SPECIAL FEATURE

Microwave potential for bioenergy production

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Despite investigations of microwave heating and biomass conversion, large-scale application of microwaves is very limited. Future industrial deployment of microwave technology depends on the understanding of the heating mechanism and the scalability options, as Dr. Beatriz Fidalgo Fernandez explains.

The design and manufacturing of magnetrons for the generation of microwave radiation goes back to the first half of the 20th century. Although their ability to heat materials was documented, the research focus was on the application of microwaves in military navigation and communication devices. It was not until the 1980s that the use of household microwave ovens rose massively, contributing to the ''culinary revolution'' of ready-to-cook meals and safe and rapid defrosting of food. Nowadays, microwave ovens are considered indispensable appliances in many homes due to their convenience and speed compare hob cookers and conventional ovens. Thus, the penetration rate of microwave oven in the UK increased from approximately 74% in 1995 to 91% in 2014. Despite the wide presence of microwave radiation in the everyday life, the understanding of the microwave heating mechanism and the recognition of its huge potential to be applied to diverse industrial processes is very limited.

What is microwave heating?

Microwaves are a non-ionising electromagnetic radiation that lies between infrared and radio waves, in the range of the electromagnetic spectrum limited by the frequencies between 0.3 and 300 GHz. The usual operating frequency for domestic and industrial microwave applications is 2.45 GHz or 915 MHz to avoid interference with radar and telecommunication frequencies.

High-frequency radiation such as microwaves causes dielectric heating. The electric field component of the microwave radiation interacts with the charged particles of the irradiated material. Heating up of the material occurs when the particles are not free to move and try to align with the alternating field. This phenomenon is known as dielectric polarisation. A common misconception is to believe that materials need to have significant water content in order to be heated by microwaves. There are in fact two types of polarisation mechanisms involved in microwave heating: dipolar polarisation and space charge polarisation. Water and other polar fluids (ethanol for example) heat due to dipolar polarisation, which occurs in dielectrics that have induced or permanent dipoles. Space charge polarisation occurs in dielectric materials with charged particles (electrons, ions, etc.) which are free to move in a delimited region. This mechanism predominates in dielectric solids such as most carbon materials and some inorganic oxides and sulphides, and it is of great relevance in the case of microwave application to conversion of fuels and biofuels.

Microwave heating is the direct conversion of microwave energy into thermal energy within the heated material, rather than a heat transfer as in the case of conventional heating. This volumetric nature of microwave heating is its distinctive feature. A number of advantages of microwave heating over conventional heating are consequence of these core differences in the heating mechanisms. Some of these advantages can be easily identified by any person who has ever used a microwave oven: rapid heating, quick start-up and stoppage or reduced processing time. Other advantages may not be so evident but are extremely important when microwaves are applied to industrial processes: non-contacting heating, higher level of safety and automation, reduction in the size of equipment and higher flexibility or selective heating of materials (Figure 1).

Microwave heating in industrial processing and research

The number of applications of microwave processing has significantly increased over the last decades. Nevertheless, these industrial applications are relatively low compared to the enormous potential shown by microwave heating. During the 1980s microwave-assisted organic chemistry attracted great interest as laboratory technique due to the dramatic reduction in reaction times and the improved

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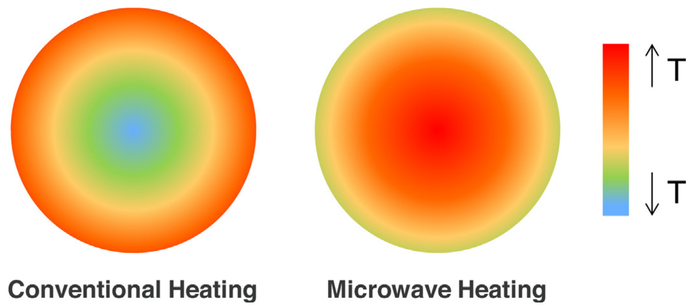

Figure 1
Qualitative comparison of the temperature gradients produced by microwave and conventional heating. Unlike conventional heating, the temperature inside a material heated by microwave is usually higher than the temperature of the surrounding atmosphere.

selectivity towards desired products. After three decades, microwave heating applied to organic synthesis has become a mature technology and is used in academia and more recently in chemical, pharmaceutical and biochemical industries with commercially available microwave chemistry equipment. Due to the potential energy savings and enhanced efficiency, microwaves has also been successfully applied to other industrial processes such as food processing, sterilisation and pasteurisation, wood drying, rubber vulcanisation, and processing of ceramics, minerals and metallic materials. Moreover, extensive investigation has been recently carried out on the use of microwave radiation in diverse processes such as ceramic and polymer processing, metallurgy and mineral processing, contaminated soil remediation, waste management, production, modification and regeneration of activated carbons, upgrading of fractions of petroleum, gas-phase catalytic reactions (dry reforming of CH_4, H_2S decomposition, NO_x and SO_2 reduction, or CH_4 oxidative coupling), or thermal conversion of biomass and upgrading of biofuels.

Microwave heating and bioenergy processes

The investigation of microwave-assisted biomass and biofuel processing in order to achieve improvements with respect to conventional approaches has increased significantly over the last decade. Microwave heating has been applied to almost any process involving biomass conversion with varying success. The aim of nearly all the studies has been to improve product quality and quantity, reduce processing time, and ultimately increase the overall efficiency of the process.

Driven by the established benefits of the application of microwaves to organic synthesis, studies on the use of microwave heating in bioethanol, biodiesel and biogas production have been carried out. In the case of bioethanol production, research has been focused on microwave pretreatment. Microwave-assisted hydrolysis of different lignocellulosic biomass have been proven to increase bioethanol yields due to enhanced degradation of lignin, cellulose and hemicellulose, and increased enzymatic susceptibility of the materials. Microwaves have also been studied as pretreatment method of various organic wastes and sludge to be processed by anaerobic digestion, enhancing larger production of methane. Moreover, microwave pretreatment favours dewatering, reduces foaming and diminishes the amount of pathogens in the sludge. Microwave-assisted biodiesel production has been widely studied. Microwaves has been successfully applied to biomass transesterification reactions both in batch and continuous set-ups; shorter processing times, higher yields and higher product purities have been obtained compared to those achieved under conventional heating. And the use of microwave radiation prior lipid extraction has been found to enhance the efficiency of the extraction processes. Despite these advantages, some reports have questioned the actual energy savings when using microwave heating in all these processes, and have highlighted the need to optimise each particular process and to carry out a thorough assessment of energy usage.

Microwave-assisted thermochemical conversion of biomass and biofuels has been far more investigated than the biochemical processes. Microwave-assisted pyrolysis of a wide range of biomass feedstocks is the process that has attracted more attention. In general, raw biomass is not good microwave absorber; meaning that it is not easily heated by microwave radiation. Its dielectric properties improve as the pyrolysis proceeds and the carbon content of the remaining residue increases. In fact, the ability of char obtained from biomass pyrolysis to be heated by the microwaves is very good and it can be used as microwave receptor to indirectly heat the biomass up to the temperatures required for thermal decomposition. Other materials such as activated carbon or metal oxides have also been used as microwave receptors. As happens under conventional heating, microwave pyrolysis gives rise to liquid, gas and solid fractions, and the proportion in which the three fractions are produced depends on the operating conditions.

Microwave-assisted pyrolysis for biochar production is carried out at low temperatures (i.e. lower input microwave power). The solid residue produced by this process has been observed to exhibit a good potential for gas adsorption and higher energy content than the char produced by conventionally-heated pyrolysis. However, lower energy efficiency has been reported in the case of microwave pyrolysis. It should be noted though that this efficiency depends on the suitability of microwave oven design for the process requirements, which may not be optimum when considering lab-scale rigs.

Various studies have established the technical feasibility of microwave pyrolysis for bio-oil (liquid fraction) production, which is carried out at high heating rates and moderates temperatures. Since the operating conditions, the biomass feedstock and the reactor configuration have an effect on the yield and composition of the bio-oil produced, it is difficult to establish general conclusions. Nevertheless, most researchers have observed that the quantity and quality of the bio-oils produced under microwave heating are significantly better than those under conventional pyrolysis. Less polycyclic aromatic hydrocarbons, increasing amount of phenolic compounds and a larger degree of deoxygenation have been observed in the bio-oils produced under microwave heating. This improved composition of the bio-oil is actually related to the selective heating provided by the microwaves. The microwave process can be carried out flowing a cold sweep gas (which is barely heated by the microwaves) and so the released volatiles are cooled and condensed rapidly. The secondary reactions of the liquid precursors due to high temperatures are largely avoided and much more compounds are preserved in the final bio-oil. The implications of the enhanced composition of the bio-oil produced from microwave pyrolysis are significant since one of the main issues on the production of pyrolysis bio-oil is its high oxygen content. Moreover, few preliminary results have shown the effectiveness of microwave heating applied to ex situ upgrading of bio-oil.