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The effect of heat properties of metallic or dielectric containers on thermal yield and energy efficiency in microwave heating applications

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ABSTRACT

This paper brings to the fore the key parameters set out on thermal yield and energy efficiency in microwave industrial processes, specifically, in the transient phases. It examines in detail two industrial operations: thermoset polymer curing and flow chemistry under pressure. Overall tuning systems are necessary for energy optimisation, but on the other hand, vessels, pipes, moulds and conveyor belts made of lossy materials are required for holding products or carrying materials. The impact of these inserts on the temperature profile of the heated product and on energy (the power usage and energy efficiency), were experimentally and theoretically examined. It was demonstrated that these parameters have to be considered for process design and calculations. Looking at these two examples, one can see how transient phases are crucial for the required power of the microwave generator and the process design.

1. Introduction

Microwave heating is often considered a volumetric and uniform method of heating and also as a selective for polar products and materials. In the past few years, some microwave processes have emerged at an industrial scale in the agri-food industry (microwave popcorn, defrosting), cosmetics (vacuum extraction of plants and herbal fragrances), vulcanisation of rubber or drying [1–5]. Most of them are batch processes using multimode ovens, cooking the material progressively over a defined cycle. Traditional heating methods are based on the principles of radiative transfer, convection and conduction. Materials are thus heated from an outside-in orientation. Conversely, burgeoning microwave heating technology processes materials through direct interaction with inner polar molecules and charged particles, as fully illustrated by Legras et al. in an adsorption-desorption process [6,7]. Due to its unique principles, microwave heating is characterised as efficient, internal and environmentally friendly. However, it has also some natural drawbacks, including non-uniform heating. Non-uniform heating can easily cause local overheating problems and hot spots. It can lead to thermal runaways as a surge in the system temperature, which causes degradation in the quality of the final product and can even cause burning and explosions, though this can also be used as a method for local heating intensification [8]. As a new technique in chemical engineering, microwave heating has been developed rapidly at a laboratory scale, due to the advantages listed above [9,10]. Energy saving, improved quality, reduced wastage, accelerated chemical reactions and instantaneous control are often seen. The major limit of microwaves is the penetration depth. In usual solvents, it is only a few centimetres and makes the use of high volume reactors difficult [11]. Coupling microwave heating and continuous flow technology eliminate this major drawback and provide an efficient way to produce chemicals, since unlike batch processes, continuous flow has been demonstrated to facilitate process intensification [12–19].

In both batch and flow chemistry, the transient stages must be taken into consideration. Even in flow chemistry where a steady state is largely maintained, the transient stages are key for the overall design of the process, particularly for microwave systems. According to the literature, there are few relevant published articles in this area. Some energy and design considerations have been compared by Estel et al. [19], showing that single-mode systems and flux chemistry give better results. Unfortunately, in the majority of the papers, the description is limited to laboratory scale batch systems, where problems of consumption and energy efficiency are poorly discussed. For example, only magnetron input power was mentioned and no energy balance was given, the use of a global tuning system was rarely mentioned and high incident powers were often used. When comparisons were made with classic heating, energy considerations were proposed without optimised global tuning and without details on the measurement of incident and reflected powers. In their paper, Benaskar et al. [20] demonstrated that the energy efficiency achieved using the single-mode microwave cavity of the Fricke-Mallah instrument reached 82% (± 4%) with an average power input of 16 W, while the multimode cavity system could at best

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be operated with an energy efficiency of only 8.2% (± 0.8%). Even if in the latter case precise values were given, no information on the power measurement conditions was given. In both cases, steady state and transient regimes, the design must be precise to obtain the best coupling with minimum reflected power. For the industrialisation of microwave processes, as for conventional processes, the reactor and reaction must be designed according to the methods of process engineering. But in the case of microwaves, the cavity and the overall tuning system must also be subjected to a precise study.

To optimise thermal uniformity and coupling, it was also necessary to control the interface transitions and the angles of incidence of the waves. This optimisation can be achieved by introducing auxiliary materials into the microwave cavity. Apart from this innovative solution, some inserts such as containers, pipes, moulds and conveyor belts are necessary to hold products or carry materials. They are made of materials with losses or whose dielectric losses exist even if they are low. In reliable studies, a fundamental and often unique role has been attributed to the dielectric properties of the material to be heated, but the role of their supports or containers has often been neglected, and thermal issues are limited to how to ensure good thermal insulation. Consequently, it is clear that for the design and calculations of microwave processes, the thermal equilibrium state of the physical system is always taken into account and less attention is paid to the transient phases. Furthermore, the effects of the inserts or of the adaptation loads are not included in the design process.

In this paper, the transient phases of two microwave processes are studied. The first, which is a batch process, is the microwave curing of thermoset polymers. The second, is the continuous production of a chemical (fragrance) in a high-pressure microwave reactor with thick metallic walls.

The effects of inserts, metal or dielectric containers on the temporal temperature evolution of the product to be heated, will be addressed. The energy efficiency of the system during these transient phases will be discussed by evaluating the effects of these inserts and containers on the required power and thermal efficiency.

2. Experimental setups

2.1. Thermoset polymer composite curing in a dielectric mould

Fig. 1 shows the experimental setup used for studying the curing of unique items made from moulded thermoset polymers. This discontinuous process was similar to the industrial one, considering its size and the use of a WR975 applicator and a 915 MHz generator. The glass-epoxy-resin composite was a parallelepiped (0.76 m × 0.1 m × 0.015 m) placed in a single mode microwave applicator. The length of the resin block followed the direction of propagation. The exact shape of the composite item was obtained by means of a silicone-glass mould which filled the free space left between the composite and the microwave applicator to permit the application of a mechanical constraint. The mould also managed the propagation conditions and performed spatial distribution of the electric field, due to a TE10 mode propagation of waves, in particular with matched interfaces (Outifa [21], Douadji and Delmotte [22]). The dielectric loss factor of the mould material was always smaller than the composite one ($\varepsilon''_r = 0.03$ and $\varepsilon''_r = 0.25$, respectively) but its volume was much higher (22.5 dm^3 versus 1.14 dm^3). For a better temperature distribution (see the Results Section 3.1), an additional dielectric support made of glass fibres and silicone was designed and added. The wave frequency was 915 MHz and the applied microwave power was 1250 W. The reflected and transmitted powers were measured directly on the waveguide by means of convenient directive couplers and power meters, and the instantaneous absorbed power (P_{abs}) was obtained from the difference.

The heating must transform the material, from the heat sensitive polymer to its solid and definitive shape. Consequently, the microwave equipment runs in a thermal transient state. In this study, we observed the predicted variation in the absorbed electromagnetic power along the entire thermal curing process.

2.2. High pressure microwave reactor for continuous chemical production

A special reactor-applicator with thick metallic walls for high pressure chemical reactions, under continuous flow, was also examined. In flow chemistry, a way to accelerate chemical reactions is to increase the temperature of the reacting medium, but in order to maintain reactants in a liquid phase, high pressures have to be applied. Considering microwave technology, a clever way to allow microwave propagation and mechanical resistance to high pressures (up to 70 bar in our case) is to use the stainless steel reactor, with thick walls, as the applicator [23].

Microwave power was delivered by a magnetron working at 2.45 GHz with a maximum power of 2 kW. This magnetron was connected to a WR340 wave guide, equipped with incident and reflected power sensors and a classical water load that prevented damage to the magnetron from reflected power. An adaptive wave system consisting of several adaptors and a window placed in series (see Fig. 2), transformed the rectangular mode of propagation TE10 into a more complex cylindrical mode. In the adaptive section, microwaves propagated at atmospheric pressure and the "window" was the piece separating the pure wave propagation section from the reaction section that was under high pressure. From the magnetron to the reactor, the wave passed through the dielectric items that absorbed part of the electromagnetic

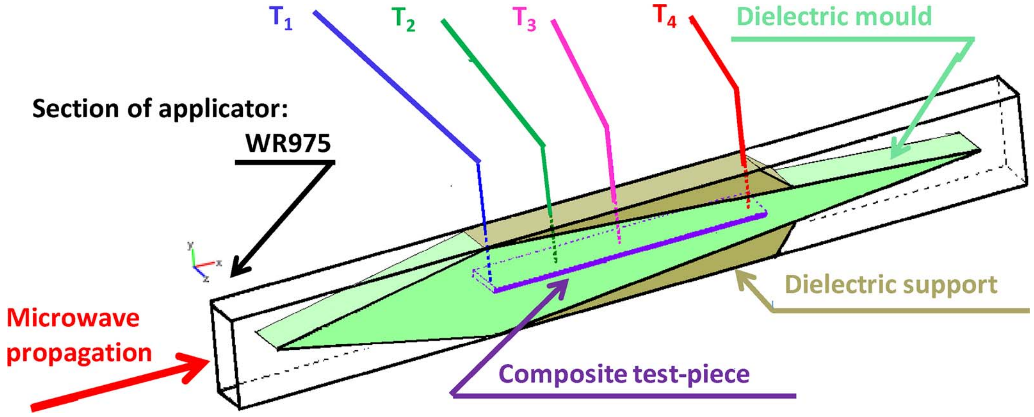

Fig. 1. Experimental setup for the thermoset polymer curing process.