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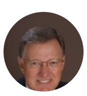

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A Microwave Oven with Variable Continuous Power and a Feedback Temperature Controller

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The power supply circuit of a domestic microwave oven was modified so that the field intensity in the cavity could be changed continuously. The oven was further fitted with a feedback temperature controller for controlling product temperatures during microwave heating by cycling the magnetron on and off. The temperature controller consists of a fiber optic temperature sensing system, a computer, an optocoupler, and a mechanical relay. White bread, moist sponges, and a 5-mL water load were used to test the performance of the oven. The temperature control capability was greatly influenced by the field intensity of the cavity and less influenced by the data acquisition rate. Experimental data indicated that it was possible to maintain the sample temperature within ±0.3 °C at 60 °C and within ±0.6 °C at 80 °C when a proper power level was used.

Introduction

The unique property of microwaves to penetrate and produce heat deep within food materials providing significant reductions in process time makes this form of heat transfer very attractive to consumers, researchers, and the food industry. In the food industry, processes that are generally considered suitable for microwave applications include dehydration, freeze-drying, blanching, baking, thawing, pasteurization, sterilization, and curing. A review of work both completed and in progress in these areas was given by Decareau (1985).

Unlike convection heating, where the solid temperature can never exceed that of the external air stream, there is no such limiting temperature in microwave heating except in the ideal situation where only the free water absorbs electric energy, in which case the maximum temperature is the boiling point of the liquid. In practice, when the moisture content is high, it often appears that there is sufficient moisture present to act as a sink for the energy absorbed by the solid. At lower moisture contents, the sink becomes increasingly ineffective and the temperature rises again, even though the loss factor (ϵ'') is smaller (2). The temperature changes of some materials during microwave heating have been given by Perkin (1979), Lyons et al. (1972), and Tong (1988).

The time-temperature history can be divided into three stages during microwave heating and drying. In the first stage, the sample is rapidly heated to the boiling point temperature. The rate of heating is dependent upon the loss factor, heat capacity, density, and size of the sample, and the electric field strength of the microwave field. At the second stage, the sample temperature is maintained at the boiling point. For most food materials during microwave heating, the temperature can be much higher than the boiling point when they become dry.

Recently, there has been increasing interest in performing controlled-temperature microwave heating and drying. The economic benefits of combined microwave-convective drying have been recognized for many years (Bhartia et al., 1973; White, 1978; Jolly, 1986); however, it is not always desirable to dry food materials at the boiling point temperature as product quality may be reduced due to excessive temperatures. Significant crack formation in the sample is also possible due to the high internal pressure associated with high product temperature. Jolly (1986) used an apparatus that consisted of a fiber optic temperature probe and sensing unit, a computer data acquisition system, and a feedback temperature controller to turn the magnetron on and off to study combined microwave-convective drying of polyurethane foam at 60 °C and showed that the product temperature could be controlled within 3-5 °C of the set point by cycling the microwave source on and off. Bisakowski et al. (1989) investigated controlled-temperature microwave activation of lipoxygenase with an apparatus similar to that described by Jolly (1986).

The basic concept of controlled-temperature microwave heating is very simple. The computer reads in the most current temperature from the temperature sensing unit and then compares that value with the higher and lower limit values which are entered into the computer by the user. When the sample temperature is above the upper limit (T_{HL}), the computer switches off the magnetron. The sample temperature decreases because of heat conduction, heat convection, and evaporative cooling. The rate of cooling depends on sample size and porosity. When the sample temperature reaches the lower limit (T_{LL}), the computer switches the magnetron on. However, in practice, overheating often occurs, as indicated by Ramaswamy et al. (1991), because the data acquisition and control rate cannot keep up with the rate of heating, especially for smaller samples. In order to have reasonable temperature control stability, Ramaswamy et al. (1991) introduced an additional 250-mL water load into the microwave cavity. The main role of the water load was to absorb microwave energy and reduce the electric field intensity in the cavity (Wickersheim et al., 1988) and, therefore, reduce the sample heating rate.

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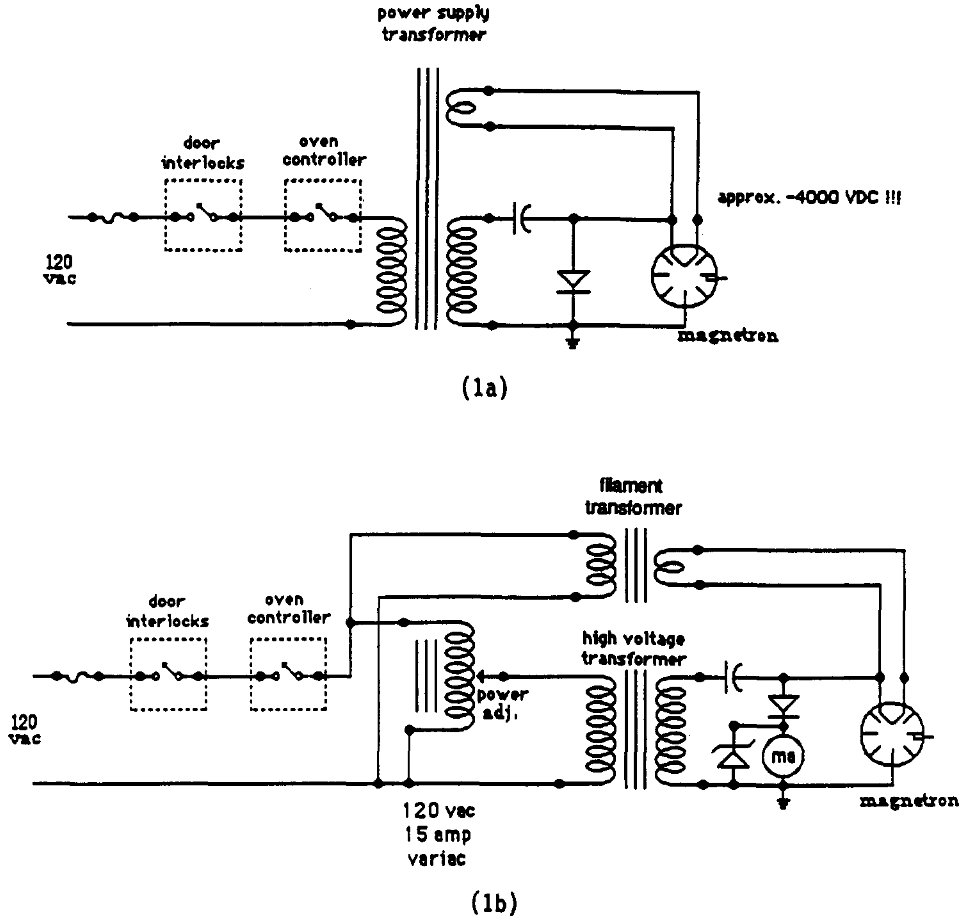

Figure 1. Basic and variable power microwave oven power supply.

There are many ways to modify the power supply circuits in a microwave oven to deliver variable continuous power (Gerling, 1987). Temperature control capability could be greatly enhanced if the feedback temperature controller was used in conjunction with a variable power microwave oven. The objective of this work was to design a microwave oven with variable continuous power and a feedback temperature controller and to test its performance. Effects of electric field intensity, data acquisition rate, and sample characteristics on temperature control were also investigated.

Materials and Methods

Microwave Oven Modifications. A Toshiba Model 6831B microwave oven rated 720 W was used for the modifications. A typical microwave oven power supply circuit and the modified microwave oven power supply circuit for delivering continuous variable power to a microwave cavity are shown in Figure 1. The filament power transformer was purchased from Basler Electric (Model No. BE17789 001, 35334P01, Highland, IL). The Zener diode was a 5-W 1N5346B which has a nominal Zener voltage of 9.1 V. The current panel meter was a 0–500 mA DC milliammeter (Simpson Electric Co., Elgin, IL). The variable transformer or variac (3PN1510, Staco Energy Products Co., Dayton, OH) had the following specifications: input, 120 V, 50/60 Hz, output, 0–120/140 V; amps, 15; maximum KVA, 2.1. The transformer setting was divided into 100 divisions. The microwave power can be changed at any time during heating by adjusting the transformer.

Although the modified circuit is simple, it should be modified only by trained personnel because of the high voltage (approximately 4000 V). The current reading on the ammeter reflects the power delivered by the magnetron. Therefore, it is possible to establish relationships between the field intensity the and transformer setting through careful calibrations. It has been found in our laboratory that the current reading (or the microwave power) is extremely sensitive to the line source. A high-current AC power line conditioner is recommended for insertion prior to the variable transformer. The ammeter reads 0 mA for 0 power and approximately 300 mA for full power. It is necessary to point out that there is no direct relationship between the transformer setting and the ammeter reading. The ammeter constantly reads 0 when the transformer settings are below 70. The reading starts to increase when the transformer setting is greater than 70.

The power supply circuit that combines a feedback control unit (on/off controller) and a variable power transformer for continuously variable power is shown in Figure 2. The mechanical power relay used to switch the magnetron on and off was a miniature power relay (JN1a-TMP-DC12V by Aromat). The relay has a 120-Ω coil resistance which can be switched on with a 12-V DC source. Maximum switching current is 15 A at 125 V AC. The optocoupler has a Darlington output (MOC119 by Motorola) with no base connection. Every electronic component except the filament transformer used in this study was purchased from Newark Electronics (Bordentown, NJ).

Sample Preparations. Sliced commercial white bread (Wonder Bread, Continental Baking Co., St Louis, MO) purchased from a local supermarket, a sponge, and a 5-mL water load were used. Bread samples had an average

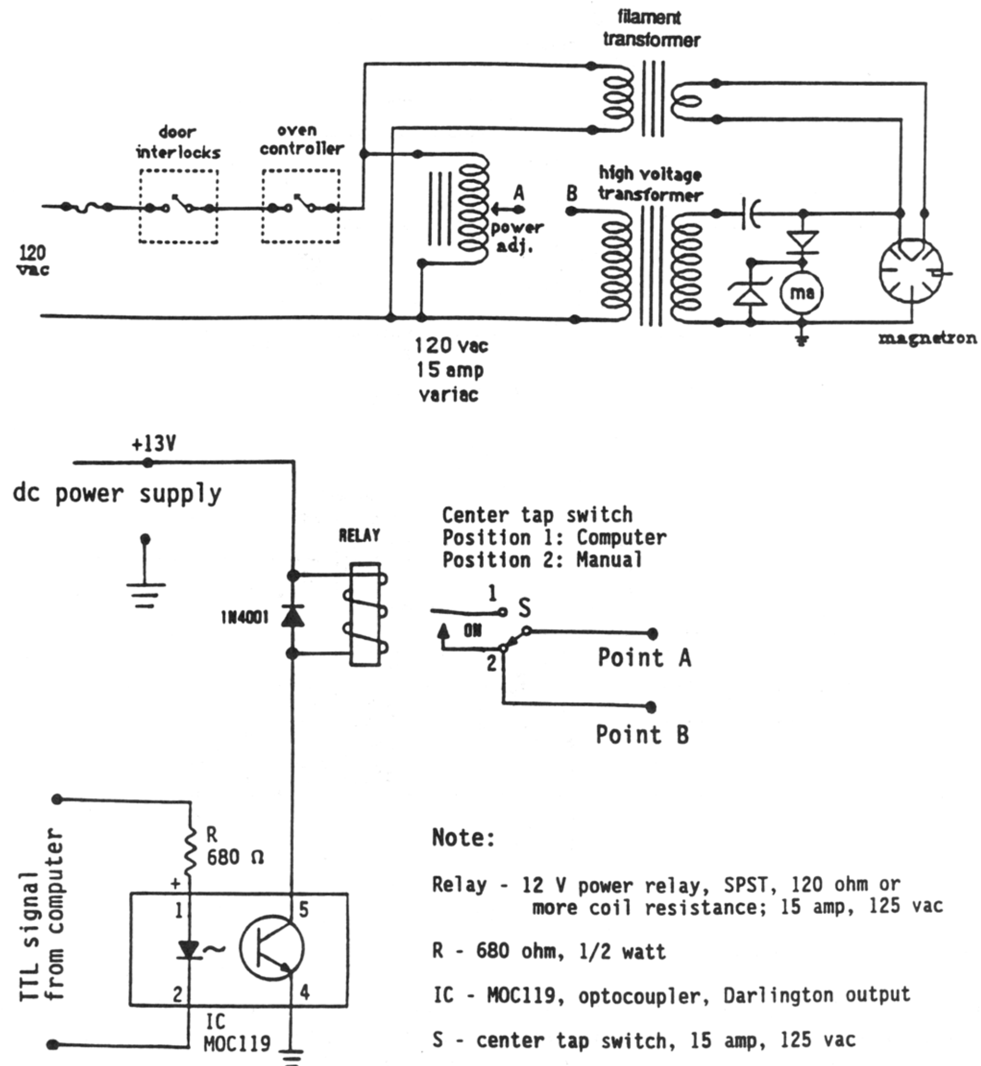

Figure 2. Electronic circuits for the on/off switches.

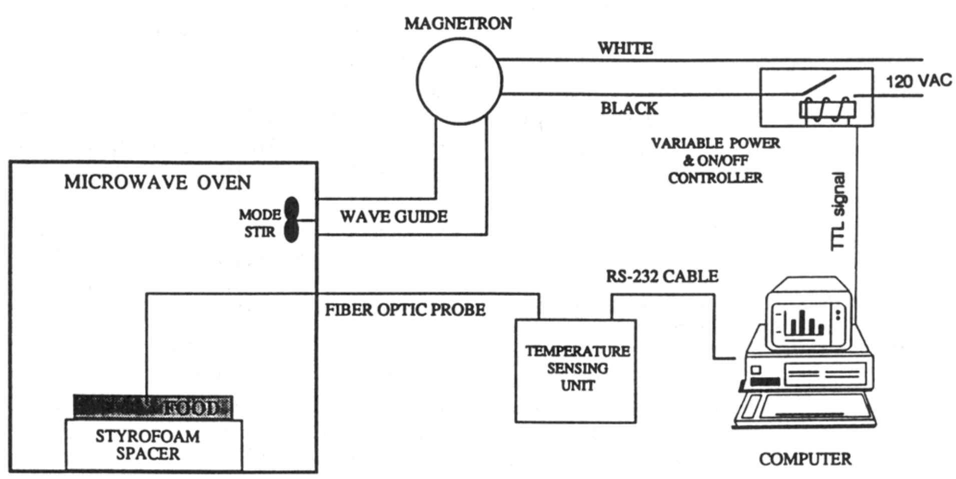

Figure 3. Schematic diagram of a microwave temperature controller.

thickness of 0.013 m and an average moisture content of 0.39 kg H_2O/kg sample (w.b.). The sponge had dimensions of 0.02 × 0.13 × 0.13 m, a bulk density of 120 kg/m^3, and an average moisture content of 0.81 kg H_2O/kg sample. The water was dispensed in a cylindrical glass bottle with a depth of 0.005 m. A styrofoam stopper was used to prevent water loss by vaporization.

Experimental Apparatus. The apparatus that combines the modified microwave oven, a temperature sensing unit with a fiber optic probe, and a personal computer is shown in Figure 3. Because of its minimally perturbing effect on the electromagnetic fields and, hence, upon the heating of the sample, a MetriCor (Woodinville, WA) thermometry system was used to measure the sample temperature. Conventional wire thermocouple probes can give inaccurate readings in a microwave-heated sample, particularly with small samples. The complete nonmetallic MetriCor temperature sensor consists of a thin film of material with a high rate of change of index of refraction with temperature affixed to the end of a fiber optic guide.

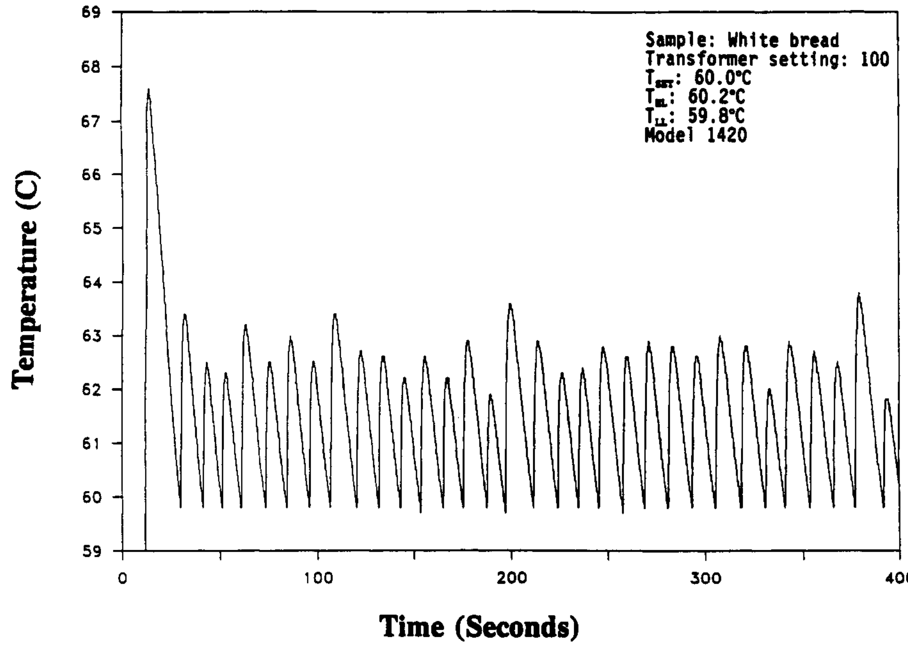

Figure 4. Time–temperature relationship of a bread sample heated in a microwave temperature controller with its full power and a set-point temperature of 60 °C.

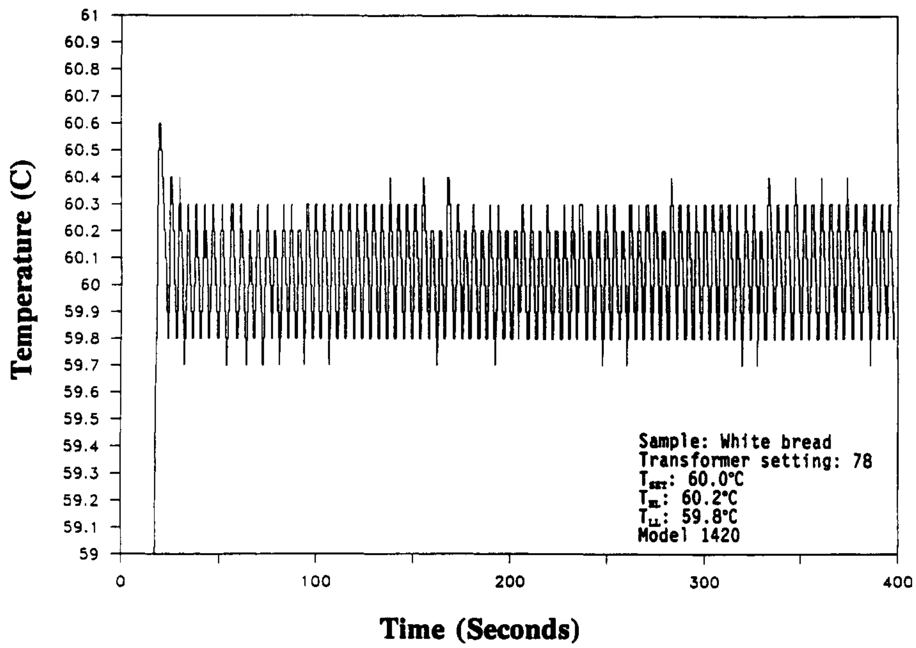

Figure 5. Time–temperature relationship of a bread sample heated in a microwave temperature controller with a transformer setting of 78 and a set-point temperature of 60 °C.

During operation, a light-emitting diode illuminates the thin film via the optical guide, and the spectrum of the reflected energy is measured. Optical interference between the reflections from the front and back surfaces of the film causes the overall reflection from the film to be spectrally, i.e., wavelength, dependent. As the film temperature changes, the index of refraction and, hence, the optical path length within the film, changes for each wavelength. The interference relationships determining the spectrally dependent reflection from the film are thus altered. The resulting change in the spectrum of the reflected energy is reported as a change in temperature. The instrument reports the temperature to 0.1 °C. The accuracy of temperature measurements is dependent upon the type of temperature probe used. In general, the accuracy is 1% of full scale or ±0.2 °C at the calibrated temperature.

The optical fiber temperature probe was centered in the sample. The computer was an IBM/AT compatible that has a 12-MHz clock speed and a hard disk with 25-ms access time. To understand the effects of data acquisition rate on temperature control, two different sensing units (Model 1400 and Model 1420, MetriCor Corp., Woodinville, WA) with a T104-03P-02 fiber optic temperature probe were used. The parallel I/O card that was plugged into the computer was purchased from MetraByte Corporation (Model PIO-24, Taunton, MA). The computer acquires temperatures from the temperature sensing unit through an RS-232 port, and the on/off switching of the magnetron depends upon the T_{HL} and T_{LL}. A user-friendly computer program was developed for data acquisition and control. In general, the computer software menu asks for the set-point temperature (T_{set}) and the upper and lower limits for the set-point temperature when a program is started.

Table I. Transformer Output Voltage as a Function of Setting

transformer setting (70–100)	output voltage (volts, AC)
70	81.5
75	87.2
80	93.0
85	99.7
90	105.5
95	111.4
100	118.0

The computer sends a TTL (transistor–transistor logic) signal (1 in this case) to the optocoupler and switches the mechanical relay on so that the magnetron will be on when the current temperature reading is lower than the upper set-point temperature. When the temperature reaches the upper set point, or on occasion a value slightly above the upper set-point temperature because of the overheating phenomenon, the computer sends a 0 to the optocoupler and switches the magnetron off. The temperature starts to decrease after a certain time (or sometimes immediately) because of evaporative cooling, heating convection, and heat conduction. The rate of cooling is dependent on the porosity, thermophysical properties, and size of the food material. The magnetron is switched on again when the temperature is lower than the lower set-point temperature.

Results and Discussion

The time–temperature relationship of a bread sample heated in the microwave oven operating at full power (transformer was set at full scale) is shown in Figure 4. The desired set-point temperature was 60 °C, and the lower and upper limit temperatures were chosen to be 59.8 and 60.2 °C, respectively. It is clearly indicated in this figure that the sample was initially overheated for more than 7.5 °C and then 2.5–3.0 °C afterward. Similar results were reported by Jolly (1986) for the study combining microwave–convective drying of polyurethane foam at 60 °C. The sample temperature decreased almost immediately when the power was switched off because of evaporative cooling and heat convection. It also shows that the degree of overheating is time-dependent which can be explained by the fact that the electric field intensity at the same location is time-dependent, possibly due to the position of the mode stirrer when the power was switched on.

The importance and necessity of having a variable power microwave cavity can be understood by comparing the tightness of temperature control between Figures 4 and 5. The bread temperature was maintained within ±0.3 °C of the set-point temperature when a proper transformer setting of 78, determined empirically, was used. The relationship between output AC voltage of the transformer and its setting is given in Table I. In order to bring the sample temperature to the set-point temperature as quickly as possible, and at the same time prevent overheating, the sample was heated in the microwave cavity with full power and then with reduced power as the sample temperature approached the set-point temperature. Although the microwave power was adjusted manually in this study, it could have been changed automatically with a step motor-driven transformer. However, a much more sophisticated computer program would have been needed.

Figure 6 shows temperature fluctuations in a bread sample when the desired set-point temperature was 80 °C and the lower and upper limit temperatures were 79.8 and 80.2 °C, respectively. The sample temperature dropped below the lower limit temperature, which was not often seen (Figure 5) even when a higher microwave power was used. The higher power also caused higher temperature overheating. The temperature control stability is within −0.4 and +0.6 °C. Ideally, it is best to use a lower power so that overheating can be avoided. However, for a sample as porous as bread, a higher microwave power is required to counterbalance the evaporative cooling effect, which is much more significant at 80 °C than at 60 °C. A lower power was used for some initial tests, but it was not possible to heat the sample properly. It can be concluded that the optimal power level to be used is dependent upon the effective moisture diffusivity, which is temperature-dependent.

It is also important to point out that a typical consumer countertop microwave oven does not immediately produce microwave power when line voltage is applied to its power supply. A delay of a few seconds is experienced while the

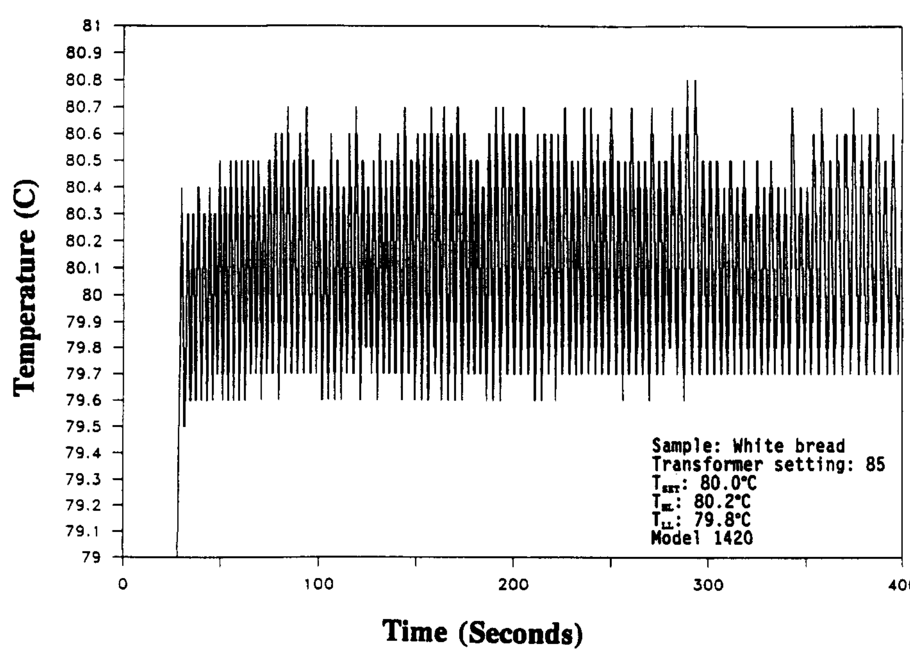

Figure 6. Time–temperature relationship of a bread sample heated in a microwave temperature controller with a transformer setting of 85 and a set-point temperature of 80 °C.

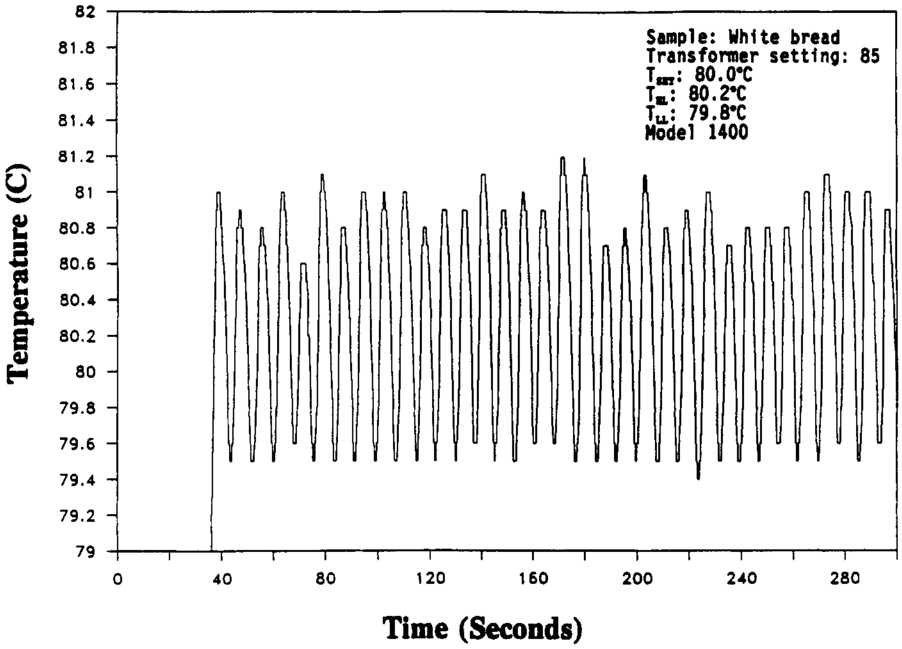

Figure 7. Time–temperature relationship of a bread sample heated in a microwave temperature controller with a transformer setting of 85 and a set-point temperature of 80 °C.

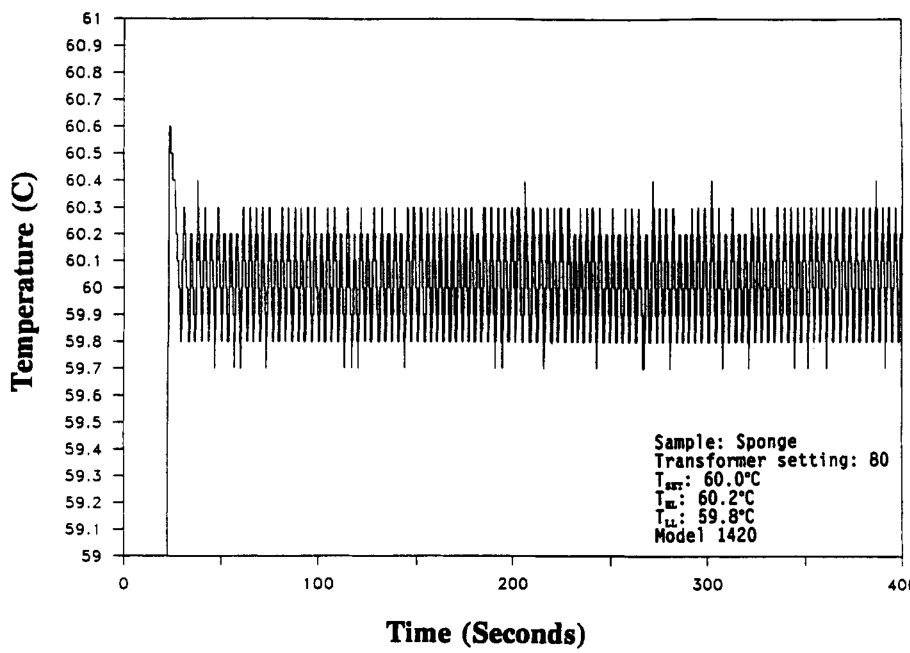

Figure 8. Time–temperature relationship of a sponge heated in a microwave temperature controller with a transformer setting of 80 and a set-point temperature of 60 °C.

magnetron filament warms up sufficiently to emit electrons and, hence, generate microwave power. For economic reasons, the filament is usually powered by the same transformer that supplies the high voltage to the magnetron anode, as shown in Figure 1a. Depending upon the power supply design and the age of the filament, microwave power is not produced for 1.5–2 s or more (Gerling, 1987). This delay precludes rapid cycling of the microwave power, which may be required for controlling the temperature of small samples.

The modified power supply circuit has the advantages of not only being able to change the electric field intensity continuously at any time during heating but also being able to reduce the delay caused by the response of the magnetron, since the filament is powered by a separate transformer which is always connected to the AC power line. The filament is always at its operating temperature, and the power control can switch the high voltage on as rapidly as the circuit constants permit (Gerling, 1987).

The temperature oscillated at a higher amplitude, as indicated in Figure 7, when the Model 1400 temperature sensing unit was used instead of the Model 1420 (Figure 6). However, the effects of the data acquisition rate were much smaller than those of the field intensity. The Model 1400 obtains and outputs data at an update rate of 2.5 times per second for four channels. The approximate update rate for a single channel is 4–5 times per second. Therefore, the data acquisition rate was limited by the speed of the temperature sensing unit. On the other hand, the Model 1420 has an data update rate from 0.7 ms for single-channel operation to 2.3 ms for four channels. The data acquisition rate was controlled by the speed of the computer and the communication rate between the computer and the sensing unit.

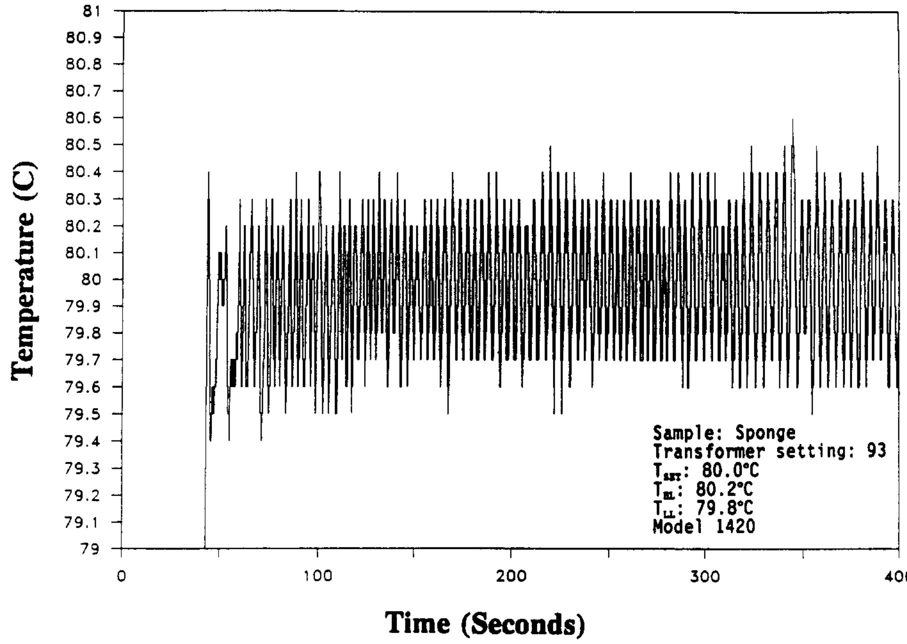

Figure 9. Time–temperature relationship of a bread sample heated in a microwave temperature controller with a transformer setting of 93 and a set-point temperature of 80 °C.

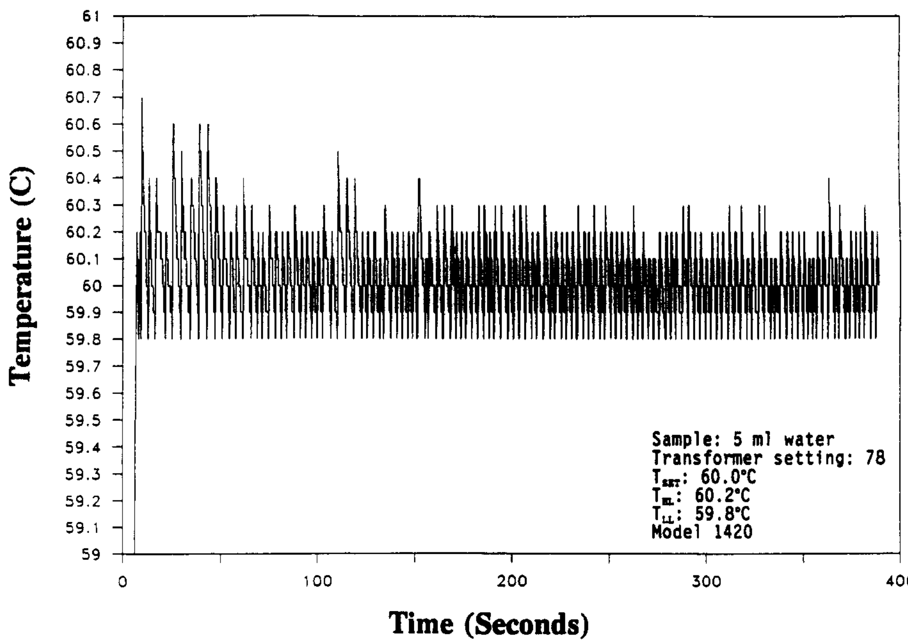

Figure 10. Time–temperature relationship of a 5-mL water load heated in a microwave temperature controller with a transformer setting of 78 and a set-point temperature of 60 °C.

Time–temperature relationships for a sponge sample heated in the microwave cavity with set-point temperatures of 60 and 80 °C are shown in Figures 8 and 9, respectively. The tightness of temperature control is within ±0.3 °C at 60 °C and within ±0.5 °C at 80 °C with transformer settings of 80 and 93, respectively. The sponge requires higher field intensities in order to maintain similar temperature control stability. This is not surprising since the heating rate of a sample in a microwave cavity is a function of field intensity and material properties, such as density, heat capacity, loss factor, and effective moisture diffusivity.

Temperature control capability and accuracy of the apparatus were within −0.2 and +0.4 °C with a 5-mL water load in the microwave cavity when the transformer was set at 78, as shown in Figure 10. Since water is a nonporous sample, there is no local vaporization and the evaporative cooling effect is restricted to the surface. Microwave power is therefore required only to counterbalance the heat transfer by conduction and convection, which is generally much smaller than that of evaporative cooling. Therefore, it is not surprising to see that water temperature never went below the lower limit temperature. Temperature control for a 5-mL water load was quite satisfactory even when a slower temperature sensing unit was used. Results are given in Figure 11.

Ramaswamy et al. (1991) designed a feedback temperature control system for a microwave oven and studied the temperature control stability of the system with small sample volumes (approximately 5 mL of water). According to the authors, temperature control was impossible to obtain due to set-point overshooting (15–20 °C beyond the set point) without introducing a 250-mL water load as a heat sink. The control stability greatly increased with the water load, to within 3 °C. While a water load is very

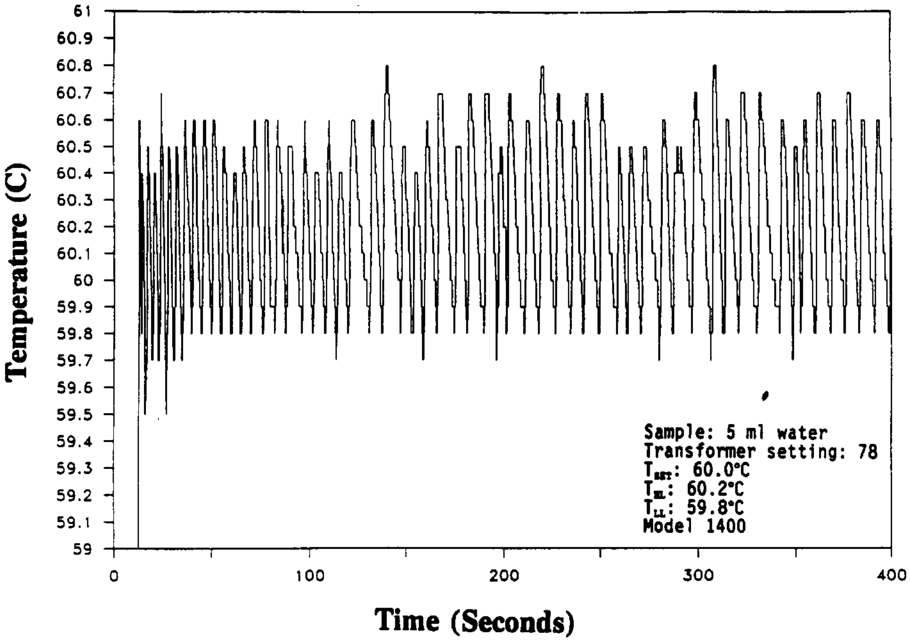

Figure 11. Time–temperature relationship of a 5-mL water load heated in a microwave temperature controller with a transformer setting of 78 and a set-point temperature of 60 °C.

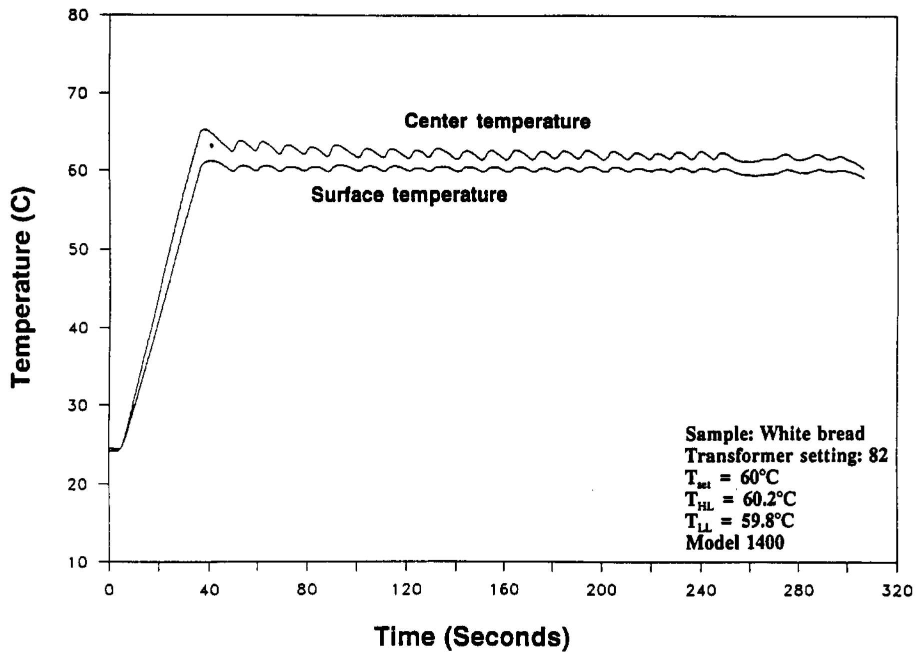

Figure 12. Center and surface temperatures of a bread sample heated in a microwave temperature controller with a transformer setting of 82 and a set-point temperature of 60 °C.

adequate to reduce the electric intensity in a microwave cavity, it suffers some disadvantages. It is well-known that dielectric properties for water are a strong function of temperature (Metaxas and Meredith, 1983). Therefore, the interactions between the water and the electric field are also temperature-dependent. The electric field intensity changes as the water load is heated up. The electric field intensity can be changed further if some water is vaporized for longer experiments. As indicated in our work, the optimal field intensity for obtaining a stable and tight temperature control is material-dependent. significant trial-and-error has to be performed to determine the size of the water load when a different material or sample load is used. These difficulties can be avoided if a microwave cavity with variable continuous power is used since on-line power modification is possible.

Because of its capability to heat samples to a desired temperature and maintain them at that temperature with negligible come-up time and thermal gradient, the microwave oven described in this work has been widely used in our laboratory to study the drying of porous food materials and reaction kinetics. The unit can be operated continuously for several hours without losing its accuracy and stability. Figure 12 shows temperatures at the center and the surface of a bread sample microwave-heated with the control set at 60 °C. The temperature control was performed on the basis of surface temperatures. The come-up time was as short as 30–35 s. The maximum observed temperature difference between those two locations was only 2–3 °C, compared to a 20–30 °C difference when it was convective-heated with dry air at 60 °C. The temperature difference could have been even smaller if heated air at 60 °C had been circulated around the sample to reduce convective heat loss to the surroundings. Therefore, it is possible to study the drying kinetics of porous food materials at different temperatures with a small or no thermal gradient using this experimental setup.

Recently, Welt et al. (1992) introduced an apparatus which consisted of a modified microwave temperature controller and a microwave-transparent pressure vessel with mixing blades for performing steady-state kinetics research. The destruction kinetics of thiamin (vitamin B_1) and spores of *Clostridium sporogenes* in buffer solutions using the apparatus and using traditional TDT tubes (Lund, 1975) heated in an oil bath were compared, and no significant differences were observed.

This system also provides an attractive alternative for quick-heating of heat-sensitive biochemicals to a desired temperature. Due to the driving force of conventional heat transfer, the rate of heating depends on the temperature difference between the sample and the heating medium. As the sample approaches the desired temperature, the rate of heating decreases, resulting in an asymptotic approach to the desired temperature. In order to speed up heating, higher heating medium temperatures than desired are often used. In contrast, the rate of temperature rise for the sample in an electric field remains essentially constant throughout the come-up period, regardless of the proximity to the set-point temperature. Since the rates of most reactions increase exponentially with temperature, less product breakdown is expected in a sample heated in the system than in a conventionally heated sample.

Conclusions

A feedback temperature control system was added onto a microwave oven to convert the microwave oven into a microwave temperature controller. The power supply circuit was also modified so that the microwave power delivered by the magnetron could be adjusted continuously. Temperature control capability depended upon the electric field intensity, set-point temperature, dielectric and physical properties of the sample, and data acquisition rate. Adequate temperature control could be obtained only when proper microwave power was used. The data acquisition rate was found to have relatively minor effects on temperature control for the systems tested. Effects of dielectric and physical properties could be avoided by regulating the field intensity. In general, temperatures could be readily maintained within ±0.6 °C of the desired set-point temperature. There are many potential uses of this apparatus.

Acknowledgment

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