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NUMERICAL SIMULATION AND EXPERIMENTAL VALIDATION OF MICROWAVE TORREFACTION FOR EMPTY FRUIT BUNCHES PELLET

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ABSTRACT

This study investigates the microwave heating and torrefaction process of empty fruit bunch (EFB) pellets. Finite element based COMSOL Multiphysics software was used to predict the microwave heating behaviour of EFB pellets during the torrefaction process. The simulated temperature data from multimode microwave system at 2.45 GHz frequency was used to compare and validate the experimental results. Quantitative validation of 10 min temperature profiles between 25-300 °C was performed by comparing the simulated and experimental results. RMSE and maximum different temperature profile were 16.42 and 38°C respectively which may cause by the moisture of pellet, exothermic reaction and placement of the thermocouple during microwave torrefaction process. The simulation work has successfully identified the hot spots of EFB pellets during microwave torrefaction. Hot spot happened in the temperature range of 250-450 °C and was observed near the waveguide and centre of the EFB pellets bed. This study provided a framework and required model parameters to predict temperature profile and hot spot location for a specific geometry of microwave cavity.

Keywords: microwave, torrefaction, simulation, temperature, hot spot

INTRODUCTION

Malaysia is a well-known exporter of oil palm product such as crude palm oil and refined palm oil for cooking. At the same time, the palm oil mill or oil palm estate Malaysia also producing abundant solid biomass such as empty fruit bunches, mesocarp fibre, palm kernel shell, oil palm frank and oil palm truck (Loh, 2017). Indeed, palm biomass is one of the most important renewable energy sources to meet the energy demand in Malaysia. These biomass have been commonly disposed through burning into ash, used as boiler fuel or composted into bio-fertilizer.

Empty fruit bunch (EFB) represents as a major palm biomass (7.34 Mt) is producing annually at palm oil mill, urgently needs to be disposed or utilized into other valuable products. Therefore, EFB pellet has been produced for heat generation by co-firing with coal in the boiler in power generation station. EFB Pellets facing limitation of low bulk density, high moisture content and relatively low calorific value have hinder its economic feasibility as a co-firing fuel. A lot of research is underway to improve the fuel quality of biomass via torrefaction (Harun, Samad, & Saleh, 2017; Sabil, Aziz, Lal, & Uemura, 2013; Sellappah, Uemura, Hassan, Sulaiman, & Lam, 2016; Uemura, Omar, Othman, Yusup, & Tsutsui, 2013; Uemura, Omar, Tsutsui, & Yusup, 2011; Uemura, Sellappah, Trinh, Hassan, & Tanoue, 2017). Torrefaction is an efficient treatment method to upgrade raw biomass with higher heating value and carbon content. Torrefaction is a heating process that carried out at 200 to 300 °C in an inert environment. Recently, torrefaction of biomass by microwave heating has shown increasing interest than conventional heating method (Siritheerasas, Waiyanate, Sekiguchi, & Kodama, 2017). Microwave torrefaction (MT) is a relatively new area in scientific research which has not been fully explored, especially from the standpoint of microwave heating and reactor design.

Most of the literature studies focused on the torrefaction by conventional heating (Bach, Chen, Chu, & Skreiberg, 2016; Chen, Huang, Chang, & Chen, 2015; Chin et al., 2013), from which research for microwave heating in torrefaction is limited (Nam & Capareda, 2015). However, microwave power and radiation duration are the focus of the current literature studies of microwave torrefaction (Huang, Cheng, Chiueh, & Lo, 2017; Iroba, Baik, & Tabil, 2017a, 2017b; Natarajan, Suriapparao, & Vinu, 2018). There is also lack of detailed understanding about microwave heating mechanism during torrefaction. Hence, a significant need of simulation of biomass heating in microwave torrefaction (MT) system to identify the heat distribution of microwave heating occurred within the EFB pellets. Investigation of temperature distribution have been carried out in the literature (Halim & Swithenbank, 2018; Salema & Afzal, 2015) by computer based simulation using COMSOL Multiphysics software to predict the electromagnetic field distributes within the cavity. Simulation also enable the different parameters study that influence the microwave heating of torrefaction inside the microwave oven.

MATERIALS

Empty fruit bunch (EFB) pellets were collected from palm oil mill at Saratok, Sarawak. Diameter of EFB pellet is 7 mm with length around 10-15 mm and about 15 wt% of moisture content. The EFB pellets was heated directly by microwave radiation without microwave absorbent. Table 1 shows the necessary materials properties used in the simulation work. Thermal and dielectric properties of 15 wt% moisture content EFB biomass were used for calculations (Table 1).

Table 1: Thermal and electrical properties of materials used for simulation work

Materials properties	Components		Units
	EFB pellet	Quartz applicator	
Electrical properties			
Electrical conductivity	0	1×10^{-14}	S/m
Relative permittivity	6.5-1.9*j	4.2	
Relative permeability	1	1	
Thermal properties			
Thermal conductivity	0.03	1.1	W/m K
Density	800	2200	kg/m3
Specific heat capacity	1150	480	J/kg K^{-1}

GOVERNING EQUATIONS AND BOUNDARY CONDITIONS

Electromagnetic and heat transfer equations for microwave heating of EFB biomass pellets were solved by COMSOL Multiphysics software (COMSOL Inc., Burlington, MA, USA) using finite element method (FEM).

Dielectric properties of materials

The materials which interact with microwaves to produce heat are called microwave absorbers. The complex dielectric permittivity (ε*) of the material is expressed in complex form as Eq. (1) which is composed of two parameters, the dielectric constant, ε' (real permittivity), and the dielectric loss factor, ε'' (imaginary permittivity). The ability of a material to be heated in the presence of a microwave field is defined by its dielectric loss tangent stated in Eq.2. The dielectric constant (ε') determines how much of the incident energy is reflected and how much is absorbed, while the dielectric loss factor (ε") measures the dissipation of electric energy in form of heat within the material [1, 2]. For optimum microwave energy coupling, a moderate value of ε' should be combined with high values of ε'', to convert microwave energy into thermal energy.

$$\varepsilon^* = \varepsilon' - i\,\varepsilon'' \qquad \text{Eq. (1)}$$

$$\tan\delta = \varepsilon'' / \varepsilon' \qquad \text{Eq. (2)}$$

Electromagnetic equations

The electromagnetic phenomena in the MW heating are solved by Maxwell's equations subject to certain boundary conditions. Maxwell's equations were used as the foundation for the electromagnetic phenomena. Basically, an electromagnetic field must satisfy all these four equations Eq. (3-6) (COMSOL, 2012):

Faraday's Law $\nabla \times E = j\omega\mu H$ Eq. (3)
Ampere's Law $\nabla \times H = -j\omega\varepsilon_o\, \varepsilon^* E$ Eq. (4)
Gauss's electric law $\nabla \,.\, (E) = \frac{\boldsymbol{\rho}}{\boldsymbol{\varepsilon_0}}$ Eq. (5)
Gauss's magnetic law $\nabla \,.\, H = 0$ Eq. (6)

Where E is electric field intensity, H is magnetic field intensity, ω is angular frequency μ, is permeability, ρ is the charge density, ε_o is free space permittivity and ε^* complex dielectric permittivity. The set of Maxwell's equations results in electric wave propagation and is given by:

$$\nabla \times \mu^{r-1}(\nabla \times E) - k_o^2\left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_o}\right)E = 0 \qquad \text{Eq. (7)}$$

where ω is the angular frequency $(\omega = 2\pi f)$(s^{-1}), microwave frequency (*f*) is 2.45GHz, $\varepsilon_o$is the permittivity of vacuum (8.85 x 10^{-12} F/m), μ_r is the relative permeability, ε_r is the relative permittivity, k_o is the wave number in free space and σ is the electrical conductivity. k_o is given by the expression in Eq.8, where c_o is the speed of light in a vacuum.

$$k_o = \omega\sqrt{\varepsilon_o \mu_o} = \frac{\omega}{c_o} \quad \text{Eq. (8)}$$

When microwave energy strikes a dielectric material, a conversion of electromagnetic energy into heat occurs. This conversion is governed by the amount of power absorbed (P_{ab}) by dielectric material which is defined by the following equation (Salema & Afzal, 2015):

$$P_{ab} = \frac{\omega \varepsilon_o \varepsilon'' E^2}{2} \quad \text{Eq. (9)}$$

where P_{ab} is the absorbed power per unit volume (W/m^3), ε'' is the dielectric loss factor, ε_o is the permittivity of vacuum (8.85 x 10^{-12} F/m), E is the electric field (V/m), and ω is the angular frequency ($\omega = 2\pi f$)(s^{-1}).

Heat transfer equation

The heat transfer by conduction of among EFB pellets to show the variation of temperature over time at a given boundary can be mathematically described with Fourier's energy balance equation as follows:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla(k\nabla T) + Q \quad \text{Eq. (10)}$$

where Q is the heat source from microwave energy, ρ is the density (kg/m^3), C_p is the specific heat capacity (J/kg/K), k is the thermal conductivity of the material (W/m.K), and T is the temperature (K).

The heat source (Q) in the Eq. (10) represents the electromagnetic losses (Q_l), due to electrical and magnetic field:

$$Q_l = Q_{rh} + Q_{ml} \quad \text{Eq. (11)}$$

where the resistive losses Q_{rh} is given by

$$Q_{rh} = \frac{1}{2} Re(J.E^*) \quad \text{Eq. (12)}$$

and the magnetic losses Q_{ml} is given by

$$Q_{ml} = \frac{1}{2} Re(i\omega B.H^*) \quad \text{Eq. (13)}$$

Thermal diffusivity of EFB pellets

$$\alpha = k/(\rho Cp) \quad \text{Eq. (14)}$$

Where (α) is the thermal diffusivity, k is the thermal conductivity, ρ is the density and Cp is the heat capacity of the EFB pellets.

Boundary conditions

Microwave cavity walls and waveguide boundary condition were defined as perfect electrical conductor boundary condition (n x E = 0). The rectangular waveguide assigned boundary condition as port and excited by a transverse electric wave at frequency of 2.45 GHz. The waveguide port condition requires a constant, β which is given by the expression in Eq. (15):

$$\beta = \frac{2\pi}{c}\sqrt{v^2 + v_c^2} \qquad \text{Eq. (15)}$$

where, c is the speed of light, v is the frequency and v_c is a cutoff frequency. When the rectangular port is excited, the Eq. (7) is solved for the electric field, E inside the waveguide and cavity.

SOLVER AND MODEL ACCURACY

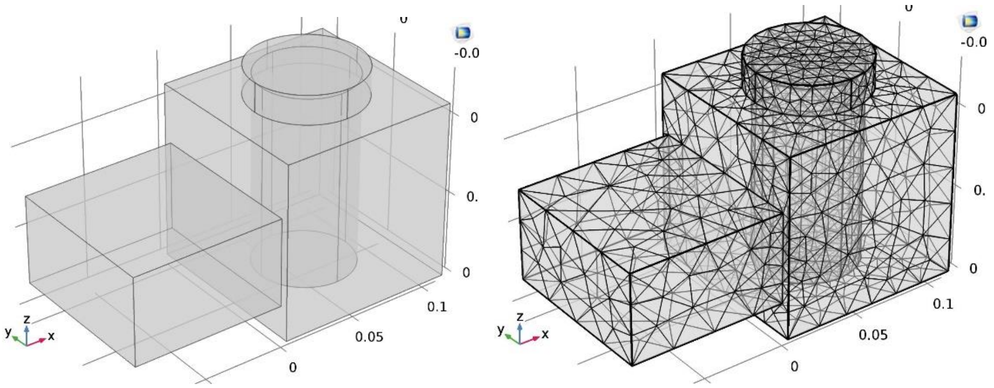
The microwave power absorbed and the temperature distribution in the porous media (EFB pellets) were computed by solving the Maxwell's equations, frequency domain electromagnetic and transient heat transfer equation simultaneously with frequency-transient solver. Segregated solver steps were used to calculate electric field wave (emw) and temperature (T). Root mean square error (RMSE) shown as Eq. (16) was used to examine the accuracy of model by calculating the error between the simulated and experimental temperature data.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(T_s - T_e)^2} \qquad \text{Eq. (16)}$$

GEOMETRY AND MESH

Geometric model shown in the Figure 1(a) was microwave torrefaction system developed in a COMSOL Multiphysics software. Geometric model was divided into 5 major parts: (1) custom made microwave cavity (110mmW*110mmH*110mmL), (2) aluminium rectangular waveguide (100mmW*95mmL*55mmH), (3) cylindrical quartz applicator (65mmD*120mmH), and (4) EFB pellets filled in the applicator and (5) port represented by 1000W, 2.45GHz microwave generator operating in the TE10 mode. Torrefaction was performed by microwave which travelled through the waveguide and heat up the EFB pellets in microwave transparent quartz application. Figure 1 (b) shown the geometry mesh, free tetrahedral mesh element was selected for the whole geometry. The number of tetrahedral and triangular elements were 12051 and 2191 respectively.

Figure 1: Microwave torrefaction system modelled in COMSOL software (a) Geometry (b) Mesh



(a) (b)

Assumptions and limitations of the model

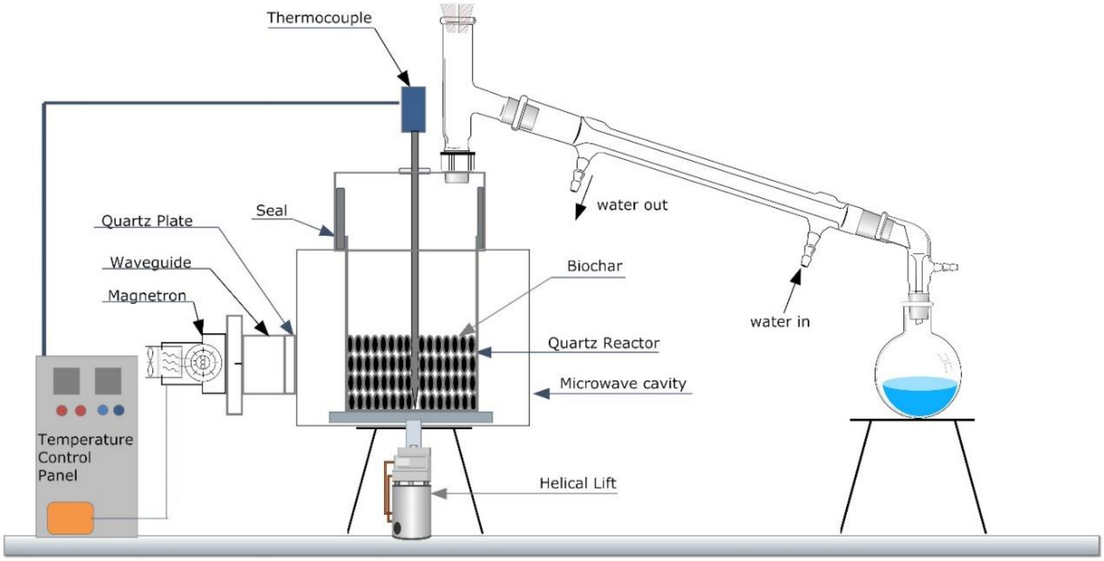
For the present simulation work, assumptions were made to simplify the problem as follows;

I. The flow of air inside the cavity was not modelled.
II. Constant dielectric property and thermal conductivity properties were applied when solving the heat transfer equations.
III. No heat transfer is considered from the quartz reactor, surrounding cavity and environment.
IV. The EFB pellets were considered isotropic and homogenous.
V. Simulation is performed by microwave at 2.45 GHz frequency.
VI. Mass and momentum transfer of moisture and chemical reactions were not considered.

EXPERIMETAL WORK

The microwave torrefaction was conducted in self-purging to create inert atmosphere (limited oxygen). No nitrogen gas purging is required throughout the torrefaction process. Each batch of 50 g of raw EFBP was placed into the quartz reactor followed by microwave heating with 1000W of microwave power to torrefied the biomass for 450s. Final temperature profile of microwave torrefaction was studied. The measurement of temperature was carried out by a K-type thermocouples (Fluke), which were inserted right into the centre of EFB biomass pellet through the top openings of the reactor as shown in Fig. 2. Thermocouples were grounded properly to avoid any discrepancy in the temperatures reading or arcing due to microwaves. Temperature of EFB pellets were measured at 60 mm height from the bottom. Furthermore, these thermocouples were connected to thermometer (Fluke) with data logger, recording temperature every second.

Figure 2: Schematic diagram of the microwave torrefaction experimental setup



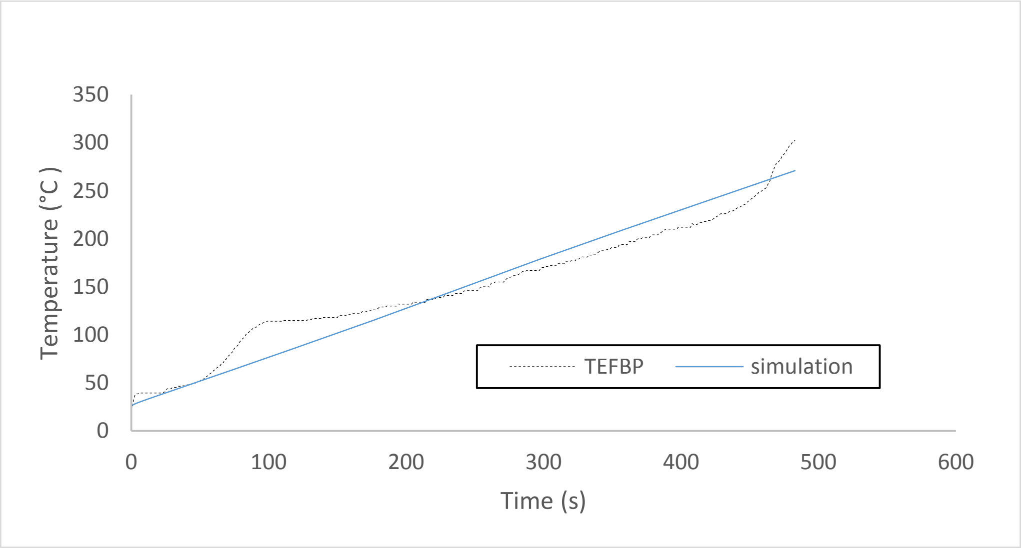
RESULTS AND DISCUSSION

Validation of temperature profile

Generally, EFB pellet showing low thermal diffusivity (α) according to the Eq. (14) with is around 3.26 $\times 10^{-8}$ m^2/s, thus indicated that the heat transfer among the EFB pellets was low. Hence, it was also indicated that the conventional heating via conduction is inefficient to perform the torrefaction of EFB compare to microwave heating via radiation. The deviation between simulated and experimental results can be attributed due to assumption of constant microwave frequency (2.45 GHz) (Pitchai et al., 2014) and inaccurate placing of the thermocouple probe (Pitchai, Birla, Subbiah, Jones, & Thippareddi, 2012). Location of probe shown significant effect to the temperature profiles due to the drastic variation of electrical field inside the MW cavity. The simulation results and experimental data of temperature profile of torrefaction process was recorded from room temperature (25 °C) until the maximum temperature of 300 °C (Fig. 3). Both of the temperature profiles agreed closely by showing linear increasing with the time. The root-mean square error (RMSE) and maximum difference between experimental and simulated results were 16.42 and 38 °C respectively.

Temperature profile of simulation showing linear increasing with single heating rate (30.6 °C/min) and reached temperature of 300 °C around 10 min. Whereas, temperature profile from experimental showing 3 different stages of heating rate before reaching 300 °C. Firstly, temperature range between 50 °C to 120 °C showing higher heating rate of around 78.3 °C/min compare to simulated heating rate (30.6 °C/min). This is due to the moisture content of EFB pellets that represents a favourable characteristic for microwave torrefaction reaction since water is a good microwave adsorbent (Intani, Latif, Kabir, & Müller, 2016; Mushtaq, Abdullah, Mat, & Ani, 2015) thus showing rapid heating of EFB pellets. Secondly, temperature range between 120-250 °C showing almost the same trend and heating rate (30 °C/min) with the simulation results. Thirdly, temperature range between 250-300 °C showing high heating rate (105 °C/min) due to the exothermic reaction during decomposition of lignocellulose (Bates & Ghoniem, 2013; Chen, Kuo, Liu, & Wu, 2014) and partial gasification reaction between volatile matter and char (Bridgeman, Jones, Shield, & Williams, 2008).

Figure 3: Experimental and simulated temperature profile of EFB pellets

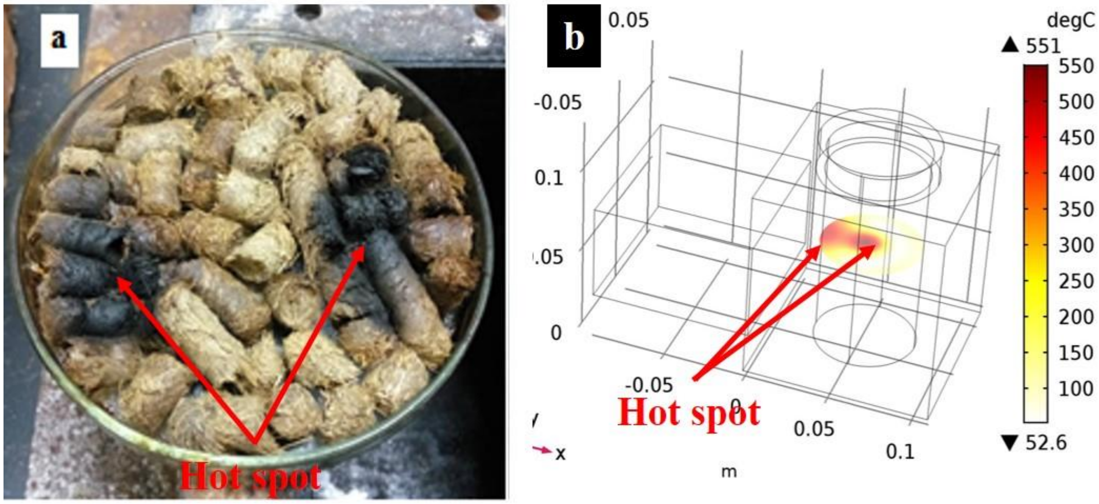


Validation of hot spot locations

Hot spot condition is commonly reported in the multimode microwave (MW) cavities where certain areas were heated at higher temperature in the sample. This is due to the uneven distribution of electromagnetic wave(Halim & Swithenbank, 2018; Salema & Afzal, 2015) in cavity. The region of hot spot in Fig. 4 were almost similar in simulation and experimental study as depicted area near the waveguide and centre of the EFB pellets bed in the temperature range between 250-450 °C. Further heating can cause carbonization and turned EFB pellets into char. This justifies that the model, geometry, and physics defined in COMSOL can accurately simulate the MW heating behaviour of EFB pellets.

Hot spot caused a large temperature gradients and an uneven heating of biomass sample in microwave due to cavity size, geometry shape, magnetron location, waveguide size, TE mode, sample size, dielectric properties of sample and etc (Klinger et al., 2018; Mekonnen, Yenikaya, Yenikaya, & Yılmaz, 2017; Soltysiak, Erle, & Celuch, 2010). Thus, microwave simulation study is important and powerful to generate the microwave heating results and electromagnetics wave distribution study with difference parameters setting. Simulation is also useful for system scale up purpose to perform microwave torrefaction at the bulk condition (Vascellari, Roberts, Hla, Harris, & Hasse, 2015). Microwave heating simulation also avoid trial and error methods and reduce the experimental cost and time. Limited studies have been carried out in the literature to reduce the hot spot condition by sample rotation, multi units of magnetron, and electromagnetic wave stirrer (Al-Rizzo, Adada, Tranquilla, Ma, & Ionescu, 2006; Geedipalli, Rakesh, & Datta, 2007; Halim & Swithenbank, 2018; Puangsuwan, Tongurai, & Chongcheawchamnan, 2015; Santos et al., 2013).

Figure 4: Hot spot locations of (a) Experimental (b) Simulation



CONCLUSION

The numerical simulation of electromagnetic and heat transfer equations were successfully solved using COMSOL Multiphysics software that described the microwave torrefaction of EFB pellets. Simulated temperature data obtained via simulation using specified geometry, thermal, and dielectric properties were found to be in an agreement with experimental temperature data. Simulated temperature profile of microwave heating has shown the linear increasing of temperature with heating rate of 30.6 °C/min and reached temperature of 300 °C around 10 min. Experimental temperature profile has shown 3 different heating rates before reaching 300 °C. Heating rate of 78.3 °C/min (50-120 °C), 30.6 °C/min (121-250 °C) and 105 °C/min (250-300 °C). Temperature profile and hot spot location between experimental and simulation were also successfully validated.

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