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Quantitative measurement of energy utilization efficiency and study of influence factors in typical microwave heating process

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ABSTRACT

Microwave heating technology has been used in many fields as a means of selective, volumetric, and instantaneous heating. In the process, input electrical energy is first converted to microwave energy, which is then absorbed by a dielectric medium and changed into thermal energy (effective heat). The energy utilization efficiency of this process is of particular concern because it provides an important index of economic performance. A good understanding of these efficiencies via quantitative measurements is necessary to optimize the microwave heating process and to use it more effectively. The research reported here divided the microwave heating process into two stages, measured their energy utilization efficiencies in detail, and studied the effects of various factors. It was found that the heating body position in microwave cavity, the heating medium type, the microwave output power and the geometry parameters of heating medium like volume can all significantly influence the energy efficiencies. But even for the best optimized microwave heating process, the total energy efficiency can only amount to about 0.8. This work built up a general idea for understanding the issue of energy utilization efficiency in microwave heating processes through a quantitative method, and provided a feasible way to assess energy utilization characteristics of any microwave heating process or to test microwave absorption abilities of different media.

1. Introduction

Microwave heating technology uses electromagnetic waves at 915 MHz or 2450 MHz to heat specific materials. Because it is a selective, volumetric, and instantaneous heating method, it has been widely used in drying [1], organic synthesis [2,3], pyrolysis of biomass or waste [4–10], material sintering [11,12], metal welding [13], plasma processing [14,15], polymer material processing [16], pollutant removal from gas or water [17,18], and so on. In spite of its distinct advantages, microwave heating is a process which converts high-grade power to low-grade heat, and that the energy utilization efficiency of the process is of particular concern. However, very few studies have focused on testing or analyzing the energy efficiency in microwave heating. The sparse literature are like the experimental measurements for some organic synthesis or organic reactions in Refs. [19,20] and the simulations using energy or exergy analyses in Refs. [21,22]. All of these studies indicated that the energy efficiencies in microwave heating might be low, scarcely surpassing 20%, but they addressed this issue mainly from the perspective of energy utilization in some application processes as a whole instead of the microwave heating itself. Clearer knowledge of energy efficiencies from electrical energy input to effective heat energy remains to be obtained to further microwave heating applications.

A microwave heating process can be divided into two stages: the input electrical energy is first converted to microwave energy, and then the microwave energy, in the form of electromagnetic waves, is absorbed by dielectric media and converted to effective heat. A macroscopic consequence of the whole process is the rising temperature of the heating media. Usually, the microwave heating device is composed of a microwave generator (microwave source) and a cavity. The generator converts the input electrical energy to electromagnetic waves at a certain frequency through a magnetron and launches them using an antenna. Subsequently, the cavity

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accommodates the microwaves and passes them repeatedly through the heating medium by frequent reflection until they are completely absorbed or dissipated. The eventual temperature rise of the heating medium reflects the effectiveness of the use of input electric energy [23].

To completely understand the energy efficiency in a microwave heating process, the different forms of energy at the two stages need to be quantitatively measured. The input electrical energy, including the part that is transformed into microwave energy and the other part that drives fans, motors and any other power-consuming components, can be obtained by using an electricity meter; however, the involvement of the latter part of energy in calculating efficiency may bring about misleading deviations due to different design of microwave system in terms of scale or structure. The output microwave energy, which fluctuates in the running of magnetron, can be measured by monitoring the voltage and current of the anode. Most significantly, the effective heat energy absorbed by heating media may be difficult to make a quantitative measurement due to uneven heating, and the correctness and accuracy, which are tightly related to energy loss or composition, geometry as well as state and location of the media, will directly affect the final characterization of energy efficiency. Without considering the non-microwave energy consumption, fluctuations of microwave output as well as variations of heating media, the knowledge of energy efficiency for microwave heating is incomplete and cannot reflect the whole profiles of the heating processes. Unfortunately, no pervious study has been done to such a degree so far.

The target of this article is to analyze and unveil the energy efficiency rules of microwave heating in a quantitative way. In a specific microwave heating system, the whole heating process was divided into stages from input electrical energy to microwave energy and from microwave energy to effective heat, and by the realization of measuring the net input electrical energy, microwave output energy and effective heat energy, the energy utilization efficiencies and the influence factors such as heating body position, heating time, heating medium type, heating medium volume and microwave output power, were investigated experimentally. Although the experiments were carried out on a specific microwave system, the results were extended to general microwave heating processes by considering the hardware differences. The conclusions can also be widely referred to in process design, scale-up or optimization of microwave heating for applications in chemistry, energy, material and other fields.

2. Experimental

2.1. Setup and method

A custom-built WLD3S-03 type microwave system was used for the experiments. Fig. 1 shows a photograph of the system, which consisted mainly of a microwave control system and a microwave reaction cavity. The microwave control system was composed of a microwave emission system and a microwave cooling system. The inner dimensions of the cavity were 33 cm × 30 cm × 20 cm. The microwave frequency was 2450 MHz and the output power could be continuously adjusted from 0 to 2000 W.

To measure the energy utilization efficiency, deionized water was selected as the main testing medium; glycerol and paraffin oil were also tried in view of their different dielectric properties. Table 1 gives the parameters of these media. Their liquid property made the measurements of temperature and effective heat absorption more convenient. In experiments, the heating medium was poured into a glass beaker and then placed on an asbestos plate in the microwave cavity. When the microwave was turned on, the instantaneous input and output power could be recorded on the control panel. The initial and final temperatures of the medium and beaker were measured with K-type thermocouples whose accuracy was 0.1 °C. While measuring the medium temperature, the probe was inserted in and stirred quickly for a couple of seconds, and stable results were obtained within 20 s; simultaneously, two other thermocouples were used to measure the beaker temperature at two different points and their average value were adopted. The environment temperature was 25 ± 1 °C. The heating medium was always replaced and the microwave cavity was kept open and idle for at least 20 min before a new round of experiments. By calculating the heat absorbed by the heating body, the energy utilization efficiency could be obtained. By changing beaker position, water volume, heating time, and microwave output power, the effects of these factors on energy utilization efficiency could be investigated.

2.2. Definition of energy utilization efficiency

To describe exactly the energy utilization efficiencies of microwave heating processes, input electrical energy, microwave energy, and effective heat were measured, and two efficiencies, from input electrical energy to microwave energy and from microwave energy to effective heat, were defined.

Input electrical energy was the net energy, excluding the part used to drive the fans, the panels, the cooling system, and so on. The total input power could be read from a CD194E-9K4 multifunction power meter, which had an accuracy of 1 W. However, when the microwave was turned on, the total input power did not remain constant and might change instantaneously. By recording the instantaneous total input power every 5 s and integrating the resulting curve, the average total input energy, Q_{total}, could be obtained for each microwave heating experiment. When the microwave system was in standby mode, the obtained average total input energy, $Q_{standby}$, consisted of the energy consumption of all the running components. Then the input electrical energy, Q_{net}, could be obtained by subtracting $Q_{standby}$ from Q_{total}.

$$Q_{net} = Q_{total} - Q_{standby} \tag{1}$$

For example, in the case that 1000 g of water was heated for 2 min at a microwave setting of 1200 W, the instantaneous total input power was as shown by the upper line in Fig. 2. By integration, the average total input energy, Q_{total}, was determined as 266,997 J. When the microwave system was in standby mode, the power meter remained stable at 220 W. By subtracting $Q_{standby}$ from Q_{total}, the input electrical energy, Q_{net}, was determined as 266,997 J− 220 W × 120 s = 240,597 J.

Not all of the input power could be transformed into microwave energy. Some loss occured during electromagnetic excitation. The instantaneous microwave output power could be read on the panel of the microwave system. In the same way that Q_{total} was determined, the instantaneous microwave output power was recorded every 5 s and was plotted as the lower curve in Fig. 2. The microwave energy, $Q_{microwave}$, could also be obtained by integration.

Effective heat energy included all the heat absorbed by the heating medium and the container as well as the thermal loss through heat transfer. Our previous studies of heating effect caused by microwave-metal discharge gave us a methodology foundation for the quantitative measurement of effective heat energy [25]. The heat loss will be analyzed in Section 2.3. The effective heat, $Q_{eff\text{-}heat}$, can be obtained using Equation (2):

$$Q_{eff-heat} = (C_1 m_1 + C_2 m_2)(t_2 - t_1) + Q_c + Q_r + Q_e \tag{2}$$

where, $Q_{eff\text{-}heat}$ is the effective heat, J; C_1, the specific heat capacity of the heating medium, J/g·°C; m_1, the mass of the heating medium,