed energy, reflected energy and even heating losses) of microwave heating as a function of the scale used. For this purpose, an analysis of the energy consumption of six different microwave-assisted processes was conducted in an attempt to find a general trend with the scale that might be extrapolated to other cases. The results obtained will help to assess the viability of microwave-heated processes.

2. Experimental

The following processes were studied: the heating of SiC and the torrefaction of wheat straw (adapted from the literature) [21,22], the heating of water, the synthesis of xerogels, the high temperature heating of charcoal and the microwave-assisted grinding of metallurgical coke (directly studied in our labs). The experimental methodologies and the equipment used (Fig. 2) for these processes are described below.

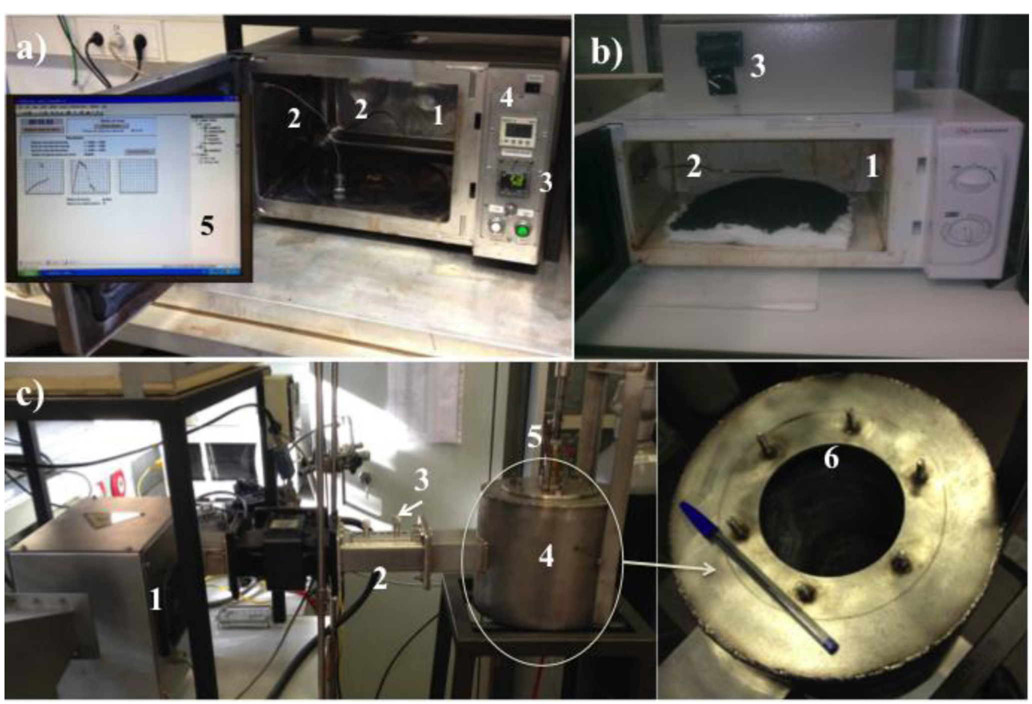

Fig. 2. Equipment used: (a) water heating and synthesis of xerogels (1. Microwave cavity; 2. Thermocouples; 3. PID temperature controler; 4. power meter; 5. Power monitoring software); (b) coke grinding (1. Microwave cavity; 2. Thermocouple; 3. Power meter); (c) high temperature heating of charcoal (1. Magnetron; 2. Waveguide; 3. Tuning screws; 4. Microwave cavity – outside; 5. Stirring shaft; 6. Microwave cavity – inside).