processes

MDPI

Supplementary Material

Microwave-Assisted Freeze-Drying with Frequency-Based Control Concepts via Solid-State Generators. A Simulative and Experimental Study.

Till Sickert [1,*], Isabel Kalinke [2,3], Jana Christoph [1] and Volker Gaukel [1]

[1] Institute of Process Engineering in Life Sciences, Food Process Engineering, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany
[2] Food and Bioprocess Engineering, TUM School of Life Sciences, Technical University of Munich, 85354 Freising, Germany
[3] Food Process Engineering, TUM School of Life Sciences, Technical University of Munich, 85354 Freising, Germany
* Correspondence: till.sickert@kit.edu

Table S1. Frequencies utilized in the electromagnetic simulations in dependence on the control concept and drying state.

	frequency f / GHz						
	1MF	6EF					
Drying state z / %	f_1	f_1	f_2	f_3	f_4	f_5	f_6
0	2.4255	2.4000	2.4200	2.4400	2.4600	2.4800	2.5000
10	2.4263	2.4000	2.4200	2.4400	2.4600	2.4800	2.5000
20	2.4272	2.4000	2.4200	2.4400	2.4600	2.4800	2.5000
30	2.4283	2.4000	2.4200	2.4400	2.4600	2.4800	2.5000
40	2.4296	2.4000	2.4200	2.4400	2.4600	2.4800	2.5000
50	2.4310	2.4000	2.4200	2.4400	2.4600	2.4800	2.5000
60	2.4326	2.4000	2.4200	2.4400	2.4600	2.4800	2.5000
70	2.4343	2.4000	2.4200	2.4400	2.4600	2.4800	2.5000
80	2.4362	2.4000	2.4200	2.4400	2.4600	2.4800	2.5000
90	2.4455	2.4000	2.4200	2.4400	2.4600	2.4800	2.5000
100	2.4418	2.4000	2.4200	2.4400	2.4600	2.4800	2.5000
	1RF	6RF					
Drying state z / %	f_1	f_1	f_2	f_3	f_4	f_5	f_6
0	2.4133	2.4071	2.4133	2.4438	2.4541	2.4698	2.4789
10	2.4135	2.4100	2.4135	2.4444	2.4566	2.4701	2.4793
20	2.4127	2.4127	2.4452	2.4523	2.4587	2.4704	2.4797
30	2.4134	2.4012	2.4134	2.4459	2.4607	2.4706	2.4802
40	2.4627	2.4036	2.4141	2.4468	2.4627	2.4708	2.4806
50	2.4646	2.4063	2.4147	2.4478	2.4646	2.4710	2.4811
60	2.4664	2.4153	2.4490	2.4531	2.4664	2.4712	2.4813
70	2.4681	2.4158	2.4504	2.4531	2.4681	2.4714	2.4813
80	2.4698	2.4163	2.4521	2.4534	2.4698	2.4715	2.4818
90	2.4713	2.4002	2.4532	2.4542	2.4713	2.4717	2.4823
100	2.4730	2.4014	2.4533	2.4566	2.4718	2.4730	2.4829

Table S2. Energy efficiencies of the frequencies utilized in the electromagnetic simulations in dependence on the control concept and drying state.

	Energy efficiency η / %						
	1MF	**6EF**					
Drying state z / %	**f_1**	**f_1**	**f_2**	**f_3**	**f_4**	**f_5**	**f_6**
0	13.22	59.52	17.43	28.55	39.93	57.71	28.51
10	11.93	58.71	17.19	22.29	53.54	56.26	23.10
20	10.90	62.66	18.35	17.83	75.28	54.74	18.62
30	10.03	53.56	19.52	14.64	82.91	52.86	15.46
40	9.20	40.05	18.58	12.50	58.88	50.48	12.97
50	8.39	33.48	21.87	12.01	35.96	47.66	11.07
60	7.53	33.69	27.30	15.29	24.10	43.92	9.51
70	6.57	43.18	16.36	12.16	18.54	39.10	8.19
80	5.48	71.91	11.52	6.57	16.53	33.44	7.14
90	4.28	96.18	8.31	4.36	17.81	26.76	5.93
100	3.05	41.30	6.35	3.10	26.52	18.92	4.43
	1RF	**6RF**					
Drying state z / %	**f_1**	**f_1**	**f_2**	**f_3**	**f_4**	**f_5**	**f_6**
0	99.27	93.43	99.27	80.95	77.68	54.47	60.12
10	98.88	96.01	98.88	76.01	78.50	54.36	57.20
20	99.96	99.96	70.58	28.40	81.91	54.78	54.86
30	96.49	56.19	96.49	64.91	85.63	55.26	52.94
40	89.11	48.31	87.68	59.54	89.11	56.30	51.35
50	92.20	41.04	79.15	55.75	92.20	57.49	50.35
60	94.81	72.90	54.73	38.04	94.81	59.63	50.08
70	96.93	67.92	58.42	35.98	96.93	63.72	52.55
80	98.46	61.95	69.35	39.48	98.46	74.28	60.23
90	98.93	98.31	88.95	81.37	98.93	98.78	73.71
100	99.72	91.67	58.94	98.89	57.39	99.72	91.68

Table S3. Frequencies and respective energy efficiencies utilized in the control concepts in the experiments with the laboratory-scale MFD system. The respective energy efficiencies and frequencies were determined as the arithmetic means from the process characterization by a frequency sweep in triplicate.

	1MF	**6EF**					
	f_1	**f_1**	**f_2**	**f_3**	**f_4**	**f_5**	**f_6**
frequency f / GHz	2.4322	2.4000	2.4200	2.4400	2.4600	2.4800	2.5000
energy efficiency η / %	23.93	23.70	60.57	63.22	61.00	62.53	58.17
	1RF	**6RF**					
	f_1	**f_1**	**f_2**	**f_3**	**f_4**	**f_5**	**f_6**
frequency f / GHz	2.4498	2.4498	2.4562	2.4652	2.4664	2.4725	2.4748
energy efficiency η / %	94.15	94.15	71.66	91.52	92.50	83.15	85.81