# HEAT TRANSFER IN A NOVEL MICROWAVE HEATING DEVICE COUPLED WITH ATOMIZATION FEEDING

by

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*The heat transfer characteristics of the microwave heating coupled with atomization feeding were investigated using ethanol as the spray medium on a pressure swirl nozzle. The effects of spray height, flow rate and temperature on the sauter mean diameter of atomized droplets were examined. The results showed that the droplet sauter mean diameter was 12-130 μm, which increased with the spray height and decreased with the flow rate and temperature of spray medium. Through the fitting of the experimental data, the dimensionless correlation of the droplet sauter mean diameter which was based on orifice diameter, Reynolds and Ohnesorge numbers was obtained. The calculated results were basically consistent with the experimental data within 15% error. The heat transfer characteristics of atomized droplets on high temperature surface of SiC bed heated by microwave were then investigated. The effects of spray flow rate, spray height, and spray temperature on the heat transfer characteristics were examined. The power of spray heat transfer decreased with the temperature and increased with the spray flow rate and spray height. The dimensionless correlation to describe the heat transfer characteristics of atomized droplets on the high temperature SiC surface under the microwave heating was obtained which included thermophysical properties of spray medium, spray parameters, and temperatures of the high temperature bed surface and spray medium, with the error of ±20%. These correlations can be used to predict the sauter mean diameter of the atomized droplets and the power of spray heat transfer in the microwave heating process.*

Key words: *spray, heat transfer characteristics, sauter mean diameter, microwave heating, dimensionless correlation*

## Introduction

With the rapid development of the economy, the development of fine chemicals has become a trend for the efficient use of resources. Pyrolysis is a kind of fast reaction for the production of fine chemicals. The fine chemicals undecylenic acid methyl ester and heptanal can be produced by the pyrolysis of methyl ricinoleate at high temperature [1, 2]. The reaction temperature and heating rate of feedstock were the main influencing factors for pyrolysis [2].

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Thus, the uniformity and speed of heating the feedstock in a stable high temperature reaction site become the key to achieve the high yield and selectivity of target products [2, 3].

Microwave heating is an efficient heating method due to its advantages of rapid, uniform, selective and non-contact heating compared with conventional thermal heating [4-6]. The SiC is often used as microwave absorbent and heating medium owing to its high dielectric constant, large specific heat capacity and good thermal conductivity [7]. The SiC under microwave heating could provide a stable high temperature reaction site for the pyrolysis reactions [3].

Spray heat transfer has the properties of high heat flux, high heat transfer coefficient, excellent temperature uniformity and no contact thermal resistance with the heating surface and thus is superior to conventional heat transfer [8-10]. Fast and uniform heating of feedstock could be achieved through spray heat transfer between the atomized feedstock and surface of SiC bed heated by microwave. Our group developed a microwave-assisted heating system coupled with atomization feeding for methyl ricinoleate pyrolysis, obtaining higher selectivities and yields of target products [1, 2, 11]. In the atomization feeding process, methyl ricinoleate was broken to small droplets by a atomization nozzle. The small droplet diameter lead to large heat exchange area between the droplets and high temperature surface, and hence improving the heating speed and uniformity of the feedstock. In addition, droplet diameter models were developed for characterizing the atomization process using methyl ricinoleate as the spray medium [12]. Since the droplet diameter of feedstock would influence the heat transfer which then has significant effect on the high temperature pyrolysis, it is necessary to explore the heat transfer between the atomized feedstock and the high temperature bed surface.

Nowadays, there are numerous investigations on spray heat transfer. Cheng *et al.* [13] utilized the phase doppler anemometry investigate the effects of spray parameters on the sauter mean diameter (SMD) of atomized droplets and the spray heat transfer using distilled water as the working medium. Dimensionless correlation of droplet SMD and spray heat transfer based on Weber, Reynolds, and Prandtl numbers were established. Zhang *et al.* [14] investigated the spray heat transfer using water as the working medium and found that the physical properties of working medium and the spray characteristics were the main influencing factors in the heat transfer. Bhatt *et al.* [15] conducted the high mass flux spray heat transfer experiments at very high initial surface temperature, with the heat transfer rate being enhanced by using ethanol-water and ethanol-tween20-water solution as working medium. The previous research mainly focused on the effects of spray and heat transfer parameters on spray heat transfer under electric heating. However, few studies on heat transfer between atomized feedstock and high temperature surface under microwave heating were reported.

In this study, cold model tests of the microwave heating device were conducted using ethanol as the spray medium. A droplet diameter model for characterizing the atomization process and a heat transfer model for describing the spray heat transfer process under microwave heating were developed. The effects of spray flow rate, spray height and spray temperature on droplet diameter and heat transfer characteristics were examined. These models can be used for the predictions of the droplet SMD and power in spray heat transfer process under microwave heating.

## Experimental

### *Measurement of the atomized droplet diameter*

The experimental device for measuring the diameter of the atomized droplets is shown in fig. 1.

The ethanol which was preheated to the investigated spray temperature by the heating jacket, was transported by the piston pump. The spray flow rate was controlled by the piston pump. After being stable atomized by the pressure swirl nozzle, the average diameters of the droplets were continuously measured and recorded by the laser particle size analyzer with recorded time interval of 1 second. The pressure at the inlet of the pressure swirl nozzle was measured by the pressure sensor inside the piston pump. The operating parameter ranges were selected to obtain the stable atomization.

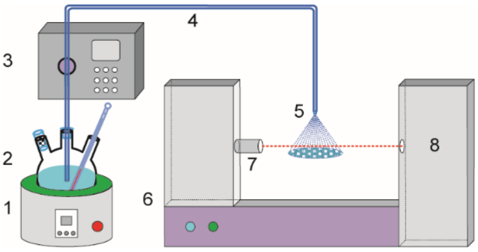


**Figure 1. Device of the measurement of atomized droplet diameter;** *1 – heating jacket, 2 – three-necked flask, 3 – piston pump, 4 – stainless-steel inlet tube, 5 – atomization nozzle, 6 – laser particle size analyzer, 7 – laser emitter, 8 – laser receiver*

The droplet SMD was the diameter of the droplet after being converted into an equal volume sphere, which was expressed by:

$$\text{SMD} = \left[ \sum_{t-(\Delta t/2)}^{t+(\Delta t/2)} \sum_{i=1}^{n} d_i^3 \right] \Big/ \left[ \sum_{t-(\Delta t/2)}^{t+(\Delta t/2)} \sum_{i=1}^{n} d_i^2 \right] \tag{1}$$

where $d_i$ represents the diameter of the droplets and $\Delta t$ – the time interval, *i.e.*, 1 second. The average SMD within 1 minute under stable spray conditions, as shown in fig. 2, was calculated and used in this study. Since the microwave should have limited influence on the atomized droplet diameter, the calculated average SMD was used for the analysis of spray heat transfer in the microwave heating device.

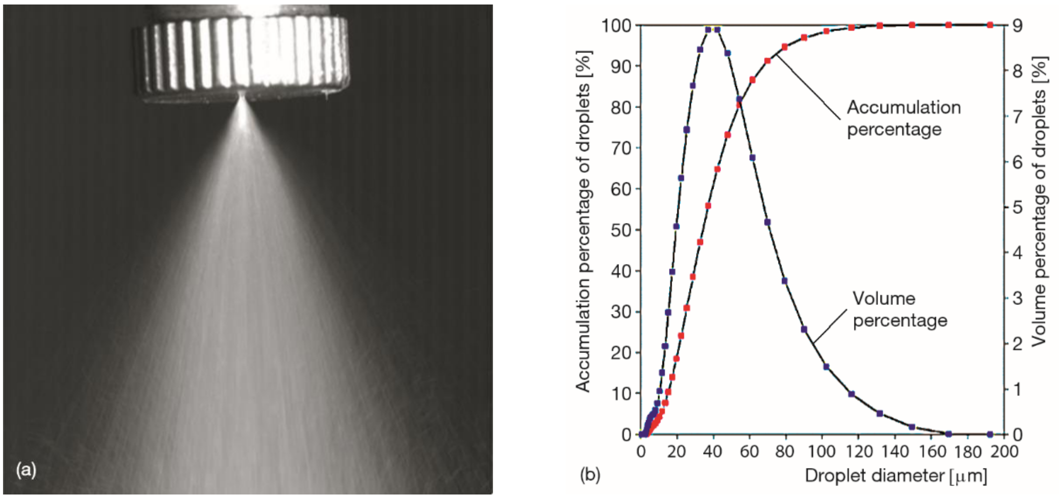


**Figure 2. Typical spray condition, (a) spray image acquired by a high-speed camera and (b) droplet diameter distribution of spray medium**

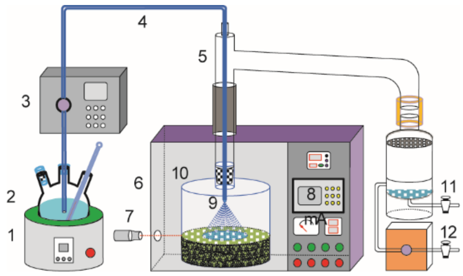


**Figure 3. Experimental device for spray heat transfer under microwave heating;** *1 – heating jacket, 2 – three-necked flask, 3 – piston pump, 4 – stainless-steel inlet tube, 5 – quartz outlet tube, 6 – microwave oven, 7 – infrared thermometer, 8 – paperless recorder, 9 – atomization nozzle, 10 – quartz reactor, 11 – condenser, 12 – water ring vacuum pump*

### *Spray heat transfer in the microwave heating device*

The experimental device for spray heat transfer under microwave heating is shown in fig. 3.

First, approximately 800 g of SiC particles was placed into the bottom of the quartz reactor to form the microwave absorbent bed. The spray height was determined by adjusting the distance between the nozzle and the surface of the SiC bed. The high-purity nitrogen was introduced into the microwave heating device to remove the air in the device. The SiC bed temperature measured by an infrared thermometer was maintained stable at the set temperature by automatically turning the microwave heating on or off.

Ethanol as the spray medium was transported by a piston pump and atomized by a pressure swirl nozzle. Heat transfer took place between the atomized droplets of ethanol and the high temperature SiC bed surface in the microwave device. The microwave powers was continuously measured by the power meter during the experiment. The powers of heat loss without and with feeding, $P_{\text{radiation}}$ and $P_{\text{heat transfer}}$, were the microwave powers to maintain the microwave continuously being on and meanwhile the temperature of SiC bed stable under these two conditions. The actual power of spray heat transfer $P_{\text{spray}}$ was the difference between $P_{\text{heat transfer}}$ and $P_{\text{radiation}}$, as shown in:

$$P_{\text{spray}} = P_{\text{heat transfer}} - P_{\text{radiation}} \tag{2}$$

### *Experimental uncertainty*

The accuracy of the laser particle size analyzer was ±1%, based on the $D_{50}$ value of standard sample using static light scattering technique. Both the accuracies of the infrared thermometer and microwave power meter were ±1%, acquired from the specification of instruments. Thus, the uncertainties of laser particle size analyzer, infrared thermometer and microwave power meter were all ±1%. According to the error propagation law [16], the uncertainty for SMD and $P_{\text{spray}}$ resulted by the data acquisition instruments was ±1%.

## Experimental

### *Measurement of the atomized droplet diameter*

The spray heat transfer between the atomized droplets and high temperature surface was affected by droplet SMD. Since droplet SMD was greatly influenced by spray parameters, the effects of spray flow rate, spray height and spray temperature on droplet SMD were firstly examined.

#### *Effects of spray flow rate and spray height on SMD*

The effects of the spray flow rate and spray height on the atomized droplet SMD were investigated. As shown in fig. 4, the droplet SMD was 12-130 μm, which decreased with increasing spray flow rate at a certain spray height. This was mainly due to the characteristics and atomization mechanism of the pressure swirl nozzle. When the liquid leaves the nozzle, a very unstable liquid film will be formed at the outlet of the nozzle [17]. As the kinetic energy of the liquid film is greater than the surface tension of the liquid, the liquid film will break into small droplets. Thus, higher spray flow rate led to larger kinetic energy of the liquid film, which caused the liquid film more likely to be broken and dispersed into smaller droplets [18]. In addition, the droplet SMD increased with increasing spray height, which was probably because that the atomized droplets gradually coalesced with the increase in the distance from the nozzle [19]. The increasing spray height would increase the spray radius, and hence improve the heat transfer area in spray heat transfer process.

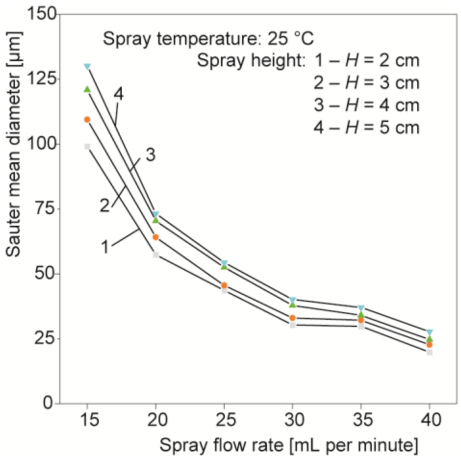


**Figure 4. The droplet SMD at different spray flow rates and spray heights**

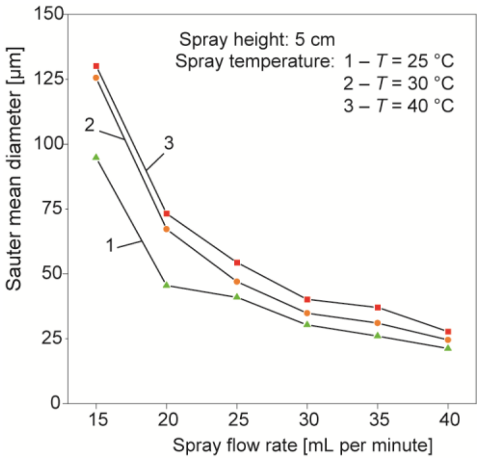


**Figure 5. The droplet SMD at different spray temperatures**

### *Effects of spray temperature on SMD*

The effect of the spray temperature on the droplet SMD was investigated. As shown in fig. 5, the spray temperature had obvious influence on the droplet SMD, especially at lower temperature. The droplet SMD was 24-130 μm, which increased with the decrease in spray temperature. The spray temperature affected droplet SMD through the density, viscosity, and surface tension of spray medium [13]. The density, viscosity, and surface tension of spray medium decreased with the spray temperature and hence the liquid film formed in atomization were more easily to be broken and dispersed into smaller droplets, which reducing the droplet SMD. Since the small droplet diameter could lead to large heat exchange area, the optimal spray temperature in this experiment was 40 ºC.

### *Dimensionless correlation of SMD*

From the previous analysis, the droplet SMD was mainly affected by the spray flow rate, spray height, and spray temperature. Among these, spray temperature mainly influence the physical properties of the spray medium. Here, the Reynolds number and the Ohnesorge number were used to describe the spray flow rate and properties of the spray medium [12].

The Reynolds number and Ohnesorge number are defined:

$$\mathrm{Re} = \frac{(P\rho_f)^{1/2} d_0}{\mu} \tag{3}$$

$$\mathrm{Oh} = \frac{\mu}{(\rho_f d_0 \sigma)^{1/2}} \tag{4}$$

where $P$ [Pa] is the pressure drop at the nozzle, $\rho_f$, $\mu$, and $\sigma$ denote the density [kgm$^{-3}$], viscosity [kgm$^{-1}$s$^{-1}$], and surface tension [Nm$^{-1}$] of spray medium, respectively, and $d_0$ [m] – the nozzle orifice diameter.

The dimensionless correlation of droplet SMD can be obtained by the least squares fitting method using the experimental data. The correlation can be expressed:

$$\frac{\mathrm{SMD}}{d_0} = 1807.319\left(\frac{H}{d_0}\right)^{0.3453} \mathrm{Re}^{-1.4998}\mathrm{Oh}^{-0.0048} \tag{5}$$

As can be seen in fig. 6, the correlated SMD was basically consistent with the experimental SMD, with the error being less than 15%. Thus, the correlation can be used to describe and predict the SMD of the atomized droplets by the pressure swirl nozzle.

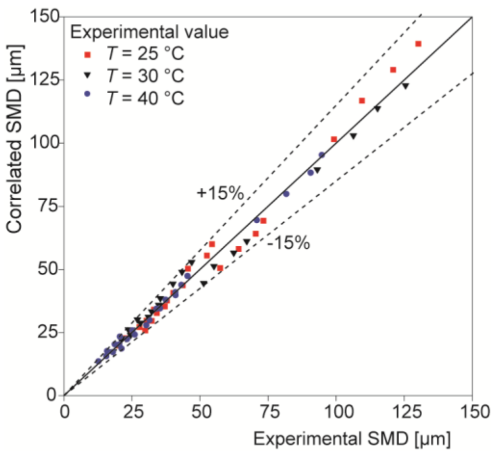


**Figure 6. Comparison between experimental and correlated SMD** *(for color image see journal web site)*

## *Spray heat transfer in the microwave heating device*

### *Effects of spray flow rate on spray heat transfer*

The spray flow rate had great influence on the droplet SMD, thereby affecting spray heat transfer. The spray flow rates of 15, 20, 25, 30, and 35 mL per minute were selected to study the effect of spray flow rate on the spray heat transfer in the microwave heating device.

The actual power of spray heat transfer at different spray flow rates and the power of unit spray flow rate are shown in fig. 7. The power increased with the spray flow rate, which was mainly because the total heat exchanged between the spray medium and the stable high temperature SiC bed surface was increased at higher spray flow rate. However, the power of unit spray flow rate decreased with the increase in spray flow rate. It was probably because a thin gas film gradually formed on the high temperature SiC surface with increasing spray flow rate, which reduced the efficiency of the spray heat transfer [20]. The maximum spray flow rate in this experiment was 35 mL per minute. Owing to the limited power of the microwave device, the spray flow rate of higher than 35 mL per minute may cause the unstability of the SiC bed temperature.

### *Effects of of spray height on spray heat transfer*

The spray height had great influence on the droplet SMD and heat transfer area, thereby affecting the power. The spray heights of 2-5 cm were selected to study the effects of spray height on the spray heat transfer in the microwave heating device.

As shown in fig. 8, the power increased with the increasing spray height. The power significantly increased from 183.3 W at the spray height of 2 cm to 369.5 W at the spray height of 5 cm at the spray flow rate of 15 mL per minute. Higher spray height led to larger droplet SMD, which was not conducive to heat transfer. Since the total transferred heat was constant at a certain spray flow rate, higher microwave heating power was required at higher spray height to maintain stable temperature of the SiC bed.

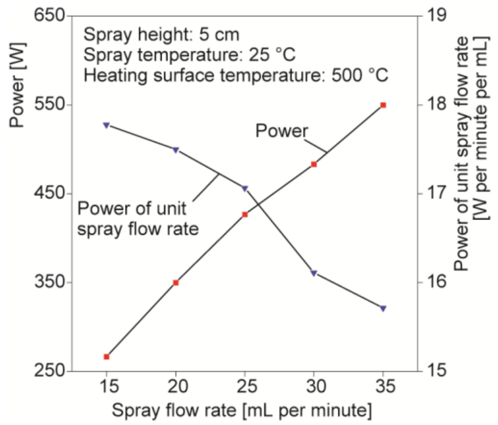


**Figure 7. Power of spray heat transfer at different spray flow rates**

### *Effects of spray temperature on spray heat transfer*

The effect of spray temperature on spray heat transfer was investigated at spray temperatures of 25 ºC, 30 ºC, and 40 ºC. As shown in fig. 9, the power of spray heat transfer decreased with increasing spray temperature. The increase in temperature of the spray medium would result in the reduction of density, viscosity and surface tension of the spray medium, and thus reducing the droplet SMD and improving the heat transfer between the droplets and SiC bed surface. Therefore, to maintain stable temperature of the SiC bed, lower microwave heating power was required at a certain spray flow rate. Thus, the power was lower at higher spray temperature. The power difference under various temperatures was increased with the spray flow rate. In addition, lower temperature difference between the spray medium and high temperature SiC bed surface led to the decrease in total transferred heat, thereby further reducing the power.

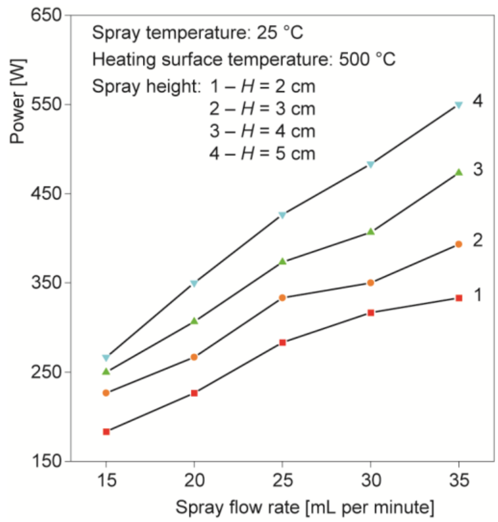


**Figure 8. Powers at different spray heights**

### *Dimensionless correlation of spray heat transfer*

The spray heat transfer between the atomized droplets and high temperature surface under microwave heating are primarily due to the impingement of droplets on the high temperature surface. The heat transfer was achieved mainly through evaporation, boiling and convection [21]. Therefore, the spray heat transfer will be influenced by the thermophysical properties of spray medium, spray parameters, and temperature difference between the high temperature bed surface and spray medium [18, 22].

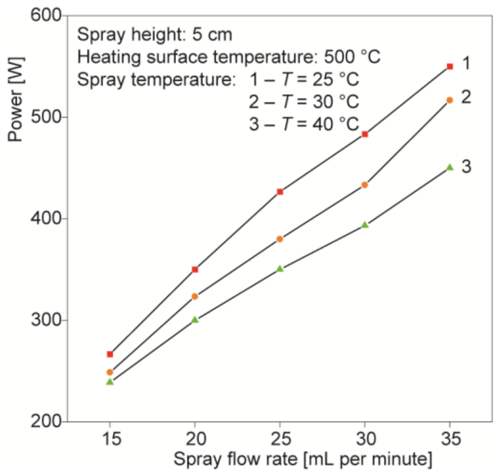


**Figure 9. Powers at different spray temperatures**

Therefore, the spray heat transfer in the microwave heating device can be expressed by:

$$f(h, D, k, \rho, u_0, \mathrm{SMD}, \sigma, \mu, C_p, T_{\mathrm{surf}}, T_f, L_{fg}) = 0 \tag{6}$$

where $k$, $\rho$, $\mu$, $C_p$, $\sigma$, $L_{fg}$ are thermal conductivity [$\mathrm{Wm^{-1}K^{-1}}$], density [$\mathrm{kgm^{-3}}$], viscosity [$\mathrm{kgm^{-1}s^{-1}}$], specific heat capacity [$\mathrm{kJkg^{-1}K^{-1}}$], surface tension [$\mathrm{Nm^{-1}}$], and latent heat [$\mathrm{kJkg^{-1}}$] of the spray medium, respectively. The $u_0$ [$\mathrm{ms^{-1}}$] refers to the outlet velocity of the spray medium, $T_{\mathrm{surf}}$ and $T_f$ [K] – the temperatures of the high temperature SiC bed surface and the spray medium, respectively, $h$ [$\mathrm{Wm^{-2}K^{-1}}$] – the heat transfer coefficient, and $D$ [m] – the diameter of the heat transfer area on the SiC bed surface, which can be expressed by:

$$h = \frac{P_{\mathrm{spray}}}{S(T_{\mathrm{surf}} - T_f)} \tag{7}$$

$$S = \frac{\pi D^2}{4} \tag{8}$$

$$D = 2H \tan\frac{\theta}{2} \tag{9}$$

where $S$ [$\mathrm{m^2}$] is the spray area, $H$ [m] – the spray height, and $\theta$ [°] – the spray angle.

The dimensional analysis method was used to analyze the eq. (6). The parameters involved in eq. (6) influencing the spray heat transfer in the microwave heating device can be summarized as the following dimensionless numbers: Nusselt number, Weber number, Reynolds number, Prandtl number, and Jacob number. These dimensionless numbers can be expressed by:

$$\mathrm{Nu} = \frac{hD}{k} \tag{10}$$

$$\mathrm{We} = \frac{\rho u_0^2 \mathrm{SMD}}{\sigma} \tag{11}$$

$$\mathrm{Re} = \frac{\rho u_0 \mathrm{SMD}}{\mu} \tag{12}$$

$$\mathrm{Pr} = \frac{C_p \mu}{k} \tag{13}$$

$$\mathrm{Ja} = \frac{C_p(T_{\mathrm{surf}} - T_f)}{L_{fg}} \tag{14}$$

Thus, eq. (6) can be transformed into:

$$f\left[\frac{hD}{k}, \frac{\rho u_0^2 \mathrm{SMD}}{\sigma}, \frac{\rho u_0 \mathrm{SMD}}{\mu}, \frac{C_p \mu}{k}, \frac{C_p(T_{\mathrm{surf}} - T_f)}{L_{fg}}\right] = 0 \tag{15}$$

The spray heat transfer correlation is then expressed:

$$\mathrm{Nu} = \mathrm{g(We, Re, Pr, Ja)} \tag{16}$$

The dimensionless correlation of spray heat transfer can be obtained by the least squares fitting method using the experimental data. The coefficient and powers of the terms of Weber number, Reynolds number, Prandtl number, and Jacob number are 32965, 0.2029, –1.4591, 1.0711, and –0.393, respectively.

Therefore, the spray heat transfer correlation in the microwave heating device is expressed:

$$\mathrm{Nu} = 32965\mathrm{We}^{0.2029}\mathrm{Re}^{-1.4591}\mathrm{Pr}^{1.0711}\mathrm{Ja}^{-0.393} \tag{17}$$

The comparison between experimental and correlated Nusselt number is displayed in fig. 10. The correlated Nusselt number was basically consistent with the experimental Nusselt number, with the error being less than 20%. The experimental and correlated values of Nusselt number were similar with those reported by Mudawar [23] and Hsieh [24].

Thus, the correlation can be used to predict the Nusselt number and hence heat transfer coefficient under various spray heat transfer conditions in the microwave heating device.

Combining eqs. (7)-(9) and (17), the power of spray heat transfer can be calculated, and hence the power provided by the microwave heating device to maintain stable temperature of high temperature SiC bed can be determined which is expressed by:

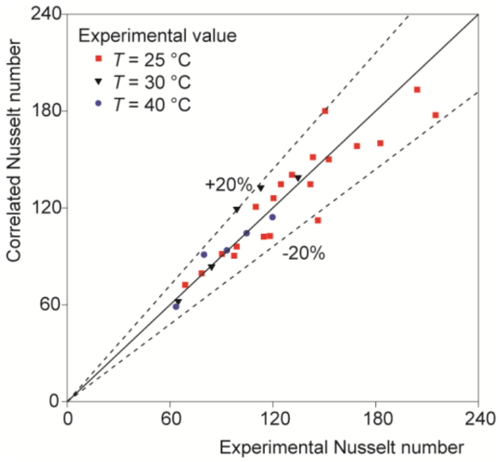


**Figure 10. Comparison between experimental and correlated Nusselt number** *(for color image see journal web site)*

$$P_{\mathrm{spray}} = 51781H\tan\frac{\theta}{2}(T_{\mathrm{surf}} - T_f)k\mathrm{We}^{0.2029}\mathrm{Re}^{-1.4591}\mathrm{Pr}^{1.0711}\mathrm{Ja}^{-0.393} \tag{18}$$

Using this equation, the required power under various spray parameters during the microwave heating process can be obtained, which provides theoretical guidance for the optimization and design of microwave heating device coupled with atomization feeding. In addition, the eq. (18) can also be used to predict the power in the microwave-assisted pyrolysis of methyl ricinoleate. The comparison between theoretical and correlated power in microwave-assisted pyrolysis of methyl ricinoleate is displayed in fig. 11 [2]. The theoretical power was

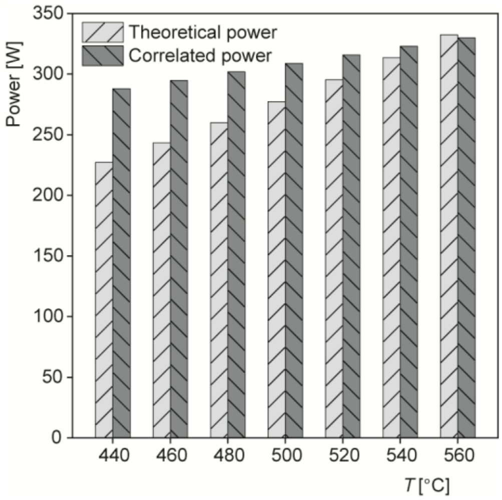


**Figure 11. Comparison between theoretical and correlated power in microwave-assisted pyrolysis of methyl ricinoleate**

calculated by the group contribution method using the sensible heat and latent heat of methyl ricinoleate. It can be noticed that the correlated power was basically consistent with the theoretical power, with the error being less than 20%.

## Conclusions

In this work, spray heat transfer characteristics in a novel microwave heating device was studied using ethanol as the working medium. The effects of operational parameters on the SMD of atomized droplets and the spray heat transfer between droplets and high temperature surface were examined. The models to describe and predict the droplet SMD and the spray heat transfer characteristics were then developed. The main conclusions were as follows.

- The SMD of atomized droplets was 12-130 μm, which decreased with increasing spray flow rate and spray temperature and increased with spray height. A dimensionless correlation of the droplet SMD involving the nozzle orifice diameter, $d_0$, thermophysical properties of spray medium, $\mu$, $\rho$, and $\sigma$, and spray height, $H$, was established. The correlated SMD agreed well with the experimental data, with the error being less than 15%.
- The power of spray heat transfer in the microwave heating device was calculated. The power decreased with the increase in spray temperature and increased with the increasing spray flow rate and spray height. A dimensionless correlation to describe the spray heat transfer was developed, which included thermophysical properties of spray medium, $k$, $\mu$, $\rho$, $\sigma$, $C_p$, and $L_{fg}$, spray parameters, $u_0$, $D$, and SMD, and temperatures of the high temperature bed surface and spray medium, $T_{\rm surf}$, $T_f$. The correlation can be used to predict the microwave heating power required to maintain stable temperature of the high temperature bed surface and the power in the microwave-assisted pyrolysis of methyl ricinoleate.

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