IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received February 14, 2020, accepted February 29, 2020, date of publication March 3, 2020, date of current version March 13, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2978124

A Temperature-Control System for Continuous-Flow Microwave Heating Using a Magnetron as Microwave Source

JINGHUA YE[1], **CHUN ZHANG**[2], **AND HUACHENG ZHU**[2], **(Member, IEEE)**
[1]College of Information Science and Engineering, Chengdu University, Chengdu 610100, China
[2]College of Electronics and Information Engineering, Sichuan University, Chengdu 610065, China

Corresponding author: Huacheng Zhu (hczhu@scu.edu.cn)

This work was supported by the Science Foundation of the Guizhou Province under Grant Qiankehezhicheng [2018] 2004.

ABSTRACT A real-time temperature control system is designed for microwave heating of a continuous-flow substance. In this system, a magnetron is used as the microwave source, and its output power can be continuously adjusted though circuit design. A programmable logic controller (PLC) is used to procedure the temperature and power data as well as lead the whole control decision. The sample temperature can be controlled by regulating the output power of the magnetron though the control signal from the PLC during the heating process. The complete system is finally assembled into a user-friendly device, where the users can operate and monitor the heating process conveniently though a touch screen. A temperature-dependent material (Phosphoric acid) is used in system tests. The results show that the designed system can successfully achieve the desired temperature with an acceptable accuracy and stability.

INDEX TERMS Temperature control, continuous flow, microwave heating, magnetron.

I. INTRODUCTION

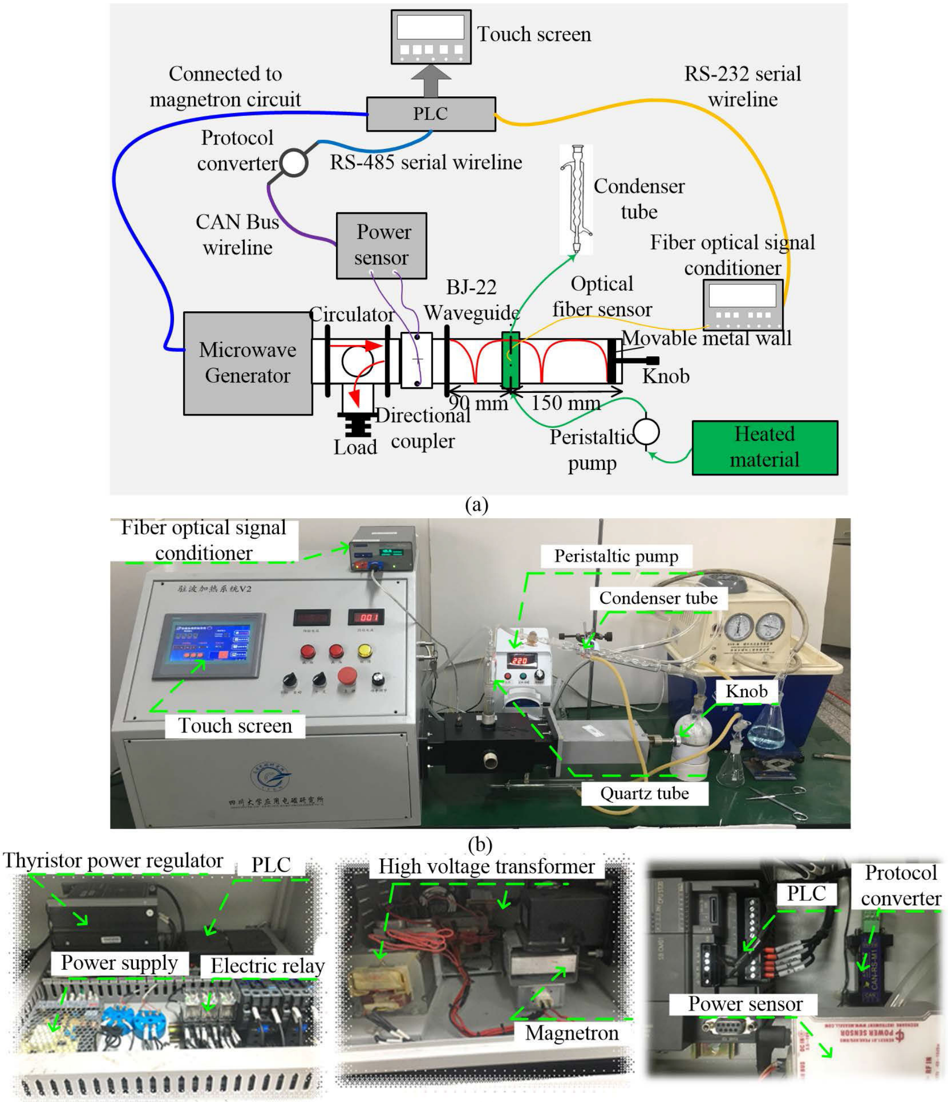
Microwave energy has been widely used in food engineering, chemical engineering and many other fields due to its advantages such as high efficiency, fast heating and environmental friendliness [1]–[3]. At first, the chemical reactions assisted by microwave were done in the batch microwave reactor, because it is easy to design and can be obtained from the ready-made microwave equipment. However, due to the lack of microwave penetration depth, it is difficult to expand the size of batch microwave reactor to an industrial one [4]. Meanwhile, the batch microwave reactor cannot meet the requirements of industrial production line [5]. Therefore, in order to improve the output of microwave-assisted chemical reaction and integrated microwave technology into the industrial chemical synthesis production, microwave continuous flow processing approach has been proposed. A large number of successful cases of microwave-assisted continuous flow chemical reactions have been reported, which show many advantages of continuous flow reactors, such as rapid temperature control, safety, and easy to scale up [6]–[9].

However, the hot spots and thermal runaway caused by microwave uneven heating still exist in the continuous-flow reactor [10]. In particular, when a high-power microwave is applied on the processed chemicals, the huge uncontrollable temperature rise due to strong dielectric loss and temperature-positive feedback of the chemical may lead to the damage of chemicals or even an explosion [11], [12]. Therefore, it is of great significance to control the temperature of continuous-flow microwave reactors during the heating process.

Currently, some methods to control the output of microwave power and the temperature of the material heated by microwave have been proposed. Paglione et al. invented a temperature controller for microwave heating a specimen [13]. Beale et al. developed an automatic feedback control system for controlling the temperature of ceramic samples during microwave heating [14]. Sanchez et al. proposed a simple control structure to overcome the problem caused by uncertainty and disturbances existed in the realist microwave heating process [15]. Ramon et al. presented a temperature controller in a focused microwave heating system for determination of chemical oxygen demand [16]. Li et al. developed a temperature controlling microwave drying system based on a feedback controlling loop, and good stability was reported [17], [18]. In order to keep the

---

The associate editor coordinating the review of this manuscript and approving it for publication was Wenjie Feng.



(a)

(b)

(c)

FIGURE 1. (a) Schematic diagram of the experimental system. (b) Photo of experimental system (Magnetron circuit and PLC are integrated into a metal box). (c) Photos inside the metal box.

heated material at a set temperature, Zhou et al. proposed a microwave reactor integrated with a heat-exchanger [19]. However, in the above methods, the heated materials are all placed in the batch reactor. In fact, for a continuous flow microwave reactor, the chemical inside the reactor is constantly flowing in and flowing out, which means the heat in the reactor is constantly exchanged with the outside world. Moreover, due to the lack of microwave penetration depth, the diameter of the reactor cannot be too large, thus in order to increase the processing capacity of the reactor, the inlet velocity of the chemical is usually set relatively fast. This further increases the difficulty of power and temperature control under such dynamic condition. Hence, literature related to this topic is seldom reported.

In this paper, a new microwave continuous flow heating system with real-time temperature controlling capability is developed. By using a specially designed feedback system based on a programmable logic controller (PLC), the output power of the magnetron can be automatically and continuously adjusted according to the difference between the set temperature and the measured temperature. The system design including the hardware design of microwave source, control algorithm based on proportional integral derivative (PID) regulation, data acquisition method, and interconnection of each components is detailly described in the paper. The temperature stability at different set temperatures and inlet velocities is analyzed. Phosphoric acid (content: 85%) is used for the system testing. Results show that the system can successfully control the temperature at the desired temperature with a fair accuracy and stability.

II. MATERIALS AND METHODS

The developed system consisted of a microwave source, a continuous-flow microwave reactor, a PLC (S7-200, Siemens Aktiengesellschaft, Munich, Germany) to lead the whole control process, and the microwave power and temperature acquisition unit, as shown in Fig. 1 (a). For ease of use, the magnetron circuit, PLC, power sensor and serial port wiring are integrated into a box with a touch screen, which can be seen in Fig. 1 (b). The continuous-flow microwave reactor included a single mode cavity (109.2 mm*54.6 mm*240 mm), a quartz tube with inner diameter of 24 mm and outer diameter of 28 mm, a condensing pipe, and a peristaltic pump. The distance from the central axis of the quartz tube to the left waveguide wall is 90 mm, as shown in Fig. 1 (a). The quartz tube is inserted through the waveguide and the size of the heating area is $(24/2)^2*3.14*54.6\ \text{mm}^3 = 24687.9\ \text{mm}^3$. A SIMATIC WinCC (V15, Siemens Aktiengesellschaft, Munich, Germany) program for the PLC control system is developed to integrate all the operations of measurements and controls.

A. MICROWAVE SOURCE

Generally, as the most economical microwave generator, magnetron has been widely used in various microwave equipment in industry [20], [21]. Due to its low price and good compatibility with the traditional microwave equipment, magnetron is used as the microwave source in this work. In order to realize the real-time control of microwave output power, the magnetron hardware design is very important. Generally, the output power of a magnetron is mainly determined by the anode voltage and anode current. On one hand, for magnetrons with non-linear working characteristics, only regulating the anode voltage cannot guarantee a stable output power, where certain fluctuations will occur. On the other hand, only adjusting anode current will have problems like large power jump and unstable output. A better choice is to adopt a switching power supply, which can collect the anode current while adjusting the anode voltage, thereby ensuring a stable output power through multi-level voltage and current regulation. However, the development cost of this method is high, while the design is difficult. Therefore, from the perspective of development cost, functional requirements, system stability and power capacity, this paper adopts a simplified method which mainly adjust the anode voltage and limit the current in a certain range to control the control the magnetron power. In order to achieve automatic power regulation, the output signal came from a thyristor power regulator (KTY3S, Sichuan Injet Electric Co., Ltd., Sichuan Province, China) integrated in the magnetron circuit is boosted by two high-voltage transformers, and then transformed into pulsating DC negative high voltage (to the cathode) after passing through the high-voltage full wave voltage doubler rectifier module composed of diode and capacitor to provide high voltage to the magnetron cathode. When the magnetron (2M410, Panasonic Corporation, Osaka, Japan) is working, its output power is measured and compared to the required value, then by using a PID control algorithm, the control signal of the thyristor power regulator will be adjusted to required value. In the final system, the output microwave power can be adjusted in the range of 150-1200 W. The diagram of the magnetron circuit is shown in Fig. 2. The acquisition method of magnetron power and PID algorithm of power control will be introduced detailly in the following contents.

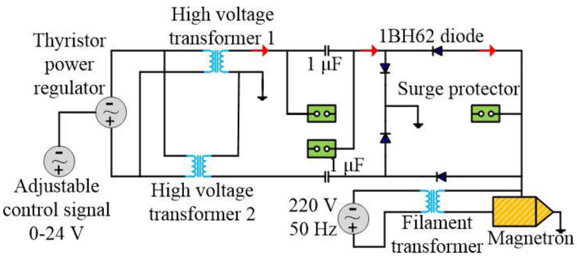


FIGURE 2. Diagram of the magnetron circuit.

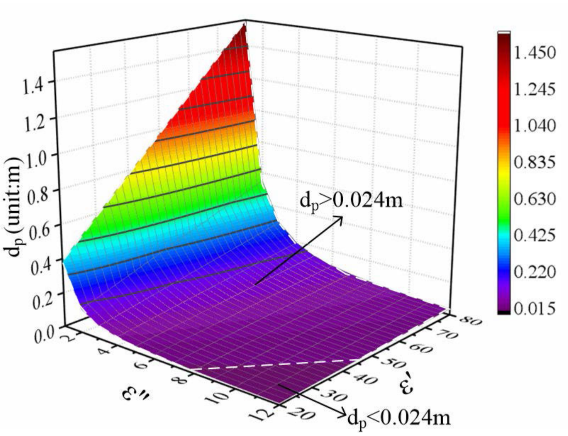


FIGURE 3. Microwave penetration depth of common organic aqueous solution (with a real part of relative permittivity from 20 to 80, and imaginary part of relative permittivity from 1 to 12).

B. CONTINUOUS-FLOW MICROWAVE REACTOR

A BJ-22 waveguide (109.2 mm × 54.6 mm × 240 mm) with a tunable metal wall is utilized for continuous-flow microwave heating. The frequency of microwave source is 2450 MHz. In order to determine the diameter of quartz tube, the microwave penetration depth of common organic aqueous solution (with a real part of relative permittivity from 20 to 80, and imaginary part of relative permittivity from 1 to 12) is calculated by Equation (1) [22], [23], and the results are shown in Fig. 3.

$$d_p = \lambda_0/2\pi \cdot \left(2\varepsilon'' \cdot \left(\sqrt{1+(\varepsilon''/\varepsilon')^2}-1\right)\right)^{-0.5} \quad (1)$$

where λ_0 indicates the microwave wavelength in free space, ε' and ε'' are the real and imaginary part of relative permittivity of the solution, respectively. From Fig. 3, we can see that the microwave penetration depth of most of the solutions is greater than 24 mm. In order to effectively heat the solution inside the tube, the size of quartz tube should be smaller than or close to the penetration depth of microwave. Therefore, the inner diameter of the quartz tube is set as 24 mm, and outer diameter is set as 28 mm. Hence, from the point of view of heating uniformity, the common organic aqueous solution (with a real part of relative permittivity from 20 to 80, and imaginary part of relative permittivity from 1 to 12) can be effectively heated in this reactor. The quartz tube is inserted through the waveguide, whose inlet is connected with a peristaltic pump (YZ1515X, Nanjing Runze Fluid Control Equipment Co., Ltd., Nanjing, China) and the outlet is connected with a condenser pipe. A small hole is drilled on the cover of the container to accommodate temperature sensor. An optical temperature sensor (T1, Neoptix, Quebec City, Quebec Province, Canada) with a response time of less than 500 milliseconds and calibrated accuracy of ±0.2°C is inserted in the center of the quartz tube for temperature measurements. More optical temperature sensors can be added to the reactor for the measurement of the temperature of complex substances. The movable metal wall is controlled by a knob connected with the rod of the movable metal wall, as shown in Fig. 1. By slowly turning the knob, the metal can be moved forward or backward slowly. In the experiment, after the reactant is filled with quartz tube, by moving the metal wall from left end (right outer wall of quartz tube) to right end and reading the reflect power from the power meter at the same time, a minimal reflect power can be detected and the metal wall in this position, which can make the electromagnetic energy density of the standing wave in the reaction pipe to be maximal, will be used throughout the heating process [24].

C. DATA ACQUISITION UNIT

1) POWER ACQUISITION

Generally, the output microwave power can be measured by a directional coupler and a microwave power meter. However, if the value of the power meter is not converted to programmable data, it is difficult to realize the real-time control of power. In our work, the output microwave power is obtained by a directional coupler (LOOPE22DC40A10N, Euler Microwave, Sichuan Province, China) and a power sensor (HX9531, KeChuang measurement Association, Sichuan Province, China). Since the data transmission protocol of the power sensor (CAN Bus Protocol) is different from that of the PLC (RS-485 serial protocol), a protocol converter is placed between the power sensor and PLC to achieve data docking. The control system based on PLC will be introduced detailly in Section 2.4.

2) TEMPERATURE ACQUISITION

As mention in Section 2.2, the temperature is first measured by an optical temperature sensor. In order to convert the temperature value to programmable data, a fiber optical signal conditioner (Reflex, Neoptix, Quebec City, Quebec Province, Canada) is connected behind the temperature sensor to send the temperature data to the PLC via a RS-232 serial data wireline. The PLC can therefore read and record the real-time temperature of the reactor during microwave heating.

D. CONTROL SYSTEM BASED ON PLC

PLC is an electronic system for digital operation, which is specially designed for application in industrial environment. In this work, the PLC is the brain of the whole control system, which collects the temperature and power data and sends signals to the thyristor power regulator to adjust the microwave output power in real time. Control algorithm and overall control method of the PLC control system, which is important to realize this process, are described below.

1) CONTROL ALGORITHM

Control algorithm is the core of control system, which is directly related to the overall performance of the system. PID algorithm, with a three-term functionality (proportional controller, integral controller, and derivative controller) covering treatment to both transient and steady-state responses, is chosen as the control algorithm in this work for its simplicity and effectiveness [25]. The differential equation of the PID controller can be described as [26]:

$$u(t) = K_p \left[e(t) + 1/T_I \cdot \int_0^t e(t)dt + T_D \cdot de(t)/dt \right] \quad (2)$$

where K_p refers to the proportional gain, T_I indicates the intergral time constant, T_D denotes the derivative time constant, $e(t)$ is the deviation between the given value $r(t)$ and the actual output value $c(t)$, and $u(t)$ is the output.

The transfer function of a standard PID controller can be expressed by [26]:

$$G(s) = K_p \left(1 + 1/T_I s + T_D s\right) \quad (3)$$

Theoretical analysis and experiments show that heating process satisfies the first order plus dead time (FOPDT) condition [27], [28], where the Laplace transform of the process response can be expressed as:

$$G(s) = K/(ts+1) \cdot e^{-\tau s} \quad (4)$$

where K is the system gain, t is the time constant and τ is the dead time parameter. Based on FOPDT system, the Ziegler–Nichols tuning method is chosen to realize the PID controller parameters tuning [29], [30]. The determination of PID controller parameters will be introduced in Section 3.1. In this work, the deviation of the measured data and the set value is used as the input of PID controller to adjust the control signal of the thyristor power regulator to make the temperature close to the set value.

2) OVERALL CONTROL METHOD

The logic block diagram of the overall control process is shown in Fig. 4. It can be known from Fig. 4 that the control process mainly includes two parts: one is to control the magnetron power supply to adjust the output microwave power, the other is to monitor the status of continuous-flow microwave reactor and the sample temperature to obtain the real-time regulating signal. During the heating process, the data acquisition, PID calculation and signal transmission in this system are ongoing to maintain a dynamic balance.

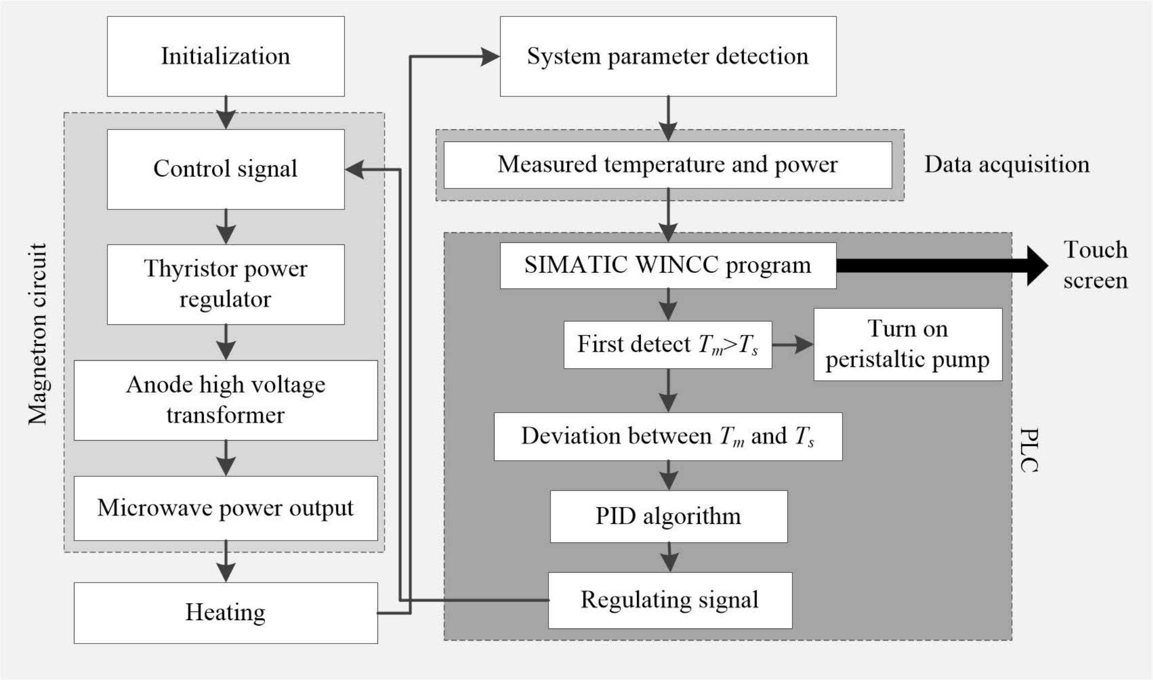
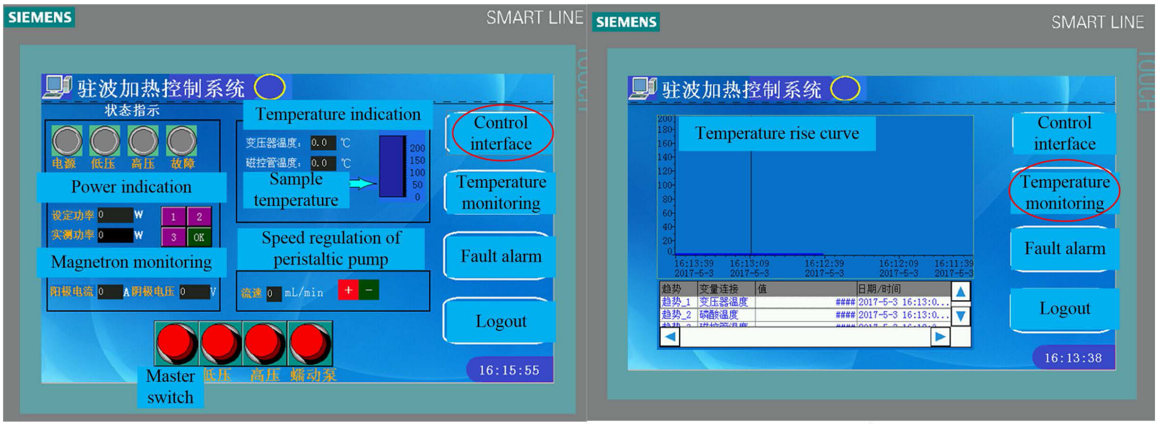


FIGURE 4. Logic block diagram of the overall control process (T_m refers to the measured temperature, T_s refers to the set temperature).



(a)

(b)

FIGURE 5. (a) Control interface on the touch screen, (b) temperature monitoring interface on the touch screen.

A SIMATIC WINCC program, which can be used to solve the visualization problems of production and process automation and complete various control tasks, is designed to realize the control process in PLC. This program is completed on a personal computer then downloaded to the PLC module. The whole system can be configured on a touch screen (Smart line 700IE, Siemens Aktiengesellschaft, Munich, Germany) by using the SIMATIC WINCC program. After the corresponding physical interface is configured reasonably in the touch screen and PLC, the temperature and power read by the PLC will be displayed on the touch screen and updated in real time, which facilitates the operation of the whole system. As shown in Fig. 5, the whole control interface is divided into control interface, temperature monitoring interface and alarm interface according to their function. By operating on the touch screen, we can monitor and control the heating process expediently.

E. CONTINUOUS FLOW HEATING OF PHOSPHORIC ACID

Phosphoric acid (content: 85%, analytical purity, Tianjing Hengxing Chemical Reagent co., Ltd, Tianjing, China) is used as the testing material to evaluate the performance of the entire system. The reason why phosphoric acid is chosen as the test material is that microwave heating has been widely used in the concentration of phosphoric acid [31], [32]. Meanwhile, the viscosity of 85% phosphoric

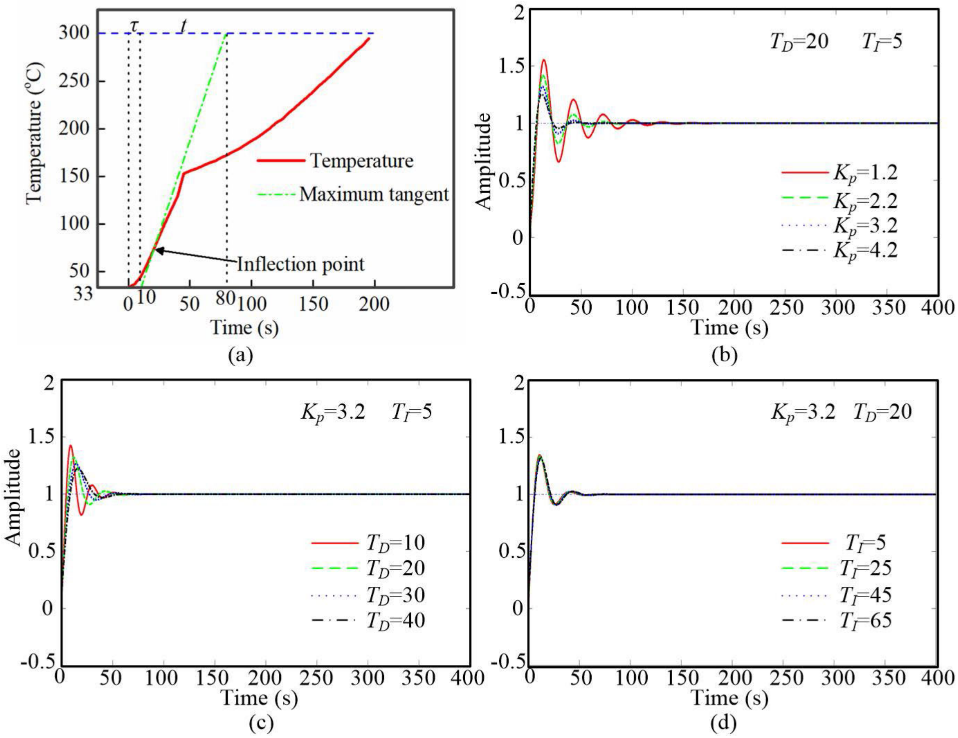


FIGURE 6. **(a) Temperature rise curve of phosphoric acid under microwave heating with 1200 W input power. (b)-(d) Response curves of the PID controller with different parameters: (a) various K_p and fixed T_D and T_I, (b) various T_D and fixed K_p and T_I, (c) various T_I and fixed K_p and T_D.**

acid is relatively moderate (2.2-28 in the temperature range of 20-140 $^\circ C$) [33], which is representative in general chemicals. In addition, 85% phosphoric acid will be gradually concentrated into the polyphosphate during heating, which makes the viscosity and dielectric properties constantly change during heating, thereby challenging the control stability of the system. Due to this reason, it is much more difficult to realize the temperature control of heating of phosphoric acid than that of the heating of other single materials such as water and oil. Hence, continuous flow heating of 85% phosphoric acid is a good example for the demonstration of the system control stability. For other heating materials, the temperature control process can be also achieved in the same procedure. Before the experiments, enough phosphoric acid is prepared in a container and the quartz tube is filled with phosphoric acid by peristaltic pump. After the control module and the data acquisition unit have been tested, the microwave source will be turned on (working at the maximum output power of 1200 W, while the absorbed power is 390-440 W, i.e. the energy efficiency range is about 32.5%-36.7%) to heat the phosphoric acid to the specified temperature. When the temperature of phosphoric acid exceeds the set temperature for the first time, the PLC will automatically turn on the peristaltic pump and adjust the microwave power according to the set temperature. During the experiments, the real-time temperature can be read on the touch screen as well as saved in PLC. By analyzing the saved temperature curves, the control performance of the system can be shown.

III. RESULTS AND DISCUSSION

A. PID PARAMETER TUNING

In order to determine the PID parameters, Ziegler–Nichols tuning method based on MATLAB is applied in this work. In this method, the approximate transfer function of the system can be obtained by analyzing the characteristic curve (i.e. temperature rise curve of the sample) [26]. The temperature rise curve of phosphoric acid under microwave heating with 1200 W input power is shown in Fig. 6 (a). From the figure, we can see that the temperature of the phosphoric acid can be higher than 150 $^\circ C$, which is the boiling point of 85% phosphoric acid. This is because 85% phosphoric acid will be gradually concentrated into the polyphosphate during heating and the boiling point of polyphosphate is as high as 856 $^\circ C$. Meanwhile, when the temperature exceeds 150 $^\circ C$, the temperature rise slows down, which is due to the generation of water vapor caused by the boiling of the phosphoric acid. In this system, in order to ensure the safety of the experiment, the temperature of the sample must not be higher than 300 $^\circ C$. Therefore, the maximum gain of the temperature is 267 or (300-33) $^\circ C$, and the system gain K, which is the maximum tangent slope of the temperature rise curve, can be calculated as 3.81 or (267/70). From Fig. 6 (a), we can also obtain the dead time τ and time constant t as 10 and 70 or (80-10). According to Equation (4), the system response can be expressed as:

$$G(s) = 3.81 \cdot e^{-10s} \Big/ (70s+1) \tag{5}$$

Then, according to the Ziegler–Nichols method, theoretical parameters of the PID controller can be calculated as [34]:

$$K_p = 1.2 \cdot t/(K\tau) = 2.2 \tag{6}$$

$$T_I = 2\tau = 20 \tag{7}$$

$$T_D = \tau/2 = 5 \tag{8}$$

However, these parameters may not be suitable for all the processes [35]. Therefore, in order to test whether these parameters meet the control requirements, MATLAB programs are used to simulate the PID controller with different parameters. The response curves are shown in Fig. 6 (b)-(d). As can be seen in Fig. 6 (b), when K_p is higher than 3.2, the response curve tends to be stable and no longer changes significantly with the increase of K_p. Hence, K_p is set as 3.2 for the PID controller. Similarly, T_D is set as 30 based on the Fig. 6 (c). As for T_I, it's change has little effect on the response curve, as shown in the Fig. 6 (c), thus it is set to the theoretical value of 5.

B. HEATING OF CONTINUOUS FLOW PHOSPHORIC ACID

By using the control system based on PLC, the continuous flow Phosphoric acid's temperatures are successfully controlled. Experiments with different set temperatures and inlet flow rates are conducted to observe the performance of the control system. Due to same control principle, for other heating materials, the temperature control process can be achieved in the same procedure.

1) PHOSPHORIC ACID HEATING AT DIFFERENT SET TEMPERATURES

Fig. 7 shows the temperature rise curve of phosphoric acid with set temperatures of 200 °C, 225 °C, and 250 °C. As can be seen in the Figure, after the temperatures reaches the set values, the fluctuation of all curves is within ±5% of the set temperature. The fluctuation is caused by the time delay between the temperature collecting and the control of the microwave power. Moreover, the change of the position of the optical fiber sensor in the heating process will also bring fluctuations to the temperature curves. However, the change of the position of the optical fiber sensor can enable the system to detect the temperature changes of more positions, which is better for the overall temperature control performance compared with the case with the thermometer at a certain position. In addition, we can find that the fluctuation of the curves increases with the rise of the set temperature. This is because the higher the set temperature, the higher the microwave power required, thus the greater the power range (absorbed power ranges and energy efficiency ranges for set temperatures of 200 °C, 225 °C, and 250 °C are 168-242 W and 29.6%-32.9%, 190-275 W and 29.9%-33.1%, and 220-310 W and 27.5%-33.2%, respectively) due to the temperature fluctuation, and the longer the response time of the temperature to power change. Overall, the system can effectively control the temperature of continuous flow phosphoric acid within %5 of the set value, which satisfies the requirements of phosphoric acid concentration process.

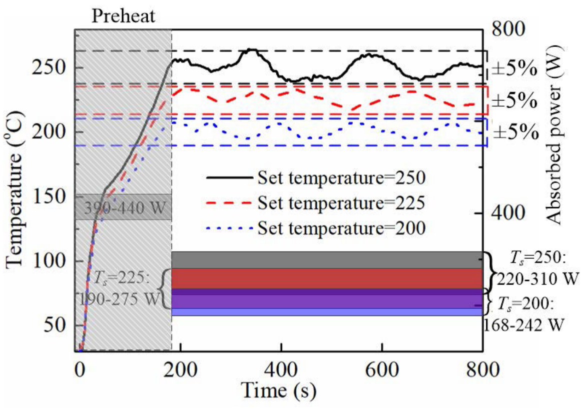


FIGURE 7. Temperature rise curve of phosphoric acid with different set temperatures (inlet flow rate is 16.2 g/min, T_S is the set temperature).

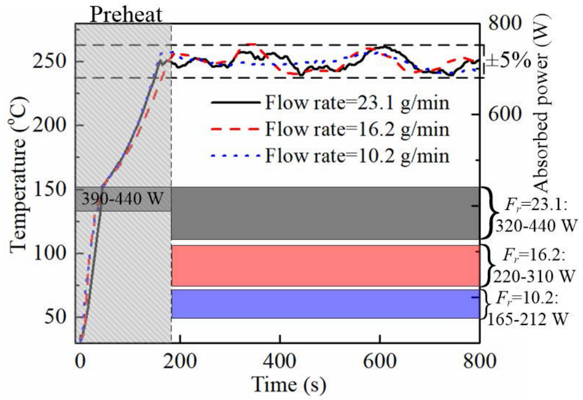


FIGURE 8. Temperature rise curve of phosphoric acid with different inlet flow rates (set temperature is 250 °C, F_r is the inlet flow rate).

2) TEMPERATURE CONTROL AT DIFFERENT INLET FLOW RATES

Fig. 8 shows the temperature rise curve of phosphoric acid with different inlet flow rates of 10.2 g/min, 16.2 g/min, and 23.1 g/min. As can be seen in the Figure, the fluctuation of the temperature curves is also within ± 5% of the set temperature for all the cases with different inlet flow rates. In addition, it can be seen from Fig. 8 that the fluctuation of the curves basically raises with the increase of the set inlet flow rate. The reason is similar with the cases with different set temperatures, which is the increase of the response time of the temperature to power change caused by the increase of the power range (absorbed power ranges and energy efficiency ranges for inlet flow rates of 10.2 g/min, 16.2 g/min, and 23.1 g/min are 165-212 W and 31.6%-33.5%, 220-310 W and 27.5%-33.2%, and 320-440 W and 30.2%-35.2%, respectively). Nevertheless, the experimental results show that temperature control stability of the system is fair under different inlet flow rates.

IV. CONCLUSION

A new microwave continuous flow heating system with real-time temperature monitoring and controlling capability is developed. Through proper hardware and software design, the system is assembled into a user-friendly device, where the users can operate and monitor the heating process conveniently though a touch screen. Moreover, experimental results show that the temperature fluctuation is within ±5% of the set temperature with different set temperatures and inlet flow rates, which validate the control stability of the system under different conditions. This system can be applied to the concentration of phosphoric acid and other chemical reactions that need to be conducted in a set temperature. The implementation of the interaction of real-time temperature signal and magnetron control signal, the integration of control algorithm and microwave circuit, and the realization of overall control program and equipment in this work will be helpful for the design of control systems for continuous-flow microwave heating in industry.

REFERENCES

[1] A. David, "Microwave chemistry: Out of the kitchen," *Nature*, vol. 421, no. 6923, pp. 571–572, 2003.

[2] S. Singh, D. Gupta, V. Jain, and A. K. Sharma, "Microwave processing of materials and applications in manufacturing industries: A review," *Mater. Manuf. Processes*, vol. 30, no. 1, pp. 1–29, 2015.

[3] M. Karlsson, H. Carlsson, M. Idebro, and C. Eek, "Microwave heating as a method to improve sanitation of sewage sludge in wastewater plants," *IEEE Access*, vol. 7, pp. 142308–142316, 2019.

[4] T. N. Glasnov and C. O. Kappe, "Microwave-assisted synthesis under continuous-flow conditions," *Macromol. Rapid Commun.*, vol. 28, no. 4, pp. 395–410, Feb. 2007.

[5] M. Damm, T. N. Glasnov, and C. O. Kappe, "Translating high-temperature microwave chemistry to scalable continuous flow processes," *Organic Process Res. Develop.*, vol. 14, no. 1, pp. 215–224, 2009.

[6] F. Motasemi and F. N. Ani, "A review on microwave-assisted production of biodiesel," *Renew. Sustain. Energy Rev.*, vol. 16, no. 7, pp. 4719–4733, Sep. 2012.

[7] C. Cong, S. Nakayama, S. Maenosono, and M. Harada, "Microwave-assisted polyol synthesis of Pt/Pd and Pt/Rh bimetallic nanoparticles in polymer solutions prepared by batch and continuous-flow processing," *Ind. Eng. Chem. Res.*, vol. 57, no. 1, pp. 179–190, Dec. 2017.

[8] L. Estel, M. Poux, N. Benamara, and I. Polaert, "Continuous flow-microwave reactor: Where are we?" *Chem. Eng. Process., Process Intensification*, vol. 113, pp. 56–64, Mar. 2017.

[9] J. P. Barham, E. Koyama, Y. Norikane, N. Ohneda, and T. Yoshimura, "Microwave flow: A perspective on reactor and microwave configurations and the emergence of tunable single-mode heating toward large-scale applications," *Chem. Rec.*, vol. 19, no. 1, pp. 188–203, 2019.

[10] J. Ye, H. Zhu, Y. Yang, K. Huang, and G. S. Vijaya Raghavan, "Dynamic analysis of a continuous-flow microwave-assisted screw propeller system for biodiesel production," *Chem. Eng. Sci.*, vol. 202, pp. 146–156, Jul. 2019.

[11] G. Roussy, A. Bennani, and J. Thiebaut, "Temperature runaway of microwave irradiated materials," *J. Appl. Phys.*, vol. 62, no. 4, pp. 1167–1170, Aug. 1987.

[12] S. Horikoshi, A. Osawa, M. Abe, and N. Serpone, "On the generation of hot-spots by microwave electric and magnetic fields and their impact on a microwave-assisted heterogeneous reaction in the presence of metallic pd nanoparticles on an activated carbon support," *J. Phys. Chem. C*, vol. 115, no. 46, pp. 23030–23035, Nov. 2011.

[13] R. W. Paglione, "Temperature controller for a microwave heating system," U.S. Patent 4 228 809, Oct. 21, 1980.

[14] G. O. Beale and M. Li, "Robust temperature control for microwave heating of ceramics," *IEEE Trans. Ind. Electron.*, vol. 44, no. 1, pp. 124–131, 1997.

[15] I. Sanchez, J. R. Banga, and A. A. Alonso, "Temperature control in microwave combination ovens," *J. Food Eng.*, vol. 46, no. 1, pp. 21–29, Oct. 2000.

[16] R. Ramon, F. Valero, and M. del Valle, "Rapid determination of chemical oxygen demand using a focused microwave heating system featuring temperature control," *Analytica Chim. Acta*, vol. 491, no. 1, pp. 99–109, Sep. 2003.

[17] Z. Li, G. S. V. Raghavan, N. Wang, and Y. Gariepy, "Real-time, volatile-detection-assisted control for microwave drying," *Comput. Electron. Agricult.*, vol. 69, no. 2, pp. 177–184, Dec. 2009.

[18] Z. Li, G. S. V. Raghavan, and V. Orsat, "Temperature and power control in microwave drying," *J. Food Eng.*, vol. 97, no. 4, pp. 478–483, Apr. 2010.

[19] Y. Zhou, C. Zhang, T. Xie, T. Hong, H. Zhu, Y. Yang, C. Liu, and K. Huang, "A microwave thermostatic reactor for processing liquid materials based on a heat-exchanger," *Materials*, vol. 10, no. 10, p. 1160, Oct. 2017.

[20] Z. Du, Z. Wu, W. Gan, G. Liu, X. Zhang, J. Liu, and B. Zeng, "Multi-physics modeling and process simulation for a frequency-shifted solid-state source microwave oven," *IEEE Access*, vol. 7, pp. 184726–184733, 2019.

[21] T. Sameshima, T. Miyazaki, G. Kobayashi, T. Arima, T. Kikuchi, T. Uehara, T. Sugawara, M. Hasumi, and I. Serizawa, "Carbon heating tube used for rapid heating system," *IEEE Access*, vol. 7, pp. 23798–23805, 2019.

[22] G. Akerlof, "Dielectric constants of some organic solvent-water mixtures at various temperatures," *J. Amer. Chem. Soc.*, vol. 54, no. 11, pp. 4125–4139, Nov. 1932.

[23] J.-H. Ye, H.-C. Zhu, Y.-H. Liao, Y.-P. Zhou, and K.-M. Huang, "Implicit function and level set methods for computation of moving elements during microwave heating," *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 12, pp. 4773–4784, Dec. 2017.

[24] C. Zhang, J. Lan, T. Hong, T. Gulati, H. Zhu, Y. Yang, and K. Huang, "Dynamic analysis and simulation on continuous flow processing of biodiesel production in single-mode microwave cavity," *Int. J. Appl. Electromagn. Mech.*, vol. 51, no. 2, pp. 199–213, Jun. 2016.

[25] K. Heong Ang, G. Chong, and Y. Li, "PID control system analysis, design, and technology," *IEEE Trans. Control Syst. Technol.*, vol. 13, no. 4, pp. 559–576, Jul. 2005.

[26] K. J. Åström and T. Hägglund, *PID Controllers: Theory, Design, and Tuning*, vol. 2. Research Triangle Park, NC, USA: Instrument society of America, 1995.

[27] F. Padula and A. Visioli, "On the fragility of fractional-order PID controllers for FOPDT processes," *ISA Trans.*, vol. 60, pp. 228–243, Jan. 2016.

[28] S. S. Deshpande and C. B. Kadu, "Design of multi scale PID controller for temperature process," in *Proc. Int. Conf. Autom. Control Dyn. Optim. Techn. (ICACDOT)*, Sep. 2016, pp. 582–585.

[29] M. J. Neath, A. K. Swain, U. K. Madawala, and D. J. Thrimawithana, "An optimal PID controller for a bidirectional inductive power transfer system using multiobjective genetic algorithm," *IEEE Trans. Power Electron.*, vol. 29, no. 3, pp. 1523–1531, 2013.

[30] D. Valério and J. S. da Costa, "Tuning of fractional PID controllers with Ziegler–Nichols-type rules," *Signal Process.*, vol. 86, no. 10, pp. 2771–2784, Oct. 2006.

[31] H. Deng, G. Zhang, X. Xu, G. Tao, and J. Dai, "Optimization of preparation of activated carbon from cotton stalk by microwave assisted phosphoric acid-chemical activation," *J. Hazardous Mater.*, vol. 182, nos. 1–3, pp. 217–224, Oct. 2010.

[32] N. A. Pinchukova, V. A. Chebanov, N. Y. Gorobets, L. V. Gudzenko, K. S. Ostras, O. V. Shishkin, L. A. Hulshof, and A. Y. Voloshko, "Beneficial energy-efficiencies in the microwave-assisted vacuum preparation of polyphosphoric acid," *Chem. Eng. Process., Process Intensification*, vol. 50, nos. 11–12, pp. 1193–1197, Nov. 2011.

[33] G.-Q. Liu, L.-X. Ma, and J. Liu, *Handbook of Substances Properties Data in Chemical and Engineering (Inorganic Vol)*. Beijing, China: Chemical Industry Press, 2002.

[34] J. G. Ziegler and N. B. Nichols, "Optimum settings for automatic controllers," *J. Dyn. Syst., Meas., Control*, vol. 115, no. 2B, pp. 220–222, 1942.

[35] K. J. Åström and T. Hägglund, "Revisiting the Ziegler–Nichols step response method for PID control," *J. Process Control*, vol. 14, no. 6, pp. 635–650, Sep. 2004.

JINGHUA YE was born in Zhanjiang, China, in 1991. He received the B.Sc. degree in electric engineering and information from Sichuan University, Chengdu, China, in 2014, and the Ph.D. degree in radio physics, in 2019. He is currently a Special Deputy Researcher with Chengdu University. His current research interests include the design of microwave equipments, computational electromagnetics, and multiphysical calculation.

CHUN ZHANG was born in Sichuan, China, in 1990. He received the B.Sc. degree in electric engineering and information from Jilin University, Changchun, China, in 2014. He is currently pursuing the Ph.D. degree. His current research interests include the design of microwave equipments and multiphysical calculation.

HUACHENG ZHU (Member, IEEE) was born in Xuzhou, China, in 1986. He received the B.Sc. degree in electric engineering and information, and the Ph.D. degree in radio physics from Sichuan University, Chengdu, China, in 2009 and 2014, respectively. From 2012 to 2013, he was a Visiting Fellow with the Department of Biological and Environmental Engineering, Cornell University, Ithaca, NY, USA, which was supported by the China Scholarship Council. Since 2015, he has been a Faculty Member with Sichuan University. His current research interests include the microwave heating of food, biological tissues, and chemical reactions.

• • •