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Developing a special microwave oven: Assessment of its performance for dough fermentation and nutrient soup elaboration

Chunhua He [a], Jianwen Zhang [a], Guangxiong Zhong [b], Qinghai Li [b], Heng Wu [c,*], Lianglun Cheng [a], Juze Lin [d,**]

[a] *School of Computer, Guangdong University of Technology, Guangzhou, 510006, Guangdong, PR China*
[b] *Midea Group, Foshan, 528311, Guangdong, PR China*
[c] *School of Automation, Guangdong University of Technology, Guangzhou, 510006, Guangdong, PR China*
[d] *Guangdong Provincial People's Hospital, Guangzhou, 510000, Guangdong, PR China*

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ABSTRACT

Bread and soup are two of the most important foods in daily life, thus dough fermentation and nutrient soup elaboration are more and more popular, but there is a lack of relevant low-cost and high-reliable household appliances on the market. Therefore, this paper proposes automatic control methods for dough fermentation and nutrient soup elaboration based on a special microwave oven. Fermentation theory, run-up microwave fermentation principle, microwave extraction principle, NTC temperature probe design and scalable fuzzy control algorithm are described in detail. Besides, the experimental platform is set up with a temperature chamber, an optical fiber thermometer and a power meter. Experimental results demonstrate that the relationship between the heating time and flour's mass is linear. For different ambient temperature tests, the volume ratios of the fermented dough to unfermented dough of different cases range from 2.2 to 2.62, and the inside of the dough after fermentation is fluffy, with small and dense cavities. Meanwhile, there is no acid taste and skin dryness, and the power consumption of microwave fermentation is less than half of that induced by grill, convection or steam fermentation. The detection error of the NTC temperature probe with microwave shielded is 0.48 °C, and the control error of the closed loop system is less than 0.5 °C. The temperature-rise slope of water is lower than that of ingredient, and the water's temperature is about 1 °C less than that of the ingredient. The soup after microwave elaboration is amber and clear, the ingredients are intact, the water loss is less than 50 g, and the total power consumption is 684 Wh. In short, microwave-based control methods for dough fermentation and nutrient soup elaboration are effective.

1. Introduction

Bread is one of the most important foods in daily life, and the sales volume of that is huge today, making dough fermentation more and more important [1,2]. Fermentation can yield products with high durability without the use of chemical preservatives. The content

* Corresponding author.
** Corresponding author.
E-mail addresses: heng.wu@foxmail.com (H. Wu), linjuze@126.com (J. Lin).

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and bioavailability of the nutrients is possible to increase due to the preliminary digestion by bacterial enzymes in fermented products [3]. Meanwhile, the fermentation process may contribute to a reduction of the content of compounds with antinutritive or toxic effects [4]. The proofing (namely fermentation) process of dough is one of the quality determining steps in the bread production [5]. The fluffiness and the flavour of the final product are influenced very much during the proofing stage [6]. One of the prime aspects is to control the proofing process in order to achieve a predictable final volume of dough pieces at the end of this step. Therefore, the automatic control of dough fermentation is more and more important, especially for home applications.

Moderate electric field (MEF) and Ohmic heating can improve the bioprocess, and positively affect the saccharomyces fermentations that are involved in the production of bakery and alcoholic products [7,8]. However, compared with the traditional fermentation methods, microwave heating can promote glucose fermentation with an increase in fermentation rates of above 20% [9]. Microwave heating can improve the indexes of fermentation and increase the content of soluble dietary fiber components, which contributes to the production and quality control of the fermentation products [10,11]. In spite of a series of merits, dough fermentation based on microwave oven is still a big challenge due to the particularity of microwave heating. The effect of microwave heating for a long time is not good because 1) the uniformity of microwave heating is worse [12]; 2) the dough becomes drier [13]; 3) yeast may be killed by high-power heating [14].

Therefore, in order to ensure the fermentation effect, it is necessary to control the microwave heating power and dough's temperature. For the real-time temperature detection and control, a fiber optic sensor (FOS) based on fluorescence intensity ratio or lifetime measurement can be used in the microwave heating system since it can work reliably and is not interfered by microwave [15,16]. However, this temperature probe based on FOS should be inserted manually into the dough, which is not convenient. Moreover, the sensor is very expensive. In our previous work, an Infrared (IR) array sensor is used for the non-contact temperature detection [17]. However, it just monitors the food's surface temperature, rather than the inner temperature [18]. Similarly, the IR array sensor is also high-cost. Owing to these disadvantages, volume detection, instead of temperature detection, can be adopted for dough fermentation control. The increase in volume is the most apparent physical change related to the process of dough fermentation [19,20]. According to this principle, a digital camera can be applied to monitor the relative volume of the dough for achieving a feedback control [21,22]. This method is feasible for traditional ovens, but it is not suitable for microwave ovens since the camera sensor is apt to be interfered by microwave. Moreover, the closed loop control system is still complex and high-cost. Therefore, the improved control method for dough fermentation is significant.

On the other hand, soup is very popular due to high nutrition, especially in China. Nowadays, people often add expensive Chinese medicinal materials to stew, such as ginseng, ganoderma lucidum, Tianqi and Xuelian, to nourish or regulate their bodies. Thus, it is so important to extract the nutrients from the ingredients. There are many extraction methods, such as microwave-assisted, ultrasound-assisted, ultrasound-microwave-assisted, enzyme-assisted, pressurized-liquid, supercritical-fluid, and synergistic extraction techniques, which are proved to be effective for nutrient extraction [23–25]. The yield, quality and efficiency of microwave-assisted extraction method are much better than those of other extraction methods [26,27], especially compared with those of traditional extraction methods [28,29]. Thus, microwave extraction method is of great significance, and the closed loop control of it is very important.

For closed loop system, temperature detection and control are essential. So far, non-contact sensors and contact sensors have been adopted for the temperature detection in the microwave oven. Non-contact sensors, such as IR array sensors or IR cameras, can be utilized to detect the food's temperature [30–32]. However, if the objective temperature is higher than 70 °C, the measured error will be larger and larger since the IR radiation is affected by the high-temperature steam. Besides, their costs are very expensive. Contact sensors mainly include FOS and Negative Temperature Coefficient (NTC) temperature sensor with microwave shielded. Similarly, FOS is not suitable for product application due to the high cost [33,34]. Instead, it is often used for comparison, that is, used as the golden reference. Owing to the low cost and high detection accuracy, a NTC temperature sensor with microwave shielded can be adopted. However, microwave shielded process is very complex and few researches have been reported about it.

Nowadays, microwave fermentation and nutrient soup elaboration are mainly based on industrial microwave ovens, which are very

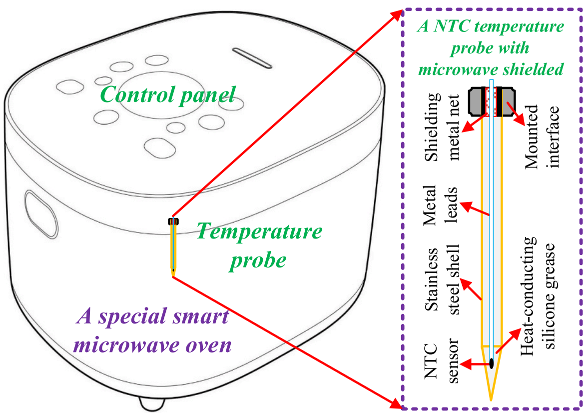

Fig. 1. Structure diagrams of a special microwave oven and a NTC temperature probe with microwave shielded.

expensive and bulky, so they are not suitable for household application. To realize household dough fermentation and nutrient soup elaboration, a novel special microwave oven and the corresponding automatic control methods should be proposed.

2. Materials and methods

2.1. System design

The structure diagram of a special microwave oven is illustrated in Fig. 1. Its shape and volume are similar to those of an electric cooker. Apart from rice cooking, reheating and defrosting, it is mainly used for dough fermentation and nutrient soup elaboration, and the functions can be selected on the control panel easily. For realizing the automatic control, a NTC temperature probe with microwave shielded is adopted, as shown in Fig. 1. This temperature probe is made of the shielding metal net, metal leads, stainless steel shell, NTC sensor, mounted interface and heat-conducting silicone grease. The mounted interface is used to install the probe on the top cover. The shielding metal net and stainless steel shell are applied for microwave shielded, and stainless steel is a food safety material that can be used to touch the food.

A NTC temperature sensor is adopted to detect the temperature. Its detection range is −40∼125 °C, while the detection accuracy is ±1 °C. Here, TTC3A103J (made by Thinking Electronic Industrial Co., Ltd.) is chosen as the NTC temperature sensor. In order to ensure the heat transfer effect, heat-conducting silicone grease is used to fill the gap between the stainless steel shell and the NTC sensor. Considering that the NTC sensor is a resistor, so it is connected to the detection circuit by the metal leads, as depicted in Fig. 2. Here, voltage-dividing circuit is used to measure the resistance R_1 of NTC temperature sensor, and R_2 is the voltage-dividing resistor. The output voltage V_{NTC} of R_2 is acquired by the Analog Digital Converter (ADC) of the Microprogrammed Control Unit (MCU). In this work, ABOV AC33M8128 ARM is used as the edge-computing MCU to achieve the algorithms of automatic control.

The side view of the special smart microwave oven is shown in Fig. 2. The mode stirrer is used to improve the heating uniformity. Besides, the filter, inverter and magnetron are placed in the electric room at the bottom. Due to the inverter, the closed loop control can be easily achieved because the heating power can be continuously adjusted. In addition, the detection and control circuit is fixed at the electric room in the top cover. The material of the outer shell is plastic, while the material of the inner cavity is stainless steel in order to prevent microwave leakage. A cylindrical flat-bottom ceramic container is applied for dough fermentation and nutrient soup elaboration. Regular shape is helpful for evaluating the food's volume. A physical picture of the microwave oven and ceramic container are depicted in Fig. 3 (a) and (b), respectively.

2.2. Microwave fermentation method

2.2.1. Fermentation theory

The factors affecting dough fermentation mainly include: 1) Physical parameters: such as temperature, stirring rate, air pressure, air flow, apparent viscosity, carbon dioxide, foam; 2) Chemical parameters: such as substrate concentration (including sugar, nitrogen, phosphorus), dissolved oxygen, product concentration, pH, nucleic acid amount; 3) Biological parameters: such as mycelium morphology, specific growth rate, bacterial concentration, respiratory intensity, key enzyme activity and substrate consumption rate. Among them, pH, dissolved oxygen, temperature, Carbon Dioxide (CO2) and foam are the most important factors. However, for home applications, pH, dissolved oxygen, CO2 and foam are so difficult to be controlled.

The best living temperature ranges for psychrophilic bacteria, mesophilic bacteria and thermophilic bacteria are 0∼26 °C, 15–43 °C, and 37–65 °C, respectively. At the early stage of fermentation, the amount of the bacteria is few. After heating, a slightly higher temperature activates a large number of bacteria, promoting the respiration and metabolism of the bacteria, and making them

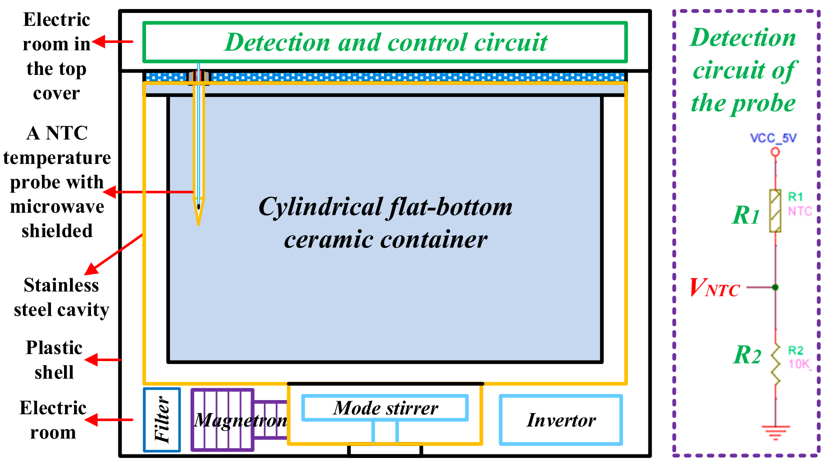

Fig. 2. Side view of the special smart microwave oven, and the detection circuit of the temperature probe.

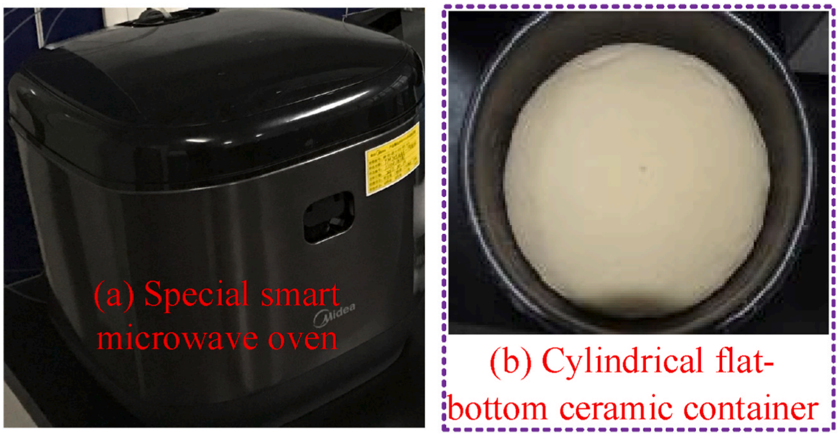

Fig. 3. (a) Physical picture of the special microwave oven; (b) A cylindrical flat-bottom ceramic container.

grow rapidly. At the medium stage of fermentation, the amount of bacteria has reached the optimum, and the temperature should be slightly lower at this time, which can delay the aging of the bacteria and increase the yield. At the late stage of fermentation, the product synthesis capacity is reduced. At this time, the fermentation process should be finished. Therefore, during the fermentation process, it is not necessary to keep constant temperature control all the time. The equation of the total fermentation energy $Q_{fermentation}$ is described as (1).

$$Q_{fermentation} = Q_{bio\log y} + Q_{stirring} + Q_{heating} - Q_{evaporation} - Q_{radiation} \tag{1}$$

where, $Q_{biology}$, $Q_{stirring}$, $Q_{heating}$, $Q_{evaporation}$, $Q_{radiation}$ stand for biology energy, stirring energy, heating energy, evaporation energy and radiation energy, respectively.

2.2.2. Fermentation materials and preparation

In terms of materials for dough fermentation, wheat flour, water, sugar and dry yeast are used, and the ratio of mass is 1 : 0.55: 0.1 : 0.01. For instance, the masses of wheat flour, water, sugar and dry yeast can be set to 1000 g, 550 g, 100 g and 10 g, respectively. Wheat flour was purchased from Jinyuan Grain and Oil Co., Ltd. (Zhengzhou, China). Dry yeast was purchased from Angel Yeast Co., Ltd. (Hubei, China). Based on the instructions of the dry yeast, the optimal fermentation time is 45min, and the optimal fermentation temperature is 30∼38 °C. If the inner temperature of the dough is too high (more than 50 °C), the yeast may be killed, affecting the fermentation effect; If the temperature is too low, the fermentation speed will be very slow. After fermentation, if the inside of the dough is fluffy, with small and dense cavities, and the volume after fermentation is 2∼3 times of that before, meanwhile, there is no acid taste and skin dryness, the effect of dough fermentation is very good. Therefore, this standard will be applied to evaluate the effect of dough fermentation with a microwave oven.

In China, fresh dough, rather than frozen dough, is more popular [35]. It means that before fermentation, fresh dough should be obtained. Here, wheat flour, water, sugar and dry yeast are fully mixed by a blender (CHIGO ZG-LZ908, China) to generate the fresh dough. After stirring, the initial temperature of the fresh dough is about 25 °C, and $Q_{stirring}$ is resulted from stirring.

2.2.3. Microwave fermentation principle

In terms of dough fermentation with a microwave oven, $Q_{heating}$ is derived from microwave heating. In order not to kill the yeast, the heating power should be moderate. Thus, in this work, it can be set to 60% of the maximum power.

During the fermentation process, the bacteria continuously use the nutrients in the culture medium to decompose and oxidize them to generate energy. Some of the energy is used to synthesize high-energy compounds to provide the energy for cell synthesis and metabolite synthesis, and the rest energy is emitted in the form of heat, which will lead to the rise of dough's temperature. At the initial stage of fermentation, the number of bacteria is few and the respiration is slow, so that $Q_{biology}$ is small. During the rapid growth stage, there are more and more bacteria, and the respiration is more intense, so more biological heat is generated and the temperature rises accordingly. At the late stage of fermentation, the bacteria basically stop reproducing, and $Q_{biology}$ decreases accordingly.

On the other hand, during ventilation and exhaust, water evaporation takes away some heat (i.e. $Q_{evaporation}$). In addition, the lower the ambient temperature is, the more energy (i.e. $Q_{radiation}$) the dough radiates. For dough fermentation with a microwave oven, the fan can be closed to minimize $Q_{evaporation}$. However, it is difficult to control $Q_{radiation}$, since ambient temperature varies with seasons. Fortunately, compared with $Q_{biology}$ and $Q_{heating}$, $Q_{radiation}$ and $Q_{evaporation}$ are smaller. Thus the influence induced by $Q_{radiation}$ and $Q_{evaporation}$ can be compensated by $Q_{biology}$ and $Q_{heating}$. As mentioned above, constant temperature control is unnecessary, hence, a novel control method of run-up microwave fermentation can be proposed, which mainly includes two steps:

1) The amount of the bacteria is few at the early stage of fermentation. Therefore, microwave heating for a short time is applied to quickly raise the dough's temperature by 17 °C to about 42 °C. During the process of heating up, the respiration and metabolism of bacteria are promoted, so that they can rapidly reproduce.
2) The temperature should be a little lower after the bacteria amount increases. At this time, microwave should be turned off to prevent high-temperature sterilization, delay bacteria senescence and increase production. When the total fermentation time reaches 45min, the dough fermentation is completed.

After the heating is stopped, energy dissipation induced by the evaporation and radiation will gradually reduce the temperature. Fortunately, bio heat is also generated gradually, which slows down the temperature drop. During the process, dough's temperature is always in the best fermentation temperature range, so it does not affect the fermentation process. Since microwave only heats briefly at the initial stage, there is no need to continue heating in the later process, so it is called run-up microwave fermentation. This run-up heating energy is called Activation Energy (*AE*). Here, *AE* is the required heating energy making dough's temperature rise by 17 °C.

2.2.4. Relationship between the heating time and the flour's mass

Based on the heating principle of microwave, *AE* can be described as (2).

$$AE = Q = P\Delta t = 55.6 \times 10^{-12} E^2 f_m V \varepsilon_r^{''} \Delta t = Mc_p \Delta T \tag{2}$$

where, Q is the energy consumption, P is the effective heating power, E is the electromagnetic field intensity, f_m is the frequency of microwave, V is the volume of the cavity, M is the dough's mass, C_p is the specific heat capacity and ε_r'' is the dielectric dissipation factor. Δt is the heating time making dough's temperature rise by 17 °C. ΔT is the temperature rise which is equal to (42–25)°C. Thus, the slope k_r of the temperature-rise curve can be derived as (3).

$$k_r = \frac{\Delta T}{\Delta t} = \frac{55.6 \times 10^{-12} E^2 f_m V}{M} \times \frac{\varepsilon_r^{''}}{c_p} \tag{3}$$

C_p and ε_r'' are approximately constant when ambient temperature changes little, thus, k_r is almost a constant. Simultaneously, the heating time can be obtained as (4).

$$\Delta t = \frac{c_p \Delta T}{P} M \approx (1 + 0.55 + 0.1 + 0.01) \times \frac{c_p \Delta T}{P} m \tag{4}$$

where, m is the mass of wheat flour. For dough, C_p is 1.8 kJ/kg/°C. The output power of the microwave oven is divided into 10 levels, ranking from small to large as P0~P10, where P10, P6 and P0 stand for the maximum power, 60% of the maximum power and zero, respectively. P10 is 1380 W and the heating efficiency is about 70%. The heating power is set to P6, i.e. 828 W. Thus, P is equal to the heating power times heating efficiency, which is calculated as about 580 W. Equation (4) figures out that Δt is proportional to m. However, taking the effects of the container and starting time of the microwave oven into account, the relationship between Δt and m is a linear function whose intercept is not zero. Thus, the relationship can be defined as (5).

$$\Delta t = km + b \tag{5}$$

where, k is the slop, and b is the intercept. These two parameters can be confirmed by experimental tests.

2.3. Microwave extraction method

2.3.1. Microwave extraction principle

The mechanisms of microwave extraction mainly include: (1) Water and ingredients are both heated by microwave, causing the temperature in the cell of the ingredients to rise rapidly. The pressure generated by the vaporization makes the cell membrane and cell wall broken, forming small holes or cracks. The existence of holes or cracks makes it easy for water to enter the cells, dissolve and release the substances in the cells; (2) The electromagnetic field caused by microwave accelerates the diffusion of the extracted components into water and accelerates the thermal movement, thus improving the extraction efficiency and reducing the requirements for extraction temperature.

Similarly, the slope k_{rw} of the water and the slope k_{ri} of the ingredient can be derived as (6).

$$\begin{cases} k_{rw} = \dfrac{55.6 \times 10^{-12} E^2 f_m V}{M_w} \times \dfrac{\varepsilon_{rw}^{''}}{c_{pw}} \\ k_{ri} = \dfrac{55.6 \times 10^{-12} E^2 f_m V}{M_i} \times \dfrac{\varepsilon_{ri}^{''}}{c_{pi}} \end{cases} \tag{6}$$

where, M_w and M_i are the masses of the water and ingredient, respectively. C_{pw} and C_{pi} are the specific heat capacities of the water and ingredient, respectively. ε_{rw}'' and ε_{ri}'' are the dielectric dissipation factors of the water and ingredient, respectively. ε_{rw}'' at 25 °C is 12.3, while ε_{ri}'' at 25 °C is larger than 15. ε_{ri}'' is always bigger than ε_{rw}'', and as the temperature rises, their gap will become larger. Besides, C_{pw} is 4.2kJ/(kg*°C), while C_{pi} is less than 1.8kJ/(kg*°C). Hence, from (6), for the same mass of water and ingredient, the temperature-rise slope of water is lower than that of ingredient. That is, k_{rw} is less than k_{ri}, as shown in (7), which is conducive to the diffusion of nutrients in the ingredient into water.

$$\varepsilon''_{ri} > \varepsilon''_{rw}, c_{pi} < c_{pw} \Rightarrow k_{rw} < k_{ri} \tag{7}$$

in addition, the thermal conductivity of water is 0.6 W/(m*k), while that of ingredient is often less than 0.5 W/(m*k). Therefore, the heat transfer effect of water is better than that of ingredient, which is conducive to the nutrient extraction as well.

2.3.2. *Extraction materials and preparation*

Given that microwave heating is very effective in extracting the nutrients of ginseng [36], thus in this paper, ginseng stewed black chicken soup is taken as an example for microwave extraction test. The main ingredients include 400 g black chicken, 100 g pork, 20 g Korean ginseng, 10 g longan, 20 g Chinese yam, 15 g red dates, 8 g wolfberry, 10 g ginger, 10 g yellow rice wine, 2000g water and moderate salt. Its nutritional values include invigorating Qi, blood, spleen and lung, calming nerves, and improving intelligence. Therefore, it is one of the favourite foods in China.

Before simmering the soup, medicinal ingredients must be soaked first, and meat must be blanched to remove blood stains in the blood vessels inside the meat. In addition, due to the low requirements on temperature, the water's temperature should not reach the boiling point during the elaboration process, which can prevent broken ingredients, serious water loss, turbid soup and excessive oil precipitation. Thus, it can be controlled at 94 °C or lower, and the closed loop control is essential.

2.3.3. *Automatic control method of microwave extraction*

For achieving the closed loop control, temperature feedback is very important. According to the detection circuit depicted in Fig. 2, based on the output voltage V_{NTC} of R_2, R_1 can be deduced as (8).

$$R_1 = 5R_2/V_{NTC} - R_2 \tag{8}$$

where, the power supply VCC is 5 V. Based on the value of R_1, the temperature T_{NTC} can be obtained by the relationship between temperature and the logarithm of resistance. The relationship between them is illustrated in Fig. 4. It indicates that the fitting formula is a three-order polynomial, as shown in (9).

$$\begin{aligned} LNR &= \ln(R_1) \\ T_{NTC} &= -0.1086\, LN\, R^3 + 2.3287\, LN\, R^2 - 31.853 LNR + 87.226 \end{aligned} \tag{9}$$

Considering that the parameter adjustment of a PID controller is relatively complicated, in this work, a fuzzy controller is adopted. So far, a fuzzy controller is widely used for temperature control since it is very robust. The fuzzy rules are designed with human beings' experience and the control algorithm is easy to be realized. In order to simplify the control system, a one-dimensional (1D) fuzzy controller is adopted, as shown in (10).

$$\begin{aligned} P_n &= P_{n-1} + \Delta P_n = P_{n-1} + fuzzy(k_i E_T) \\ E_T &= T_g - T_{NTC} \end{aligned} \tag{10}$$

where, P_n is the output microwave power of the *nth* moment, *fuzzy* () is a fuzzy function, k_i is the gain of the control error E_T. E_T is equal to the target temperature T_g minus the current temperature T_{NTC}. ΔP_n is the increment that determined by the fuzzy rule table. E_T and ΔP_n consist of seven language values {*nb, nm, ns, ze, ps, pm, pb*}. *nb, nm, ns, ze, ps, pm, pb* represent negative big, negative medium, negative small, zero, positive small, positive medium and positive big, respectively. The rule table is set based on experience, as shown in Table 1. The 7 fuzzy rules indicate that: (a) ΔP_n varies with E_T linearly to reduce the control error. (b) The larger E_T is, the bigger ΔP_n is. If E_T is small, ΔP_n should be also small to eliminate the static error.

With the fuzzy rule table, Mamdani algorithm and centroid algorithm are applied to obtain ΔP_n. Finally, the control look-up table is obtained and realized in the MCU. Compared with the formula of a PID controller, this fuzzy controller is similar to an I-controller,

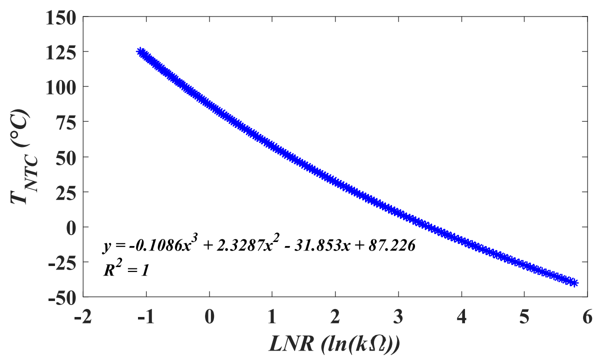

Fig. 4. The relationship between the ambient temperature T_{NTC} and the logarithm of resistance R_1.

Table 1
One-dimensional fuzzy rule table.

E_T	nb	nm	ns	ze	ps	pm	pb
ΔP_n	*nb*	*nm*	*ns*	*ze*	*ps*	*pm*	*pb*

which leads to low control speed due to the lack of a P-control component. Besides, finite fuzzy rules and quantized steps will result in a bad control precision. Hence, the traditional fuzzy algorithm should be improved. Here, a scale factor α is introduced to adjust the quantized step size and control increment, as shown in (11).

$$P_n = P_{n-1} + \Delta P_n = P_{n-1} + \alpha \cdot fuzzy(\alpha k_i E_T) \tag{11}$$

where, α is set to 2^k (k is a natural number). Thus, the quantized step size and control increment can be scaled down or up, so as to advance the control speed and precision. The scalable rules include: (a) If E_T is judged as "*ze*", α is reduced by half to guarantee the control precision. (b) If E is judged as "*pb*" or "*nb*", α is double to advance the control speed. (c) Otherwise, α is not changed. The initial value of α is set to 1 ($k = 0$). Thereby, the 1D scalable fuzzy controller can achieve an accurate and rapid control for any uncertain or nonlinear system with finite quantized steps and fuzzy rules.

2.4. Experimental platform

As mentioned above, the automatic control system for microwave extraction is a closed-loop system, while that for dough fermentation is an open-loop system. Due to constant temperature control for microwave extraction, the closed-loop control method is very robust and not disturbed by the varied ambient temperature. However, owing to non-constant temperature control for dough fermentation, the open-loop control method may be affected by the varied ambient temperature. In order to verify whether the open-loop control method is reliable, different ambient temperature tests should be conducted. Thus, the special microwave oven will be put into a temperature chamber for different experimental tests, as illustrated in Fig. 5. The temperature chamber is manufactured by Ceprei Co. Ltd., Guangzhou, China. The temperature of the chamber can be set from −40 °C to 125 °C, and the control precision is ±1 °C.

Besides, an optical fiber thermometer (GND-00865) is applied to detect the dough's temperature in real time, as shown in Fig. 5. It is made by Shanghai GND eTech Co., Ltd, China. Its measurement range is −50 °C–250 °C, and the detection accuracy is about ±0.5 °C. This optical fiber thermometer is not a component of the microwave oven, but only used for evaluation and comparison. Here, COB–C silica fiber is applied as the temperature probe. A power meter (AN8721PV3) is utilized to monitor the power consumption, as shown in Fig. 5. It is made by Qingdao Ainuo Intelligent Instrument Co., LTD., China. In addition, a Personal Computer (PC) is adopted to acquire the output signals or data from the optical fiber thermometer and power meter, and make the results visible. Therefore, a series of dough fermentation tests can be conducted based on the test platform.

On the other hand, the detection accuracy of the NTC temperature probe with microwave shielded, as well as the constant-temperature control precision of the closed loop system for microwave elaboration, should be tested. Similarly, the optical fiber thermometer and power meter are applied for measurement.

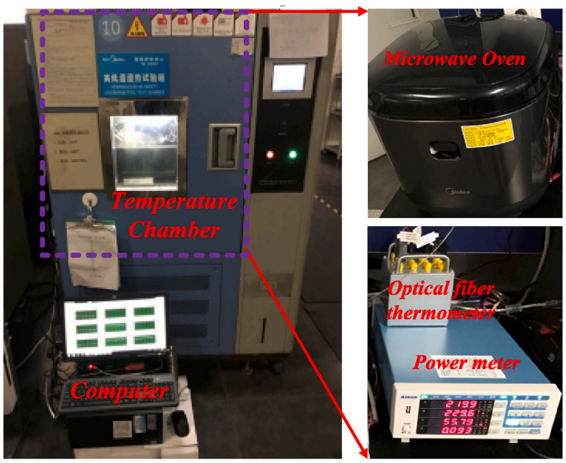

Fig. 5. Special microwave oven is put into a temperature chamber for different experimental tests.

3. Results and discussion

3.1. Test results of dough fermentation

3.1.1. Experimental tests at room temperature

Firstly, experimental tests are conducted at room temperature to obtain the relationship between the wheat flour's mass and heating time. In this work, the room temperature and the dough's initial temperature are both about 25 °C. At the beginning, the heating power of the microwave oven is set to P6, and then set as P0 once the dough's internal temperature rises by 17 °C. The total fermentation time is 45min (i.e. 2700s). The internal temperature of the dough in the microwave oven is monitored by the optical fiber thermometer in real time. Taking 1000 g wheat flour as an example, the curves of the heating power and dough's internal temperature are depicted in Fig. 6. It indicates that the dough's temperature rises linearly and fast when heating, but it falls non-linearly and slowly when heating is stopped. Owing to the function of biology energy, the final temperature is still larger than 30 °C, and during the process, the temperature is always within the optimal fermentation temperature range.

Besides, the part of rising curve of the dough's temperature is amplified, as shown in Fig. 7. It is clear that the starting time of the microwave oven is about 10s, and the heating time is about 79s when the temperature rises by 17 °C. Although the power is shut down at the moment of 79th second, the internal temperature still rises for a few seconds and then falls down. The overshoot, generally within 2∼4 °C, is measured to be 2.2 °C. The dough's volume is small before fermentation. However, after fermentation, it increases to 2.3 times of that before, as depicted in Fig. 8 (a) and (b). The fermentation effect is good since the dough is fluffy, without dry, sour and cooked. Hence, the control method of run-up microwave fermentation is effective.

For the dough fermentation of the wheat flours with the masses of 500 g, 600 g, 700 g, 800 g and 900 g, the corresponding heating times can be acquired with the similar experimental tests at room temperature. The relationship between the wheat flour's mass and the heating time is illustrated in Fig. 9. It demonstrates that Δt changes with m linearly, which accords with the theoretical analysis. After fitting analysis, k and b are measured as 0.0277 and 51.381, respectively. Although the fermentation effect is good at room temperature, the fermentation effects under other ambient temperatures still need to be further verified.

3.1.2. Experimental tests at other ambient temperatures

In general, the mass of wheat flour for domestic fermentation is larger than 500 g and less than 1000 g, hence, the wheat flours with the masses of 500 g, 750 g and 1000 g are selected for the fermentation tests under different ambient temperatures. Given that the ambient temperature at home is generally higher than 5 °C and lower than 35 °C, thus the ambient temperatures of 5 °C, 20 °C and 35 °C are selected for fermentation tests, which can be controlled by the temperature chamber. With Equation (5), the heating times of the wheat flours with the masses of 500 g, 750 g and 1000 g are calculated to be 65s, 72s and 79s, respectively. The dough fermentation is controlled by the run-up microwave fermentation method, and the test platform is illustrated in Fig. 5. Experimental results are illustrated in Fig. 10 and summarized in Table 2.

During different tests, the ambient temperature in the temperature chamber is set to 5 °C, 20 °C and 35 °C, respectively. The actual ambient temperature and dough's internal temperature are both detected by the optical fiber thermometer. The control errors of the chamber are all less than 1 °C, as shown in the last column in Table 2. In addition, the power meter is utilized to measure the power consumption. For dough fermentation of the flours with the masses of 500 g, 750 g and 1000 g, they are measured to be 14.9 kW h, 16.6 kW h and 18.2 kW h, respectively, as shown in the penultimate column in Table 2.

Owing to the function of stirring energy, the initial dough's temperatures in different cases are all around 25 °C, and the deviations are less than 1.5 °C. After shutting down the power, due to the function of biology energy, there are inevitably overshoots with about 2∼4 °C, but the dough's maximum temperatures are all less than 46 °C, which does not hurt the bacteria. Besides, the dough's final temperatures are all within 29∼38 °C, as shown in Table 2, and the dough's temperatures during the whole fermentation process are always suitable for the survival and reproduction of the bacteria. Finally, the volume ratios of the fermented dough to the unfermented dough of different cases range from 2.2 to 2.62, and the average is 2.45, as depicted in Fig. 11. In addition, the inside of the dough after

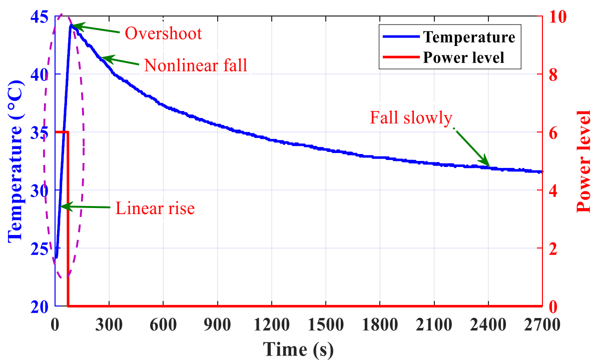

Fig. 6. Dough's internal temperature varies with the heating power during the whole fermentation process, and the mass of the wheat flour is 1000 g.

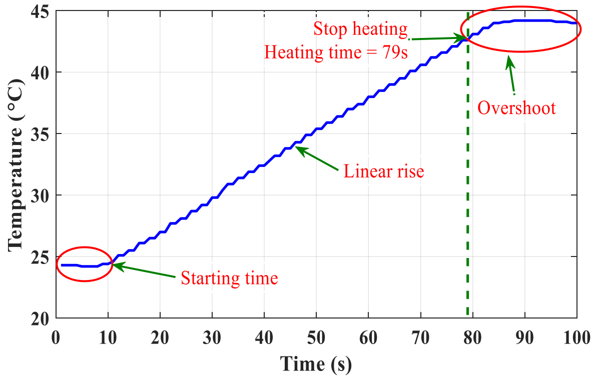

Fig. 7. The part of the rising curve of the dough's internal temperature is amplified for analysis.

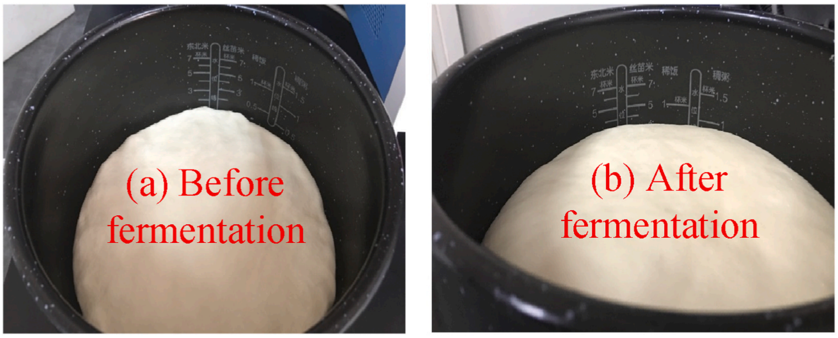

Fig. 8. (a) Dough's volume is small before fermentation; (b) Dough's volume is enlarged after fermentation.

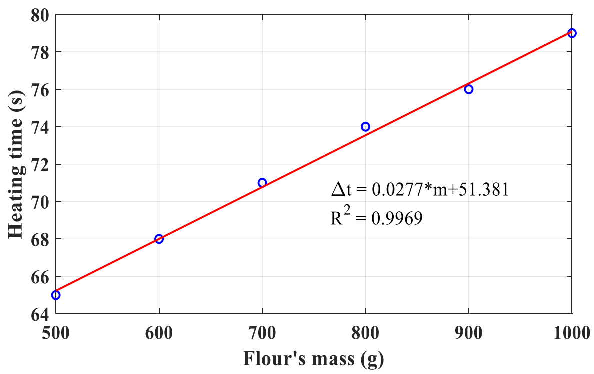

Fig. 9. Heating time changes with the wheat flour's mass linearly.

fermentation is fluffy, with small and dense cavities, as shown in Fig. 12 (a) and (b). Meanwhile, there is no acid taste and skin dryness, so the fermentation effect with the microwave oven matches the evaluation standard mentioned above.

3.1.3. *Comparison of the dough fermentation effects*

Owing that the control method of run-up microwave fermentation is adopted, the power consumption is saved. Here, a comparison is made for different fermentation modes. Since dough fermentation can be accomplished by the heating of microwave, grill, convection or steam, the power consumption can be measured. In this work, dough fermentation with grill, convection or steam is achieved by a multi-functional oven (Midea X7-321B).

Taking the dough fermentation of 1000 g flour as an example, the power consumption of different heating modes is listed in Table 3. It is clear that the power consumption of microwave fermentation is the least, less than half of the others. Hence, the proposed microwave fermentation method is not only energy-saving, but also zero-cost. Meanwhile, it is easy to be realized.

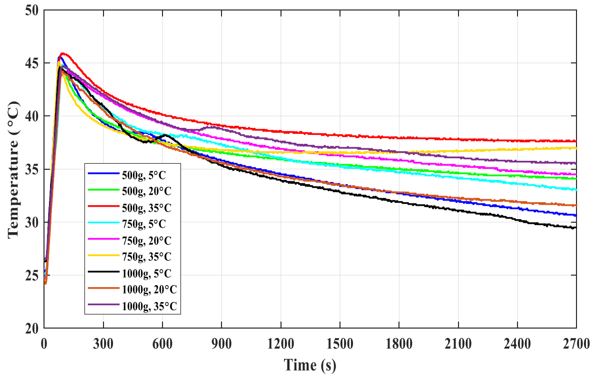

Fig. 10. Dough's temperature varies with time in different ambient temperature tests.

Table 2
Experimental results of dough fermentation under different ambient temperatures.

Setting ambient temperature (°C)	Flour's mass (g)	Dough's initial temperature (°C)	Dough's maximum temperature (°C)	Dough's final temperature (°C)	Heating time (s)	Power consumption (kW·h)	Actual ambient temperature (°C)
35	1000	26.5	44.7	35.5	79	18.2	35.3
	750	24.5	45.1	36.9	72	16.6	34.1
	500	24.3	45.9	37.6	65	14.9	34.7
20	1000	24.2	44.2	31.5	79	18.2	20.2
	750	25.8	44.2	34.5	72	16.6	20.8
	500	24.6	44.7	34.1	65	14.9	20.4
5	1000	26.3	44.6	29.5	79	18.2	4.3
	750	25.2	44.8	33	72	16.6	4.6
	500	25.4	45.6	30.6	65	14.9	4.7

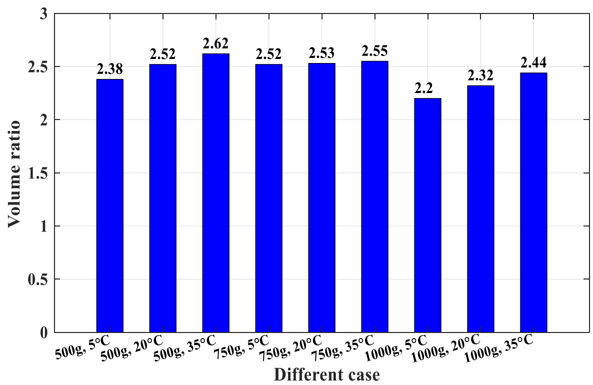

Fig. 11. Volume ratios of the fermented dough to the unfermented dough of different cases range from 2.2 to 2.62, and the average is 2.45.

3.2. Test results of microwave elaboration

3.2.1. Experimental tests of the automatic control system

For evaluating the detection accuracy of the NTC temperature probe with microwave shielded, the results measured by the optical fiber thermometer are used for comparison. Here, 10 measurements of the different temperatures are made and compared, as shown in Fig. 13. The results measured by the NTC temperature probe are close to those of the optical fiber thermometer, and the average of the differences is 0.48 °C and the standard deviation is 0.32 °C, which indicates that the detection accuracy of the NTC temperature probe is very high.

With the feedback of the NTC temperature probe with microwave shielded, constant-temperature control test based on the scalable fuzzy control algorithm can be performed. For evaluation, the control target is set to 80 °C, and the measured temperature curve is shown in Fig. 14. To facilitate observation, the smooth part of the curve in the green box is amplified, as depicted in Fig. 14. It figures out that the average is 79.99 °C and the standard deviation is 0.15 °C. The maximum control error is less than 0.5 °C, which indicates

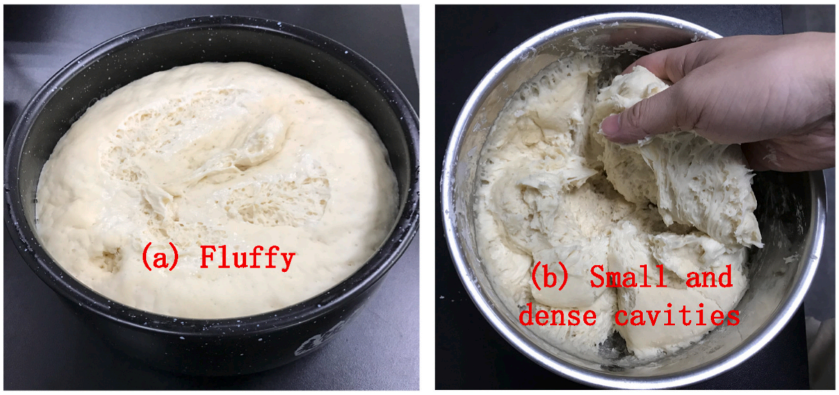

Fig. 12. (a) The inside of the dough after fermentation is fluffy; (b) There are many small and dense cavities, and there is no acid taste and skin dryness.

Table 3
Comparison of power consumption of different fermentation modes.

Fermentation mode	Power consumption (kW·h)	Appliance
Microwave	18.2	 Special microwave oven
Grill Convection Steam	38.9 67.8 40.9	 Midea X7-321B

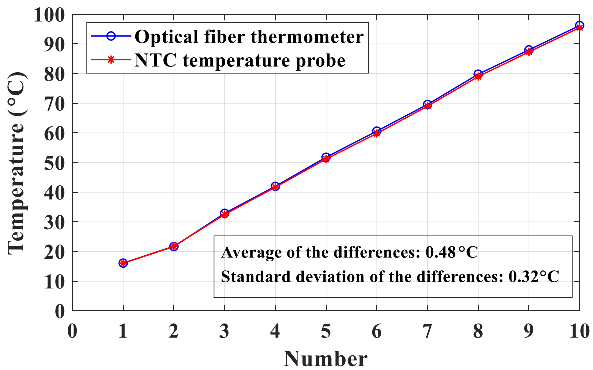

Fig. 13. Comparison of the temperatures measured by the optical fiber thermometer and NTC temperature probe with microwave shielded.

that the proposed scalable fuzzy control algorithm is effective.

3.2.2. Experimental tests of nutrient soup elaboration

With the special microwave oven, ginseng stewed black chicken soup is made, and the temperatures of the water and ingredient are measured by different channels of the optical fiber thermometer together. The results are illustrated in Fig. 15. Here, the heating

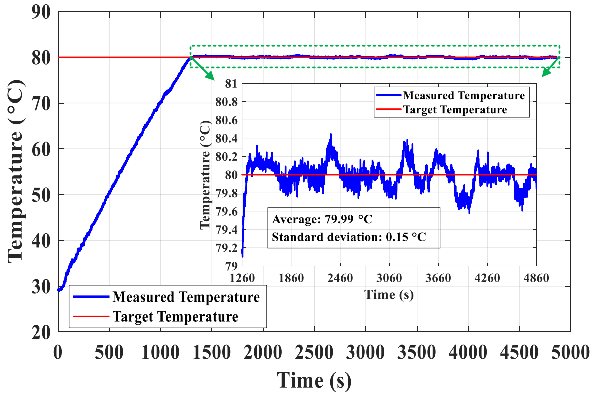

Fig. 14. Constant temperature control effect of the novel scalable fuzzy control algorithm.

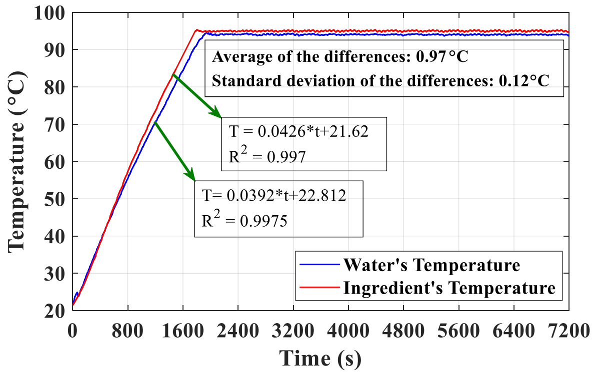

Fig. 15. The temperature-rise slope and stable-period temperature of the water are less than those of the ingredient, respectively.

temperature is set to 94 °C to prevent boiling. The heating time is set to 2 h. It figures out that the temperature-rise slopes of the water and ingredient are 0.0392 and 0.0426, respectively. Obviously, the temperature-rise slope of water is lower than that of ingredient, which accords with the theoretical analysis mentioned above.

At the stable period from 2001th second to 7200th second, the average temperatures of the water and ingredient are measured to be 94.05 °C and 95.03 °C, respectively. Besides, the average and standard deviation of the differences of the two signals are calculated as 0.97 °C and 0.12 °C, respectively. Therefore, the water's temperature is about 1 °C less than that of the ingredient, which is a significant phenomenon conductive to the diffusion of the nutrients.

Fig. 16. (a) The water is transparent and clear before elaboration; (b) It becomes amber and clear after elaboration, and the ingredients are intact.

On the other hand, the water is transparent and clear before elaboration, then it becomes amber and clear after elaboration, as illustrated in Fig. 16 (a) and (b). The amount of the precipitated oil is moderate and less than half a spoon. The ingredients are intact, and the soup is not turbid. Due to the water's temperature is smaller than the boiling point during the elaboration process, the water loss is little, less than 50 g. The total power consumption measured by the power meter is 684 Wh, less than 1 kWh. To sum up, the control method is energy-saving, and the soup is beautiful, delicious and nutritious, which verifies that microwave elaboration is effective and promising.

4. Conclusions

This paper proposes automatic control methods for dough fermentation and nutrient soup elaboration based on a special microwave oven. Fermentation theory, run-up microwave fermentation principle, microwave extraction principle, NTC temperature probe design and scalable fuzzy control algorithm are described in detail. Besides, the experimental platform is set up with a temperature chamber, an optical fiber thermometer and a power meter. Experimental results demonstrate that the relationship between the heating time and flour's mass is linear. For different ambient temperature tests, the volume ratios of the fermented dough to unfermented dough of different cases range from 2.2 to 2.62, and the inside of the dough after fermentation is fluffy, with small and dense cavities. Meanwhile, there is no acid taste and skin dryness, and the power consumption of microwave fermentation is less than half of that induced by grill, convection or steam fermentation. The detection error of the NTC temperature probe with microwave shielded is 0.48 °C, and the control error of the closed loop system is less than 0.5 °C. The temperature-rise slope of water is lower than that of ingredient, and the water's temperature is about 1 °C less than that of the ingredient, which accords with the theoretical analysis. The soup after microwave elaboration is amber and clear, the ingredients are intact, the water loss is less than 50 g, and the total power consumption is 684 Wh.

To sum up, this work has demonstrated the feasibility and effectiveness of microwave-based dough fermentation and nutrient soup elaboration in theory and control methods. In the future, some more food quality indicators will be detected to further testify whether the special microwave oven is prior to the traditional household appliances.

Author contribution statement

Chunhua He: Conceived and designed the experiments; Wrote the paper.
Jianwen Zhang, Guangxiong Zhong: Performed the experiments.
Qinghai Li: Conceived and designed the experiments.
Heng Wu, Lianglun Cheng: Analyzed and interpreted the data.
Juze Lin: Contributed reagents, materials, analysis tools or data.

Data availability statement

The authors do not have permission to share data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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