Appendix

Optimization of Microwave-Assisted Hot Air Drying Conditions of Okra Using Response Surface Methodology

This Appendix of supporting information consists of 6 pages, which include details of specific energy calculations, 2 tables and 2 figures as follows:

Table A1 Specific Energy Consumption in Microwave-Convective Drying of Okra

Table A2 Color parameter values of okra dried under various drying conditions

Fig. 6 Microwave heating system

Fig. 7 Appearance of okra after microwave-convective drying and rehydration

1. Specific Energy calculations

Specific energy consumption, energy required to remove unit amount of moisture content was estimated by calculating the energy required by different components of the drying system during microwave-convective drying process (Eqn 1) (Kumar, 2009; Sharma and Prasad 2005; Sharma 2000). Okra was dried from an initial moisture content of about 89% (wet basis) to a desired moisture content of approximately 10% (dry basis).

$$E=\frac{E_1+E_2+E_3+E_4+E_5}{W_e} \tag{1}$$

where, E=specific energy consumption, MJ/kg; E_1 = energy required to heat the air, MJ; E_2 = energy requirement of the air blower, MJ; E_3 = energy requirement of the microwave generator, MJ; E_4 = energy requirement for turn table, MJ; E_5 = energy requirement of water pump for cooling system of microwave generator, MJ and W_e = amount of moisture removed, kg.

1.1 Energy consumed by heater

The energy demand for heating the air (E_1), knowing the drying time was calculated using equation 2.

$$E_1=\frac{Q_a t}{\eta_h} \tag{2}$$

where, Q_a = sensible heat gained by ambient air; E_1 = energy demand for heater, kJ, t = drying time, s; η_h = efficiency of electrical heaters.

Efficiency of electric heater was assumed as 90%.

Sensible heat gained by ambient air to get heated up from initial temperature (T_i) to required temperature (T_f) was estimated from the following equation (Eqn 3):

$$Q_a = G(1.005+1.88w)(T_f - T_i) \tag{3}$$

Where, G = mass flow rate of air, kg/s; w = absolute humidity of air, kg of water/ kg of dry air.

Mass flow rate of hot air flowing through the hot air duct was estimated from the following equation (Eqn 4):

$$G=\frac{\pi D_i^2 \rho v}{4} \tag{4}$$

where, D_i= internal diameter of the air supplying duct, m; ρ = density of the air, kg/m^3; v = velocity of air in duct, m/s.

Dry bulb and wet bulb temperature of the ambient air were measured using a hygrometer and partial pressure of water vapor in the ambient air was estimated from the Carrier's equation (Eqn 5):

$$P_v = P_v' - \frac{(P-P_v')(T-T_w)1.8}{2800-1.3(1.8T+32)} \tag{5}$$

where, T = dry bulb temperature of ambient air, °C; T_w = wet bulb temperature of the ambient air, °C; P_v = partial pressure of water vapor in ambient air, kPa; P'_v = partial pressure of water vapor at temperature T_w, kPa; P = atmospheric pressure.

Knowing the value of P_v, the absolute humidity in the air was then estimated by the following equation (Eqn 6):

$$w = 0.622 \frac{p_v}{p - p_v} \quad (6)$$

where, w = absolute humidity of air, kg of water/ kg of dry air

1.2 Energy consumed by blower

An overall efficiency of 70% was assumed for both motor and the blower. Energy demand of the blower, E_2 was calculated using equation 7.

$$E_2 = \frac{P_m t}{\eta_b} \quad (7)$$

where, P_m = power of the motor, kW; t = drying time, s; η_b = overall efficiency of the blower and motor.

1.3 Energy requirement of microwave generator

Microwave generators are 60-70% efficient in converting the line power to the microwaves as recommended by the manufacturing companies. Further in the drying system, all microwave energy is not absorbed by the product but some microwaves are reflected back. So, overall efficiency of the system reduces to about 50%. Microwave energy demand E_3 was calculated using equation 8.

$$E_3 = \frac{P_{mw} t}{\eta_{mw}} \quad (8)$$

where, P_{mw} = microwave power applied to the food material, kW; t = drying time, s; η_{mw} = efficiency of microwave system, 0.5.

1.4 Energy requirement of rotating motor

In the present system, there was a system made to rotate the product holder inside the drying chamber (for uniform heating). Energy consumed by the rotating motor E_4 in the system was calculated using equation 9:

$$E_4 = \frac{P_{rm} t}{\eta_{rm}} \quad (9)$$

Where, P_{rm} = power of rotating motor, kW; t = drying time, s; η_{rm} = efficiency of motor, 0.9.

1.5 Energy requirement of water pump

Microwave generator used in current study was a water cooled system. So there was a water pump to regulate the cold water in the system. Energy consumed by that pump E_5 was calculated using equation 10:

$$E_5 = \frac{P_{wp} t}{\eta_{wp}} \quad (10)$$

Where, P_{wp} = power of water pump, kW; t = drying time, s; η_{wp} = efficiency of water pump, 0.9
By calculating energies required by individual parts in the system through the drying time and total moisture removed, specific energy values were calculated.

Table A1 Specific Energy Consumption in Microwave-Convective Drying of Okra

Process Variables											
Air Speed (m/s)	Air Temp. (°C)	MW Power (W/g)	Flow Rate (m^3/s)	Drying Time (min)	E1 (kJ)	E2 (kJ)	E3 (kJ)	E4 (kJ)	E5 (kJ)	Total Energy (kJ)	Specific Energy (MJ/kg)
1.8	63.9	2.1	0.0142	60	2140.4	1080	1512	14.0	100.0	4846.4	55.26
1.8	63.9	0.9	0.0142	130	4637.5	2340	1404	30.3	216.7	8628.5	98.16
1.8	46.1	2.1	0.0142	75	1134.3	1350	1890	17.5	125.0	4516.8	51.50
1.8	46.1	0.9	0.0142	175	2646.6	3150	1890	40.8	291.7	8019.1	91.23
1.2	63.9	2.1	0.0095	55	1308.0	990	1386	12.8	91.7	3788.5	43.19
1.2	63.9	0.9	0.0095	130	3091.7	2340	1404	30.3	216.7	7082.7	80.67
1.2	46.1	2.1	0.0095	70	705.8	1260	1764	16.3	116.7	3862.8	43.95
1.2	46.1	0.9	0.0095	165	1663.6	2970	1782	38.5	275.0	6729.1	76.73
2	55	1.5	0.0158	110	3104.2	1980	1980	25.7	183.3	7273.2	82.65
1	55	1.5	0.0079	95	1340.5	1710	1710	22.2	158.3	4941.0	56.34
1.5	70	1.5	0.0118	85	3025.7	1530	1530	19.8	141.7	6247.2	71.23
1.5	40	1.5	0.0118	120	808.1	2160	2160	28.0	200.0	5356.1	61.14
1.5	55	2.5	0.0118	50	1058.3	900	1500	11.7	83.3	3553.3	40.51
1.5	55	0.5	0.0118	180	3809.7	3240	1080	42.0	300.0	8471.7	96.6
1.5	55	1.5	0.0118	100	2116.5	1800	1800	23.3	166.7	5906.5	67.35
1.5	55	1.5	0.0118	105	2222.3	1890	1890	24.5	175.0	6201.8	70.56
1.5	55	1.5	0.0118	100	2116.5	1800	1800	23.3	166.7	5906.5	67.35
1.5	55	1.5	0.0118	105	2222.3	1890	1890	24.5	175.0	6201.8	70.71
1.5	55	1.5	0.0118	100	2116.5	1800	1800	23.3	166.7	5906.5	67.35
1.5	55	1.5	0.0118	100	2116.5	1800	1800	23.3	166.7	5906.5	67.2

Table A2 Color parameter values of okra dried under various drying conditions

Process Variables						
Air velocity (m/s)	Air Temp. (°C)	MW Power (W/g)	L	a	b	ΔE
1.8 (+1)	63.9 (+1)	2.1 (+1)	20.29	-0.12	4.03	29.56
1.8 (+1)	63.9 (+1)	0.9 (-1)	21.42	0.1	3.79	29.24
1.8 (+1)	46.1 (-1)	2.1 (+1)	22.46	-1.96	4.34	27.13

1.8 (+1)	46.1 (-1)	0.9 (-1)	24.23	-2.42	4.21	26.07
1.2 (-1)	63.9 (+1)	2.1 (+1)	20.45	-0.56	5.32	28.47
1.2 (-1)	63.9 (+1)	0.9 (-1)	21.71	0.16	3.92	29.06
1.2 (-1)	46.1 (-1)	2.1 (+1)	21.36	-2.05	4.51	27.55
1.2 (-1)	46.1 (-1)	0.9 (-1)	23.28	-0.12	4.85	27.56
2 (+1.682)	55 (0)	1.5 (0)	22.94	0.2	2.92	29.11
1 (-1.682)	55 (0)	1.5 (0)	23.21	0.3	3.09	28.94
1.5 (0)	70 (+1.682)	1.5 (0)	21.37	0.07	3.48	29.44
1.5 (0)	40 (-1.682)	1.5 (0)	22.58	-0.33	4.68	27.86
1.5 (0)	55 (0)	2.5 (+1.682)	22.26	-0.85	3.63	28.34
1.5 (0)	55 (0)	0.5 (-1.682)	23.65	-3.15	4.02	26.04
1.5 (0)	55 (0)	1.5 (0)	26.23	-2.12	3.29	26.02
1.5 (0)	55 (0)	1.5 (0)	25.58	-2.45	3.45	25.97
1.5 (0)	55 (0)	1.5 (0)	25.98	-2.02	3.14	26.29
1.5 (0)	55 (0)	1.5 (0)	26.01	-2.61	3.1	25.94
1.5 (0)	55 (0)	1.5 (0)	26.25	-2.17	3.39	25.92
1.5 (0)	55 (0)	1.5 (0)	25.72	-1.98	3.16	26.40

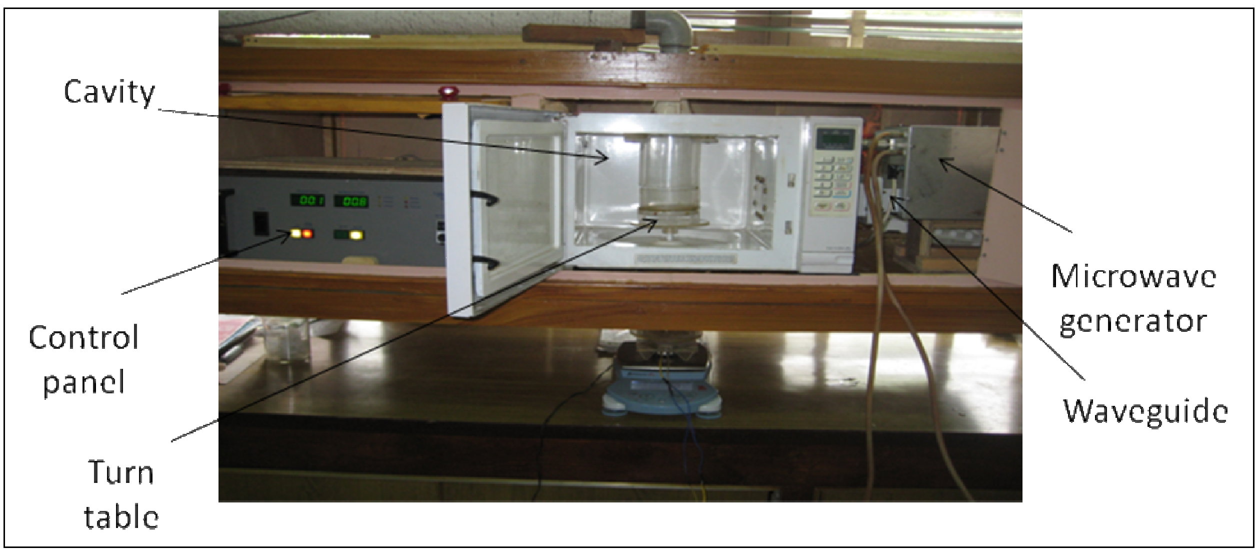

Fig. 6 Microwave heating system

Fig. 7 Appearance of okra after microwave-convective drying and rehydration

References

Kumar D (2009) Studies on Microwave-Convective drying of okra. M.Tech Thesis, Kharagpur: Indian Institute of Technology, Kharagpur, Agricultural and Food Engineering Department.

Sharma GP (2000). Microwave convective drying of garlic cloves. PhD Thesis, Kharagpur: Indian Institute of Technology, Kharagpur, Agricultural and Food Engineering Department.

Sharma GP and Prasad S (2005) Specific energy consumption in microwave drying of garlic cloves. Energy 31: 1921–1926.