CHAPTER III: DESIGN AND TESTING OF MULTIMODE MICROWAVE DRYING APPLICATOR

3.1 POWER CONTROL MODES

Several methods have been used to control the output microwave power in microwave drying applicators. They are: (1) control of the magnetron electric power supply [40] [70], (2) control of the magnetic field strength inside the magnetron [46] [70], and (3) control of microwave electromagnetic fields inside the applicator cavity [13] [38] [71].

Electrical power applied to the magnetron can be regulated by varying the value of input AC voltage given to the magnetron circuit. The techniques which have been developed so far for adjusting the single-phase input voltage supplied to microwave equipment are described in various documents [70] [76]. Power conversion and control are operated by the power regulator. The main components in the power regulator are the power switches like the Silicon Controlled Rectifier (SCR) and the triac [30] [86]. Electrical power to the microwave drying unit can be controlled by the use of any one of the four control modes described during prototype experimentation. The multimode controllers designed as part of the present research are-

1. Integral cycle control (ON/OFF).
2. Phase control (using fast switching or quasi-continuous).
3. Pulse width modulation control (using fast switching or quasi-continuous).
4. Linear voltage control (continuous).

3.1.1 Integral cycle control mode

Integral cycle control is the most widely used method to control the power in domestic and commercial microwave equipments. This method is effected by changing the number of full cycles applied (ON cycles), compared to the number of cycles when the supply is not connected to the load (OFF cycles). The relation of ON cycles to OFF cycles is arranged such that the average load voltage and power is achieved. The components of the regulator include a timer and a thyristor power switch.
The operating time is relatively long and at least a few seconds. Load voltage and load power are controlled from 0% to 100% of the related maximum values. The load power can be calculated from the number of applied cycles during each period:

\[
P_{\text{avg}} = P_{\text{max}} \frac{N_{\text{ON}}}{N_{\text{ON}} + N_{\text{OFF}}} \quad \text{Eq. 3.1}
\]

and

\[
P_L = \frac{P_{\text{avg}} \times 100\%}{P_{\text{max}}} \quad \text{Eq. 3.2}
\]

where

- \( P_L \) = power level (%)
- \( P_{\text{avg}} \) = average load power (W)
- \( P_{\text{max}} \) = maximum power (W)
- \( N_{\text{ON}} \) = No. of cycles in which power is in ON state
- \( N_{\text{OFF}} \) = No. of cycles in which power is in OFF state

**Prototype design of integral cycle controller**

Microwave power is controlled by switching ‘ON’ the input line voltage for \( N_{\text{ON}} \) number of integral AC cycles and keeping the line ‘OFF’ for \( N_{\text{OFF}} \) number of cycles.

The microcontroller subunit is programmed to accept the input power value from the keyboard. For simplicity, 10 different and discrete power values can be entered. Assuming 230V AC as a nominal input value, the processor feeds the pre-calculated ratio of \( N_{\text{ON}} / (N_{\text{ON}} + N_{\text{OFF}}) \), hereafter designated as a *cycle ratio*, for the cycle control algorithm which in turn determines \( n \) number of complete cycles after which, for at least one cycle, the SCR switch is held in the OFF condition. The algorithm closely follows the cycle ratio \( N_{\text{ON}} / (N_{\text{ON}} + N_{\text{OFF}}) \). The extended algorithm can exactly track the ratio, but yet maintaining one OFF cycle after \( n \) conducting cycles

\[
\left( \frac{3}{40} \Rightarrow \frac{1}{13} \cdot \frac{1}{13} \cdot \frac{1}{14} \right) \quad \text{Eq. 3.3}
\]

The microcontroller samples the resulting output voltage (average over 100 cycles) and compares it with the set reference level. Close tracking of the desired output is achieved.
Appendix A

by applying integral control where in one cycle is added or deleted from \( N_{ON} \) value successively after each control cycle duration.

Cycle ratio changes as

\[
\frac{N_{ON} \pm 1}{(N_{ON} + N_{OFF}) \pm 1} = \frac{N_{ON} \pm 2}{(N_{ON} + N_{OFF}) \pm 2} = \frac{N_{ON} \pm 3}{(N_{ON} + N_{OFF}) \pm 3}
\]

Output from the zero crossing detector (ZCD) is detected as an interrupt input and every alternate interrupt is used to count the number of input cycles. A timer counter channel \( TC_0 \) is used to count \( (N_{ON} + N_{OFF}) \) cycles and \( TC_1 \) for ‘Trigger source generator’. The port output line \( Px.0 \) works as an Enable / Inhibit line (\( EN / INH \)) to the SCR trigger circuit. Another control line works as the trigger pulse generator appropriately gated by the control algorithm.

- **Design procedure:**

A back-to-back SCR pair is used for line voltage cycle switching. The gate trigger circuit including SCR pair \( (SQ_1 \text{ and } SQ_2) \) is triggered ‘ON’ during positive and negative half cycles successively, whenever enabled by the microcontroller sub-unit. A trigger pulse is generated immediately after zero crossing detection without any delay. Thus, the full cycle is switched ‘ON’ or ‘OFF’ as per the control signal from the microcontroller sub-unit.

**Hardware design of microcontroller sub-unit:** The control sub-unit based on microcontroller 89C51 is designed with the hardware interface recommended by the device manufacturer (Atmel Inc.) It is powered with a regulated 5 V power supply using 3 terminal regulators. Regulation is maintained within ± 0.1 V and ripple at < 1 mv – pp. A standard Re-set Circuit with hardware ‘Reset’ key is used to restart the device. A 12 MHz crystal provides the desired system clock. Port lines are supported with pull-up resistor arrays wherever necessary.

**Peripherals used:**

i. A dual line 20 character LCD display requires one complete port (\( Pxx \)) for data transfer and additional 2 lines for device control.

ii. A small keyboard of max. 9 keys are interfaced as a 3 x 3 matrix requiring 6 port lines. Two spare port lines in this port (\( Pxx \)) are reserved for additional functions.
iii. One complete port of 8 lines is consumed to sample feedback data from an 8-bit ADC (ADC 0808). The ADC is driven in continuous conversion mode, approximately requiring 100 µs per conversion cycle.

iv. Remaining port (Pxx) is available for power unit interface. This port can be assigned with alternate port functions.

v. Two port lines (Pxx) and (Pxx) are used for hardware interface to the power unit in each control mode.

vi. One port line (Pxx) is reserved for the interrupt input whenever necessary.

vii. Two lines (TC0 and TC1) are used for timer output or counter input purpose.

viii. Two port lines (Pxx) and (Pxx) are reserved for PC interface through null modem cable connection.

3.1.2 Phase control mode

The phase control method only allows one-time switching during each half-cycle. For the 50Hz AC power input, the switching is 100 times per second. The load voltage and power are controlled with the applications of thyristors. The triac devices are commonly used for lower current rating while the SCRs are for higher current rating. Phase control is achieved by varying the electrical phase angle of the applied AC voltage waveform [35] [36].

The delay angle $\alpha$ is the number of electrical degrees of the applied AC voltage waveform during which the thyristor is in an OFF state, that is, the main current is blocked by the thyristor. The conduction angle $\beta$ is the number of electrical degrees of the applied AC voltage waveform during which the thyristor is in an ON state, that is, the main current flows through the load. The relationship between the two angles is $\alpha + \beta = \pi/2$.

In actual applications, most loads such as motors, solenoids, and transformers have inductance, the high voltage transformer in the microwave equipment is an inductive load.

For an inductive load the current would continue, but in the reverse direction, for a finite time. The triac continues to conduct while the stored inductive load energy is fed back to the supply [30].

Because of the load inductance, the SCRs or triacs continue conducting for a limited angle until they reach the extinction angle. If the extinction angle is equal to or larger than the trigger delay angle, a full output waveform is obtained. If it is less than the delay angle, the
load voltage will be discontinuous. For a resistive load, the extinction angle is zero. The rms value of the load voltage and the load current, and the average value of power can thus be calculated. Metaxas and Meredith (1983) described a block schematic of a phase-controlled power regulator with closed-loop feedback used in the microwave equipment [101]. The supply power was automatically regulated by the feedback signal which was the anode current of the magnetron. Two SCR thyristors were used to control the AC power supply to the high voltage transformer. The thyristors were turned ‘ON’ by a trigger unit. The trigger unit was directed by an electronic processor which included comparators, amplifiers and a filter. This system was claimed to be capable of good long-term stability.

Prototype design of a phase controller

Considering the power handling requirement of about 1500 W, AC phase control system is designed with back-to-back SCRs, rather than a triac device. In Fig. 3.1 a standard microcontroller sub-unit is interfaced to the SCR trigger circuit to form the desired AC-phase controller. As described further, output AC line voltage is controlled through the switching delay in SCR gate firing circuit during each half cycle. The microcontroller sub-unit is programmed to compare the output voltage with the reference set point and to increase or decrease the trigger delay proportional to the error value. The microcontroller output port line then enables the trigger circuit in SCR interface sub-unit.

Controller specification:

Input supply: AC 1k, 50 Hz, 230 V. Nominal voltage + 30, -60 V (Range 170 - 260 V).
Output to magnetron circuit: AC line voltage with delay angle variation from 0 to π/2.
Output current: 5 amps max. Output waveform – Typical phase controlled AC output.
Output control: Through a back-to-back SCR pair.
Controller sub-unit: 89C51 microcontroller based standard unit with port output lines.

Design procedure:

The sub-unit based on microcontroller 89C51 is a standardized hardware, programmed to work as an AC phase control unit. The following are the software implemented blocks as conventionally used in typical phase control systems.

i. Zero crossing detectors (ZCD): To synchronize the SCR triggering circuit with line frequency, the input supply waveform is sampled and zero volt crossover
points are detected. The resulting pulse train as shown in Fig. C.6 is applied as ‘Interrupt Input’ to the microcontroller. Interrupt service routine then implements the trigger delay ‘\( \alpha \)’.

**Figure 3.1** Microcontroller interface to phase control SCRs.

**ii. A main line program:** After power is switched ON, the microcontroller continuously samples the digitized feedback voltage from ‘ADC’ and calculates the average over \( n \) number of samples. This average feedback value is compared with the set point value (desired output voltage) to generate the error value. Using a proportional-integral control algorithm, the necessary delay angle for the next half cycle is found and stored.
iii. **Trigger pulse generator:** The microcontroller uses one timer counter channel (TC\(_0\)) to implement gated trigger generator at 1 KHz. This output is directly used by the ‘Power Device Interface’ through opto-coupler IC\(_3\) for SCR firing. Gate control or enable / disable operation of this TC\(_0\) output is controlled through another channel TC\(_1\).

iv. **Delay generator:** Every ZCD output pulse initiates a time delay operation as per already calculated ‘\(\alpha\)’. A look up table approach is used to find the time constant value corresponding to each value of \(\alpha\). Accuracy of 0.5\% is quite adequate in this application. Timer-counter TC\(_1\) of the microcontroller is used as a mono-shot and is triggered upon detection of a ZCD pulse. Upon time out (Flag detection) channel TC\(_0\) is enabled and also the ‘MR’ (master reset) is cleared. Trigger burst continues up to next ZCD output pulse. At this instant, trigger generator TC\(_1\) is reset and also ‘MR’ is set. The delay cycle then repeats.

v. **Power device interface:** This is the interface scheme with a back-to-back SCRs pair. Opto-couplers are used to isolate the microcontroller circuit from the power circuit. A pulse transformer is driven with transistor Q2 and at secondary; both SCRs are appropriately fired during each half cycle of the line frequency. Transistor Q1 is controlled through master reset line ‘MR’ which helps to keep the total triggering circuit disabled. A triac device may be used for line control applications up to 5 amps or 10 amps load current values. However, the use of back-to-back SCRs is more reliable for load current above 5 amps.

### 3.1.3. Pulse width modulation control mode

Pulse width modulation is a relatively new technique for power regulation in domestic and commercial microwave drying applicators. The power switch is switched ‘ON’ and ‘OFF’ as high as 20 times during a half cycle of the input AC voltage. The output voltage is determined by the pulse width. The switching operation is carried out by the power transistors such as IGBT (insulated-gate bipolar transistor). The pulse width modulation (PWM) circuit may take different configurations. A damped resonant inverter circuit is employed in microwave equipment [15]. PWM can offer better output power spectral characteristics than phase control and is increasingly being adopted in modern electronic power converters [113].
The principle of pulse width modulation is to control the source voltage by using converter switches in such a manner that the output voltage consists of a train of pulses interspersed with notches. It can be used both as a constant voltage source or an alternating voltage source, and can even convert a DC source to a variable AC source by adjusting the ratio of the pulses. By increasing the frequency of the control pulses, changes in the current between the corresponding “jumps” of the output voltage can be largely prevented and high quality output can be obtained. However, the allowable switching frequency in practical electronic power converters is limited by two factors: (i) transition time of the semiconductor from the ‘ON’ state to the ‘OFF’ state and (ii) speed of the control system, or the so-called switching losses in a practical switch. According to Trzynadlowski (1998), a PWM converter’s switching frequency balances the output quality and operation efficiency of the converter [113].

- **Prototype design of PWM controller**

In the practical prototype design of a PWM power controller, power Metal Oxide-Semiconductor Field Effect Transistors (MOSFETs) in a half bridge configuration are used. Again, the microcontroller sub-unit is used to generate a PWM signal modulated with 50 Hz sinusoidal wave form. The power supply block uses SCR semi-controlled bridge to develop ±100 V, DC line voltage for the half bridge power module. The half bridge power module block drives the output transformer that feeds the supply into the magnetron circuit. An LC filter is added to remove the carrier from the PWM output. Power MOSFETs are driven through a complementary transistor pair interfaced to the microcontroller port lines with optical isolation. The microcontroller sub-unit provides the PWM output signal. Two port lines are used to have complementary wave forms for two power MOSFETs in the bridge circuit.

- **Design procedure:**

  a. Power supply block is designed using a semi-controlled SCR rectifier to get ±100 V, DC line voltage for the power module. An input transformer is thus avoided to reduce weight, space and cost.

  b. The half bridge in the power module requires only two power MOSFETs and the resulting design is adequate to provide output power levels of about 500 W. The output transformer is an iron-core step-up transformer with a small air gap (about 10 mils) in the magnetic path. This avoids the possible saturation of the core and...
subsequent core heating. Power MOSFETs are selected with a minimum rating of 400 V, $V_{ds_{\text{max}}}$ and $I_d$ in excess of 7 amps.

c. Fast diodes $D_1$ and $D_2$ of 600 V, 10A rating are used in anti-parallel with the Power MOSFETs. These protect the power devices from possible reverse conduction during commutation. An additional secondary winding provides approximately 10 V peak output suitable for monitoring and feedback.

d. The gate driver circuit requires a complementary transistor driver to drive the gate capacitance with currents up to 100 mA. Current sinking ability helps to remove the charge quickly and thus results in fast switching of the power devices.

e. Opto-couplers again provide the required ‘Galvanic isolation’ between microcontroller subunit-ground and power module power supply. Fig. 3.2 shows the complete driver circuit for Power MOSFETs.

![Power MOSFET Driver circuit](image)

**Figure 3.2** Power MOSFET Driver circuit
f. The microcontroller sub-unit is programmed to provide complementary PWM signals on Port lines Px0 and Px1 which in turn drive the Power MOSFETs. The PWM waveform basically requires a square wave carrier frequency where the ‘ON’ line is modulated in a sinusoidal form. As a standard practice, the carrier is selected at 40 times the modulating frequency of 50 Hz sinusoid i.e. 2 KHz. The modulating signal is 50 Hz, sinusoidal in nature. The processor uses look up tables to store pulse width values over the entire cycle for different output power levels. For prototype trials three different power levels are used.

g. The Timer counter channel TC0 is used as a trigger generator at 2 KHz. This represents the switching carrier source. Another Timer counter channel TC1 works as a Monoshot triggered by the TC0 trigger source. The microcontroller sequentially reads the look-up table for successive pulse width values and loads the same as a TC1 monoshot delay. The resulting pulse train from TC1 represents the PWM waveform at 2 KHz with the ‘ON’ time set successively as per stored pulse width values. A keyboard is used to select output power levels and the display indicates the same. The diagram of the microcontroller block providing complimentary PWM signals on its port lines.

3.1.4 Linear voltage control mode

In a linear resistive regulator, the load voltage and the load current are adjusted through a resistive device. The load current flows through the controlling resistor which converts excessive electric energy to heat. The power consumption is always at ‘full power’ level no matter what power level is actually used. Typical linear regulators include variac, potentiometer, rheostat etc. The main advantages of linear resistive control are: 1. the magnitude of the voltage can be adjusted continuously and simultaneously, and 2. the output wave form is exactly the same as the input wave form except that the magnitude is changed.

The linear resistive control was predominantly used in the past for continuous regulation of the voltage level for various industrial applications. Because of significant power dissipation, nowadays, it is only used where the power level is low and the energy efficiency is not of great concern. Prior to the advent of SCR and PWM technologies, adjustable resistors had been widely used for controlling the magnitude of load voltages. Even today, resistive control remains in use in relay-based starters for electric motors and
near-obselete, adjustable-speed drive systems, and some are employed in the power control of microwave ovens.

- **Prototype design of linear controller**

  As the power requirement in microwave heating is normally within the range of 500 W to 1500 W, linear voltage control is implemented using a dimmer stat (auto transformer) and an output buck-boost transformer.

  Here, the input AC voltage to the HV-transformer-rectifier circuit of the magnetron anode can be changed in a continuous manner either in manual or in automatic mode. The microcontroller can be used for the automatic mode. The necessary microcontroller interface is designed.

- **Controller:**

  Block of a linear controller consists of a standard 89C51-based microcontroller unit having an on-card regulator and keyboard-display unit to set the desired microwave power. Feedback is sampled from the input voltage to the magnetron anode circuit and for a fixed load (food sample). Power input remains constant within ± 5 watts.

- **Controller specifications:**

  b. Output to magnetron circuit: AC line voltage adjustable from 100 V AC to AC line input.
  c. Output current: 5 amps max.
  d. Output control: Through a dimmer stat and series transformer.
  e. Actuator: Motorized actuator using a stepper motor and 89C51 microcontroller drive with keyboard and LCD display.
  g. Variac coupling: standard worm gear with 6:1 gear down coupling.
  h. Continuous AC line voltage controller
  i. \( vo = vi \pm n \Delta V \)
Appendix A

j. \( T_1 \): 300 V AC, 1.2 kva variac / auto transformer

   **Terminals:**
   - A. Line Input
   - B. Fixed reference tap
   - C. Common to Neutral
   - D. Adjustable wiper Tap

k. \( T_2 \): Series transformer, 500 VA

   **Primary:** 200 V AC max.
   **Secondary:** 100 V AC, 5 Amp max.

   **Note:** (+) indicates in phase signal with input at L
   (-) indicates out of phase signal with input at L

l. \( M_1 \): AC stepper motor, 230 V, 1 rps, 6 kg-cm motor

• **Design procedure:**

  Electronic control unit is based on a standard microcontroller 89C51. As a hardware design strategy, the total control hardware is divided in two parts. The sub-unit is designed as a standardized hardware with 89C51 microcontroller, LCD display, a small keyboard and 8-bit ADC. Single chip on-card voltage regulator provides the DC supply to this unit.

  The same microcontroller sub-unit with separate application software is used to evaluate the drying performance in other control modes i.e., phase control, PWM control and cycle control indicates the necessary microcontroller interface to the system.

  The interface sub-unit is specific to each control mode. It includes an opto-coupled triac drive for AC stepper motor control that further drives the shaft of the dimmer-stat. Fig. 3.3 as shown indicates the corresponding circuit configuration.

1. **AC stepper motor** – A DC servo motor with shaft encoder, DC stepper motor and AC stepper motor are standard actuators commonly used in practice. In the present application, for a desired correction speed and setting accuracy, the use of an AC stepper motor provides a simple and low-cost solution. A time delay of 5 seconds to cover the entire setting range is suitable for this application. A 60-rpm motor with gear down ratio of 6:1 is selected. This requires the motor shaft torque of about 4 kg-cm. Therefore a 6 kg-cm, 230 V AC, two phase synchronous motor (AC stepper motor) with standard RC combination is used.
2. Triac drivers provide static switching of the motor in the corrective direction. The motor winding operates on 230 V AC demanding about 400 - 600 mA AC winding current. Triacs of 400 V, 6 amps, in a flat package (SC240D) are selected as driver devices.

3. An Opto-coupler MCT2E with an isolation level of 1.8 kv is used to electrically isolate the triac drive (Galvanic Isolation) from the microcontroller control circuit.

3.2 MULTIMODE POWER CONTROL UNIT

Fig. 3.4 shows such a multimode power control unit. A rotary switch is used to select the desired control mode. The microcontroller sub-unit is a common hardware for all power controllers. Only application software is appropriately selected by the switch. An additional
A de-multiplexer unit is used to connect the control signals from the microcontroller to the selected unit. ZCD circuit is included on the same de-multiplexer card. ZCD output is activated only when ‘AC phases control’ or ‘Integral cycle control’ modes are selected. The system thus framed helps to easily select and operate in one of the modes.

![Diagram](image)

Figure 3.4 Multimode power control unit

3.3 TESTING OF MULTI MODE POWER CONTROL UNIT

The multimode power control unit can be tested considering the microwave power absorbed, $P_{\text{abs}}$ (W) by the sample and the load efficiency $\eta_L$ (%) of the microwave drying applicator. In the present testing the microwave power absorbed by the sample for different

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42
values of input voltages given to input side of the HV transformer for each control mode were plotted and the maximum power absorbed and linearity of the graph was analyzed. The same procedure was done for finding out the load efficiency \( \eta_L (%) \) of the microwave drying applicator for each control mode.

3.3.1 Calibration of the microwave power absorbed

The power requirement in the low power microwave heating system is normally within the range of 500 W to 1500 W. The variable AC voltage of 230 V, 50 Hz is given to the multimode control system connecting only one control mode through the switching arrangement for each experiment. The output voltage of the control mode circuit is connected to the H.V. transformer. This voltage can be measured easily. Due to the high DC voltage obtained from the transformer rectifier circuit, the magnetron is excited thus generating microwave power. As per the variations in AC voltage, the microwave power from the magnetron varies. The generated microwave power is given to the microwave cavity through a waveguide feed. It was observed that the microwave power absorbed is maximum (580 W) in the case of integral cycle control mode, and minimum (518 W) in the case of linear control mode. It is observed that the microwave power absorbed by the PCM has a moderate value (556 W).

Material and Methods

Distilled water of 1000g in a glass container weighing 250g was used with the initial temperature of water being 25\(^{\circ}\)c. The microwave drying applicator with a multimode control unit was used with a microwave power setting of 900 W. Temperature was measured with an Omega OS533E handheld infra-red (IR) thermometer and the weight of the water was measured with an electronic balance.

Experimentation

The sample (water) absorbed the microwave power and the temperature of the water increased due to volumetric heating. The change in the sample temperature was noted down with the help of the IR thermometer and the microwave power absorbed by the cavity load was calculated. The input AC voltage given to the HV transformer was varied and changes in the values of the microwave power absorbed and hence the changes in water temperature were noted down for each power control mode.
The observations of microwave power absorbed as per the variations in the AC input voltages are tabulated in Table 3.1 below.

<table>
<thead>
<tr>
<th>AC input voltage (V)</th>
<th>Microwave power absorbed $P_{abs}$ (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I-CM</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>60</td>
<td>0</td>
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<td>80</td>
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<td>180</td>
<td>580</td>
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<tr>
<td>200</td>
<td>580</td>
</tr>
<tr>
<td>220</td>
<td>580</td>
</tr>
<tr>
<td>240</td>
<td>580</td>
</tr>
</tbody>
</table>

Table 3.1 The microwave power absorbed $P_{abs}$ (W) and AC input voltage (V) to HV transformer.

**Result**

From the recorded observations, graphs have been plotted as shown in Fig. 3.5. They show the relationship between the microwave power absorbed by the load and the applied AC voltage to H.V. voltage transformer for multi control modes.

44
Figure 3.5 Microwave power absorbed (W) versus AC voltage to H.V. transformer (V) for multimode control system.

a) Integral cycle control mode (I-CM)

The graph of the microwave power absorbed and the AC voltage applied to H.V. transformer can be divided into three different zones; as a slow rise of microwave power absorbed at AC voltage above 80 V, followed by a rapid jump between 130 to 180 V, after which the curve becomes flat. The maximum microwave power absorbed by the load is observed to be equal to 580 W. No temperature rise was recorded, when AC voltage to H.V. transformer was less than 80 V. This is because the electric field inside the magnetron was so weak, that the resonance of the electrons could not happen and, as a result, no microwave energy was generated and hence no energy was absorbed by the sample.

b) Phase control mode (P-CM)

The graph can be divided into three zones; a slow rise of microwave power absorbed during AC voltage of 80 V to 110 V, then a slightly rapid jump between 110 and 200 V, after which the curve becomes flat. The maximum microwave power absorbed by the load was found to be 556 W. This amount is smaller than that absorbed by the integral cycle control mode. No temperature rise was recorded below 80 V. The linearity of the curve has been smoothed in a better manner as compared to the linearity of the graph of the integral cycle control mode.
c) Pulse width modulation control mode (PWM-CM)

Though the relationship between the microwave power absorbed and the AC voltage given to the HV transformer can be divided into three zones, the variation in the microwave power absorbed is smoother. A slow rise of microwave power absorbed was observed during 80 V to 85 V. Then a slightly rapid jump occurs between 100 V to 210 V, and thereafter the curve becomes flat. The minimum microwave power absorbed was recorded equal to 536 W, which is less than that in case of the integral cycle control mode and the phase control mode. No temperature rise was recorded below 80 V. Though the maximum microwave power absorbed as per observations is less when compared to both the integral cycle control mode and the phase control mode, the linearity of the curve is smoother than those in case of the previous two control modes.

d) Linear control mode (L-CM)

The first and last zones in the case of the linear control mode are reduced to a negligible value. The middle zone is linearly increasing and the linearity is better as compared to the previous three modes. The microwave power varies between 80 V to 220 V linearly. The maximum microwave power absorbed by the load was found to be 518 W, which is observed to be very little as compared to the previous three modes. Below 80 V AC, no microwave power was generated and hence no power was absorbed by the load.

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Conclusions

The observations for multimode controlled microwave drying applicator are shown in Table 3.2.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Control mode</th>
<th>Maximum microwave power absorbed, $P_{abs}$ (W)</th>
<th>(Linear) Rapid zone between AC voltage</th>
<th>Linearity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I-CM</td>
<td>580</td>
<td>130-180</td>
<td>Less linear</td>
</tr>
<tr>
<td>2</td>
<td>P-CM</td>
<td>556</td>
<td>110-200</td>
<td>Moderately linear</td>
</tr>
<tr>
<td>3</td>
<td>PWM-CM</td>
<td>536</td>
<td>100-210</td>
<td>Linear</td>
</tr>
<tr>
<td>4</td>
<td>L-CM</td>
<td>518</td>
<td>90-220</td>
<td>Highly Linear</td>
</tr>
</tbody>
</table>

Table 3.2 Observations for the multimode control microwave drying system.

In the case of the PWM control mode and the linear control mode, though the linearity of the plots are better, the maximum microwave powers absorbed are observed to be less (536
Appendix A

W and 518 W). In the case of the integral cycle mode, the maximum microwave power absorbed is very high (580 W), but the linearity of the plotted line is less. In the case of the phase control mode, the maximum microwave power absorbed is moderate (556) and the plotting seems moderately linear. Hence, the phase control mode is preferable for the purpose of microwave drying.

3.3.2 Load efficiency, $\eta_L$ (%) of the microwave drying applicator

Load efficiency is one of the important parameters. It is essential to calculate the average microwave power absorbed by the sample inside the cavity and the microwave power generated from the magnetron. Experimentation has been carried out for each control mode and the average microwave power has been computed for maximum microwave power setting of the magnetron. From the observations and calculations, it is estimated that the average load efficiency is maximum (57.6%) in the case of the I-CM and minimum (31.9%) in the case of the L-CM for the maximum microwave power setting (900 W).

❖ Material and Methods

Distilled water of 1000 g in a Pyrex glass container weighing 250 g was used with the initial temperature of water being 25°C. The microwave drying applicator with multimode control unit was used with a microwave power setting of 900 W. The temperature was measured with an Omega OS533E handheld IR thermometer and the weight of the water was measured with an electronic balance.

❖ Experimentation

The samples i.e., distilled water in a Pyrex glass container was put inside the cavity and microwave power was applied. Microwave radiation was applied for various durations of time. From the initial and final temperatures of the sample, changes in temperature were recorded. Then, from those readings the microwave power absorbed by the sample for each radiation time was calculated. Then load efficiency for each radiation time was calculated and then the average load efficiency readings were obtained.
The observations of microwave power absorbed by the load were taken for each radiation time, and the load efficiency was calculated and tabulated as in Table 3.3 below.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Radiation time (sec)</th>
<th>IC-CM</th>
<th>P-CM</th>
<th>PWM-CM</th>
<th>L-CM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>wave</td>
<td>ul wave</td>
<td>wave</td>
<td>ul wave</td>
<td>wave</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>0.28</td>
<td>392.0</td>
<td>43.6</td>
<td>0.27</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>0.48</td>
<td>336.0</td>
<td>37.3</td>
<td>0.46</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>0.68</td>
<td>410.6</td>
<td>45.6</td>
<td>0.8</td>
</tr>
<tr>
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<td>12</td>
<td>1.27</td>
<td>444.5</td>
<td>49.4</td>
<td>1.15</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>1.69</td>
<td>473.2</td>
<td>52.6</td>
<td>1.57</td>
</tr>
<tr>
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<td>18</td>
<td>2.09</td>
<td>487.2</td>
<td>54.2</td>
<td>2.22</td>
</tr>
<tr>
<td>7</td>
<td>21</td>
<td>2.53</td>
<td>506.0</td>
<td>56.2</td>
<td>2.48</td>
</tr>
<tr>
<td>8</td>
<td>24</td>
<td>2.46</td>
<td>480.5</td>
<td>47.8</td>
<td>2.35</td>
</tr>
<tr>
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<td>27</td>
<td>2.9</td>
<td>451.1</td>
<td>50.1</td>
<td>2.44</td>
</tr>
<tr>
<td>10</td>
<td>30</td>
<td>3.56</td>
<td>498.4</td>
<td>55.4</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Table 3.3 The relation between microwave powers absorbed, $P_{abs}(W)$, rise in temperature, $\Delta t$ (°C), load efficiency, $\eta_L$ (%) and radiation time (sec.) for multimode control microwave drying system.

*Result*

From the recorded observations of change in temperature ($\Delta t$) in °C, microwave power absorbed, $P_{abs}(W)$ and load efficiency, $\eta_L$ (%) can be plotted for different radiation times separately in Fig. 3.6, Fig. 3.7 and Fig. 3.8 respectively as shown below.
Figure 3.6 Relation between temperature rise, $\Delta t$ ($^\circ$C) of the sample and radiation time (sec) for multimode control of the microwave drying system.

Figure 3.7 Relation between microwave power absorbed, $P_{\text{abs}}$ (W) by the sample and radiation time (sec.) for multimode control of the microwave drying system.
Figure 3.8 Relation between load efficiency, $\eta_L$ (%) of the microwave drying applicator and radiation time (sec) for multimode control.

a) Rise in temperature for multimode control

1. The rise in temperature, $\Delta t$ ($^\circ$C) is maximum (3.56 $^\circ$C) in case of I-CM and minimum (2.8 $^\circ$C) for P-CM at 30 sec. radiation time.

2. The rise in temperature, $\Delta t$ ($^\circ$C) is approximately same (3.14 $^\circ$C) for PWM-CM and (3.05$^\circ$C) for L-CM at 30 sec radiation time.

3. The rise in temperature, $\Delta t$ ($^\circ$C) is (2.53 $^\circ$C) for I-CM and (2.48$^\circ$C) for P-CM at 21 sec radiation time.

4. The rise in temperature, $\Delta t$ ($^\circ$C) increases continuously from 3 sec to 21 sec and than decreases upto 24 sec and again increases upto 30 sec. for all control mode.

b) Microwave power absorbed, $P_{abs}$ (W) for multimode control.

1. The microwave power absorbed, $P_{abs}$ (W) varies in a zigzag manner; it decreases at 6 sec, then increases at 18 sec., further decreases at 24 sec., and again increases at 30 sec. radiation time for all control modes.
2. The microwave power absorbed, $P_{\text{abs}}$, is maximum (518 W) at 18 sec radiation time for P-CM and minimum (287 W) at 6 sec. radiation time for L-CM.

3. Overall, the microwave power absorbed, $P_{\text{abs}}$, is at a higher level for I-CM and at a lower level for L-CM for all radiation times. The microwave power absorbed is at intermediate levels for both P-CM and PWM-CM at all radiation times.

c) Load efficiency for multimode control

1. The load efficiency, $\eta_L$ (%), varies in a zigzag manner; it decreases at 6 sec., then increases at 18 sec., decreases at 24 sec., and again increases at 30 sec. radiation time for all control modes.

2. The load efficiency, $\eta_L$ (%), is maximum (57.6%) at 18 sec. radiation time for P-CM and minimum (31.9%) at 6 sec. radiation times for L-CM.

3. Overall, the load efficiency is at a higher level for I-CM and at a lower level for L-CM for all radiation times. The load efficiency values are at intermediate levels for both P-CM and PWM-CM at all radiation times.

Conclusions

1. The average temperature, $\Delta t$ (°C), rise is maximum (1.814 °C) in case of I-CM and minimum (1.542 °C) in case of L-CM.

2. The average microwave power absorbed, $P_{\text{abs}}$, by the load is maximum (443 W) in case of I-CM and minimum (377 W) in case of L-CM.

3. The average load efficiency, $\eta_L$ (%), is maximum (49.22%) in case of I-CM and minimum (41.93%) in case of L-CM.

4. Microwave power absorbed, $P_{\text{abs}}$, is maximum (518 W) at 18 sec. radiation time in case of P-CM.

5. Load efficiency, $\eta_L$ (%), is maximum (57.6%) at 18 sec radiation time in case of P-CM.

6. The average values of $\Delta t$, microwave power absorbed, $P_{\text{abs}}$, (W) by the load and load efficiency, $\eta_L$ (%), for P-CM are at moderate levels i.e. average $\Delta t$=1.654 °C, average $P_{\text{abs}}$=411.29 W and average load efficiency, $\eta_L$ (%), =45.7%.

7. Hence, P-CM is the most suitable control mode for a microwave drying applicator.
3.4 MICROWAVE DRYING APPLICATOR:

The applicator system for microwave drying is based on a typical microwave oven with nominal power of 100 W to 1500 W. The schematic diagram of the proposed applicator with necessary instrumentation is shown in Fig. 3.9. The microwave oven has been modified according to the requirements with a suitable electronic multimode power controller and with other essential accessories and components. The additional heater and hot-air blower has been provided as a convective heating system to support the microwave source. The sample holder with its tray has been kept suspended on an electronic weighing balance enabling measurements of the sample weight and hence the removal of moisture content. The temperature measurement is carried out in a two-fold manner e.g. the thermocouple is embedded inside the sample, whereas the IR thermometer is located outside the chamber to carry out the surface temperature measurement remotely. A microcontroller-based data acquisition system is used to compute i) the temperature of the sample, ii) the weight of the sample and iii) the radiation time, and this data is finally fed to a PC. The PC is supported with suitable software for online measurements and analysis. This complete unit of electronic multimode drying applicator has been tested and approved for its validity / suitability for experimentation by Mr. V. B. Bapat, Technical consultant, Pune.
3.5 SUMMARY

The microwave drying applicator has been designed such that online measurements and continuous sampling are possible without interrupting the drying process. While designing and assembling the applicator, utmost care has been taken to employ the required instrumentation. Allied parameter measuring sensors are used and interfaced properly to get the most precise and accurate results.

In the case of the phase control mode, the microwave power absorbed, $P_{abs}$, was observed to be moderate (556 W) and the calibration plot is moderately linear. Load efficiency, $\eta_L$ (%) is maximum (57.6%) at 18 sec radiation time for P-CM. The average values of $\Delta t$ $^\circ$C, microwave power absorbed, $P_{abs}$ (W), and the load efficiency, $\eta_L$ (%) are all at a moderate level for P-CM, thus making it the best choice for the control of a microwave drying applicator.