KOREAN J. FOOD SCI. TECHNOL.
Vol. 21, No. 5, pp. 676~685 (1989)

Optimum Drying Conditions of On-Farm Red Pepper Dryer

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Abstract

Optimal operating conditions of on-farm red pepper dryer were searched by using the simulation-optimization algorithm combining the drying and quality deterioration models of red pepper with Box's complex method. Determination of control variables such as air temperature, air recycle ratio and air flow rate was based on a criterion of minimizing energy consumption under the constrainst conditions that satisfied the specified color retention of carotenoids. As quality constraint was stricter, energy consumption increased and total drying time decreased with lower recycle ratio and higher air flow rate. Product mixing during drying was found to be able to improve the energy efficiency and product quality. Currently used air flow rate was assessed to be increased for the optimal operation. Two stage drying at the fixed optimal air flow rate was proven to be useful means for further saving of energy consumption. In the optimal bistaged drying, the second stage began at about one third of the total drying time and low air temperature in the first stage increased to a high value and air recycle ratio increased slightly in the second stage. Optimal control variable scheme could be explained by the dryer performance and the carotenoids destruction kinetics in red pepper drying.

Keywords: red pepper drying, optimization, energy, quality, carotenoids

Introduction

Heated air dryer is widely used in the farm in order to dry large amount of red pepper within a limited harvest season. In the near future use of dryer for red pepper drying is estimated to increase further(1). Despite considerable application of dryers on a farm level, the present informations of dryer operation are as yet insufficient(2). Only experience based on trial and error helps a little. Guidelines for the optimal operation of on-farm red pepper dryer are thus needed for the product quality and economized energy consumption. The guidelines should be able to specify the air temperature, the recycle ratio of the exhaust air and the air flow rate, which are the main control variables of the dehydration.

It is known that drying at about 60 °C produces high quality red peppers(3,4). Lee *et al.*(5) studied quality optimization in the drying of thin layer red peppers by using simulation-optimization technique. Their results suggested that relative humidity be maintained at lower limit and air temperature at around 60 °C. They also tried two stage drying, which improved the objective function of quality retention a little. But low relative humidity can be achieved by the low recycle ratio, which causes the high energy consumptions(6). Therefore, energy consumption and product quality are two important factors in the dehydration. In optimization of practical drying these can be treated as objective function and constrainsts, respectively. In the heated air dryer red pepper drying is carried out in deep bed. The present authors studied the optimal operating conditions of red pepper dryer, which can serve as a simple guide to farm drying of red pepper. The objectives of this study are to develop a drying simulation model and to determine optimal operating condi-

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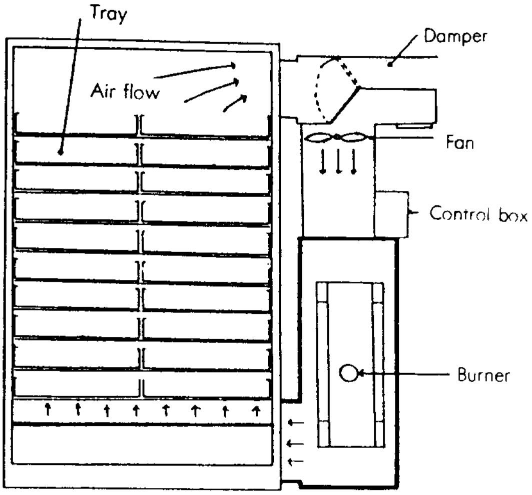

Fig. 1. Schematic diagram of red pepper dryer.

tions of an on-farm red pepper dryer.

Materials and Methods

Dryer

Fig. 1 shows an on-farm red pepper dryer. The dryer is oil fired with the air being drawn in at the top by a fan and heated via a heat exchanger by flue gas of the burner. The air in the plenum chamber passes up through the drying chamber, which consists of ten product trays loaded with red peppers. A hand operated damper is positioned at top side to allow for partial recirculation of the exhaust air. Variations in the dryer structure exist for makers and dryer capacities. For the simplicity of our analysis the assumptions were as followings;

1) Air flows in parallel path and with uniform velocity through red pepper mass.
2) Some of the exhaust air is recycled to be mixed with an ambient fresh air.
3) The weight of dry red pepper per cross-sectional area of one square meter of a tray is 5.680 kg. The depth of product on a tray is 9 cm and equivalent to 5 thin layers.
4) The dryer consists of 10 consecutively stacked trays. The drying proceeds from lower trays to upper ones.

The assumptions such as tray loading and air flow were based on the actual investigations of red pepper drying. Some irregularities of air flow in the dryers of some manufacturers, were thought to be able to be improved by proper operation and thus disregarded.

Simulation model

Prior to optimization the simulation model is needed for evaluating the performance of the dryer. The drying simulation model of Thompson *et al.*(7) was used with minor modification to obtain moistures and temperatures of red peppers, relative humidities and temperatures of drying air, and energy consumption during drying. Thin layer drying process during time increment Δt is considered to consist of three separate processes; temperature equilibrium between food and air, moisture removal under equilibrated air temperature and evaporative cooling of air and food.

Firstly, the equilibrium temperature of air and red pepper can be calculated by equation (1) derived from an energy balance.

$$T_e = \frac{(C_a + C_v H_o) T_o + C_1 G_o}{C_a + C_v H_o + C_1} \tag{1}$$

At this temperature and specified humidity, the rate of moisture removal is described as equation (2) of the thin layer equation of Cho *et al.*(8)

$$\frac{dm}{dt} = -\left(\frac{0.50201}{60}\right) \exp\left(\frac{-186.51}{T_{db}}\right) (100m - 100m_e)^{(0.5384 - 0.2585RH)} \tag{2}$$

where equilibrium moisture is given by equation (3).

$$m_e = \frac{\left(\frac{\ln(1-RH)}{-1.2188 \times 10^{-3} (T_{db} + 2.576)}\right)^{1.0088}}{100} \tag{3}$$

The moisture content after drying can be calculated by the integration of equation (2).

Final temperatures of red peppers and air are then determined from the heat balance of water evaporation as equation (4).

$$T_s = \frac{(C_a + C_v H_o) T_e + C_1 T_e - \Delta H (i_g + \lambda)}{C_a + C_v H_f + C_2} \tag{4}$$

If the the resultant relative humidity in the dryer is infeasible, condensation is assumed to occur for the compensation of the moisture content of red pepper(7).

At this red pepper temperature and mositure, rate of carotenoids destruction can be described by Lee *et al.*(9) as following;

$$\frac{dC}{dt} = -kC \tag{5}$$

$$k = k_o \exp(-E_{ac}/RT_s) \tag{6}$$

$$\ln k_o = 4.1879 - 1.9466m + 3.2619m^2 \tag{7}$$

$$E_{ac} = 7698.3 - 692.58m + 1911.2m^2 \tag{8}$$

Carotenoids were considered as the sole quality criterion because the other important quality factor, browning showed similar optimization results(5).

The solutions of each thin layer can now be combined to obtain average moisture content and carotenoids of the whole bed.

For the evaluation of energy consumption only the energy used for heating the air to inlet temperature was involved. Since the objective of this study was to minimize energy cansumption by the optimal operation of the dryer, the simulation model focused on the energy for air heating which can be usually manipulated by the operation(10). Energy through wall loss was disregarded because of relative negligibility and invariableness of this term(6,10). Air circulation energy of electric source was not included either in the calculation of energy consumption. The energy required to heat the air can be derived by equations (9) to (12).

$$\frac{dE}{dt} = G(T_{in} - T_{mix}) C_{pmix}. \tag{9}$$

where $T_{mix} = (C_{pex} r T_{ex} + C_{pam}(1-r) T_{am}) / C_{pmix}$ (10)

$$C_{pmix} = C_a + C_v H_{mix} \tag{11}$$

$$H_{mix} = rH_{ex} + (1-r) H_{am} \tag{12}$$

For the simulation of red pepper drying under various conditions, equations (2), (5), and (9) must be integrated with respect to time. Euler-Cauchy numerical integration formula was used to solve these equations. Time interval of 5 minutes was used for the integration throughout the study. Initial moisture content of 3.4 g water/g dry solid, initial carotenoids of 370 mg/100g dry solid and initial red pepper temperature of 25 °C were assumed. Ambient air conditions used were 24.4 °C and relative humidity of 85% which are the average weather data in Seoul area during August, 1987(11) as most of red pepper is harvested in August. Psychrometric properties were calculated by the equations suggested by ASAE(12).

Optimization

The established simulation model was linked to the optimization routine. Drying air temperature, recycle ratio and air flow rate minimizing energy consumption in drying red peppers were searched by Box's complex method(13). The search was undertaken under the constraint conditions that the moisture content of top layer reached 0.2g water/g dry solid and simultaneously specified carotenoids retention was satisfied. For the first, control variables of time invariable drying were optimized. Search regions were 50-80 °C of inlet air temperature, 0-1 of air recycle ratio and 0-50 $m^3/min.m^2$ of air flow rate. These ranges were chosen from the practical availability. Implicit constraint of total drying time below 60 hours was also imposed on the search. After analyzing the optimized time invariable drying, optimization of two stage drying was undertaken for further saving of energy. The stagewise air temperatures, recycle ratios and step changing time at the previously optimized constant air flow rate were searched by using the method of Umeda *et al.*(14). In order to alleviate the discreteness of the control variables in step changing, air temperature and air flow rate were linearly interpolated during the stage change of 20 minutes. In the practical food dehydration air flow rate is determined by fan capacity and is difficult to change with time or

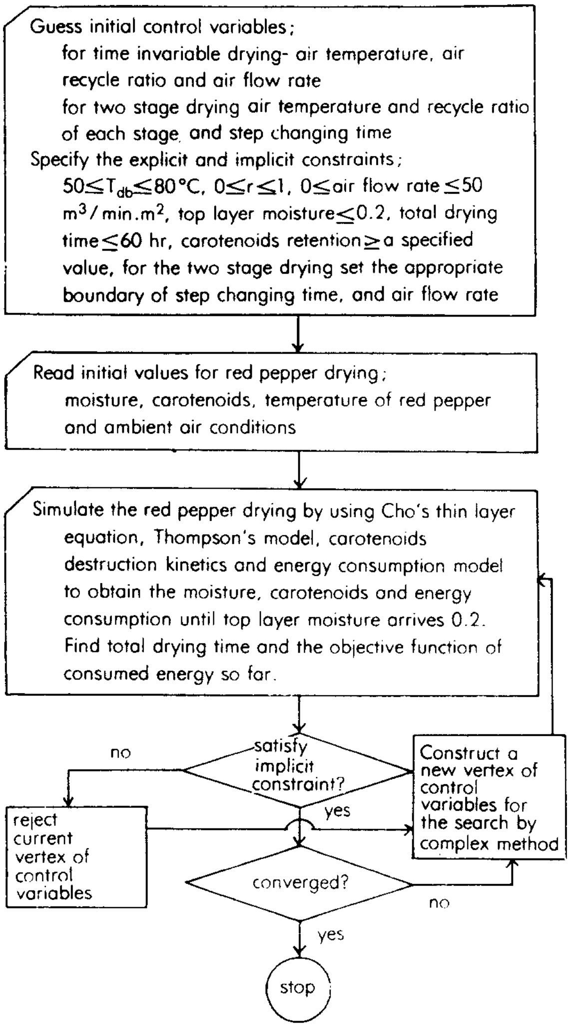

Fig. 2. Overall algorithm of optimization in the operation of on-farm red pepper dryer

stage. However air temperature and recycle ratio can be controlld in limited dynamic change by simple means. Thus two stage drying at fixed air flow rate was considered for improvement of product quality or energy efficiency, and tried in optimization. The overall optimization algorithm is shown in Fig. 2. All the computation was done by TeleVideo TS2605 personal computer.

Results and Discussion

Time invariable drying

Table 1 shows the optimized conditions of drying red peppers in fixed bed trays when control variables are constant with respect to time. Optimized energy consumption increases and total drying time to achieve the moisture removal required decreases with higher quality retention of carotenoids. Energy consumption increases rapidly at the constraints of carotenoids retention above 170 mg/100g dry solid. At carotenoids retention greater than 195 mg/100g dry solid much greater energy was consumed, which was assessed to be practically infeasible and thus not tried in optimization. At higher carotenoids retention level the recycle ratio of exhaust air becomes low and air flow rate takes high value, which results in short total drying time and large energy consumption. At lower quality constraint of no constraint to 95 mg/100g dry solid, air temperature rises to the upper limit of 80°C, recycle ratio of air

Table 1. Optimal operating conditions of time invariable red pepper drying satisfying carotenoids retention constraint when drying is done in fixed bed trays.

Carotenoids retention constraint[a] (mg/100g dry solid)	Optimal control variables			Total drying time (hr)	Energy consumption (kJ/kg water evaporated)
	Air temperature (°C)	Air recycle ratio	Air flow rate ($m^3/min.m^2$)		
No constraint	76.6	0.992	21.2	59.8	5122
70	75.7	0.979	23.3	38.4	5179
95	79.4	0.976	42.1	23.9	5290
120	78.2	0.945	35.1	23.2	5468
145	77.2	0.929	42.9	20.0	5646
170	78.5	0.865	48.1	16.4	6144
195	75.1	0.569	49.9	16.2	8480

a) Initial carotenoids; 370 mg/100g dry solid decreases and air flow rate increases with strictness of quality constraint. This range of quality constraints seems to affect the optimization little. Therefore high limit temperature can be used with appropriate combinations of the other control variables. Above this range of constraint, air temperature becomes a little low, and air flow rate takes a little low value and then increases again with increase of constraint level. Basically energy is consumed less when drying is undertaken in long time with optimized high recycle ratio with proper combination of air temperature and air flow rate. Quality constrainst seems to restrict the total drying time which is shortened by low recycle ratio and high air flow rate.

It should be noted that air temperature in Table 1 is inlet temperature to the dryer plenum. The temperature of air flowing though the bed of trays decreases with temperature equilibrium and moisture evaporation. Thus change of inlet air temperature influences not greatly on the red pepper temperature of whole trays. Therefore the optimized air temperature does not vary greatly with quality constraints. Even though temperature of around 60 °C is beneficial to the quality of red pepper(3-5), this cannot directly apply to the multilayered drying.

In drying energy consumption is known to be highly affected by the air recycle ratio and be reduced by use of high recycle ratio of air(6,10). But in red pepper drying quality can be maximized at low humidity(5), which can be attained by low recycle ratio. Therefore, the recycle ratio should be restricted when energy consumption is to be minimized under quality constraint. The optimization would give the conditions which possibly maximize air recycle with the use of temperature and air flow both satisfying quality constraint and shortening total drying time.

When optimal time invariable drying of red pepper with carotenoids constraint 195 mg/100g solid was simulated, the moisture, red pepper temperature, carotenoids and energy consumption were given in Fig. 3. There are wide differences in these state variables among the layers during drying. The moisture difference between top and bottom layer enlarges with proceeding of drying and eventually narrows at the final drying. Great difference in the red pepper temperature between bottom and top layer in initial drying stage reduces with completion of drying. This comes from the fact that drying advances from the lower

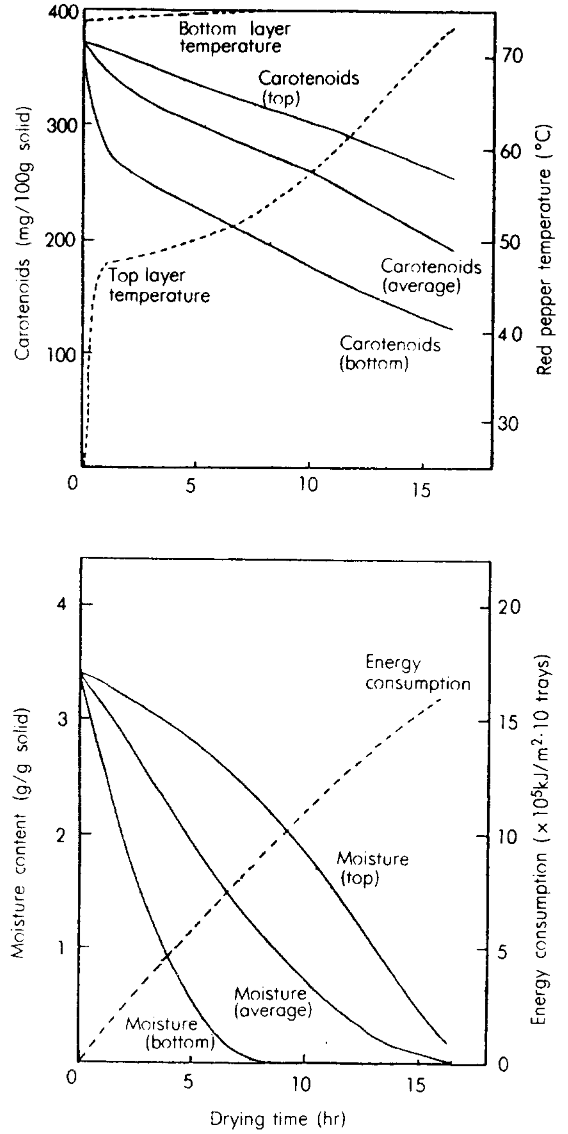

Fig. 3. Changes of state variables during the optimized drying of fixed bed red pepper trays (constraint of carotenoids retention: 195 mg/100g dry solid).

layer to the upper layer. This results in the sharp gradient in the carotenoids distribution among layers. It is reasoned that sharp gradient in moisture lengthens the total drying time to reduce the moisture of top layer to suitable level, thus resulting in large energy consumption and relatively low carotenoids. It is expected that higher quality and lower energy consumption can be attained by mixing red peppers within the dryer. Actually in the farm trays are intermittently exchanged and product in tray is mixed manually during drying of red pepper. Product mixing can also be achieved by proper equipment or fluidization. Therefore product mixing during drying was assumed and optimization was also conducted. The optimized results are summarized in Table 2.

As expected the product mixing can give higher quality and more economized energy consumption compared with non-mixing fixed bed drying. This effect is more pronounced with high quality constraint. The carotenoids retention above 220 mg/100g dry solid may not be possible for the non-mixing fixed bed drying. However it would be readily achieved with reasonable energy consumption by the product mixing. At the carotenoids retentions of 170 and 195 mg/100 g dry solid, product mixing decreases the energy consumptions from 6144 kJ/kg evaporated water and 8480 to 5366 and 5509, respectively (Table 1, 2). These are large energy savings corresponding to 12.7-35.0%. It comes from the possible use of higher recycle ratio and lower air flow rate. This proves that product mixing or tray exchange is crucial to the quality of dried red pepper and energy consumption. It is suggested that the appropriate means be taken for proper mixing of product during drying. Except these points the dependences of optimized control variables, total drying time and energy consumption on the quality constraints are similar to the case without mixing. Analysis of control variables effect would be same as described above in the cases of fixed bed drying.

The optimized air flow rates of Table 1 and 2 are much higher than those of actual practice, which usually are below 10 $m^3/min.m^2$. From results it is suggested that fan of higher power be installed in the presently used dryers for higher air flow rate.

Two stage drying

Optimal time invariable drying shows very high energy consumption under relatively high quality constraint. In order to find possibility of improvement in energy utilization two stage drying was further tried in optimization. Fig. 4 shows the optimal profiles of air temperature and recycle ratio of fixed bed red pepper drying at carotenoids constraint of 195 mg/100g dry solid when drying is done with the optimal air flow of 49.9 $m^3/min.m^2$ in Table 1. The total drying time increases from 16.2 hours of optimal time invariable drying

Table 2. Optimal operating conditions of time invariable red pepper drying satisfying carotenoids retention constraint when product is mixed through the drying

Carotenoids retention constraint[a)] (mg/100g dry solid)	Optimal control variables			Total drying time (hr)	Energy consumption (kJ/kg water evaporated)
	Air temperature (°C)	Air recycle ratio	Air flow rate ($m^3/min.m^2$)		
No constraint	75.3	0.985	15.5	58.8	5129
70	75.9	0.988	24.2	46.0	5149
120	79.6	0.987	47.3	23.0	5205
170	78.9	0.951	31.8	22.3	5366
195	77.6	0.915	27.7	22.9	5509
220	76.5	0.857	31.9	19.7	5828
245	77.4	0.649	38.7	15.4	6956

a) Initial carotenoids; 370 mg/100g dry solid

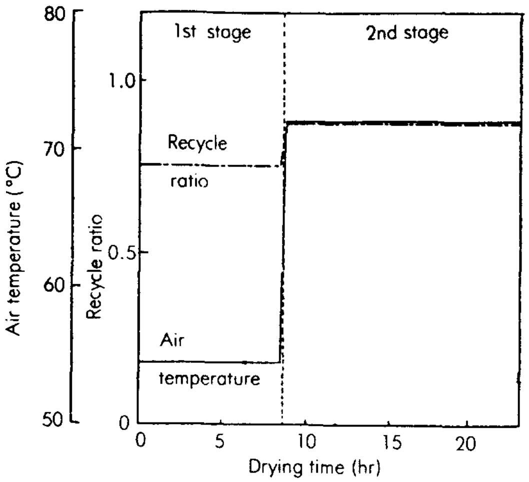

Fig. 4. Optimal profiles of air temperature and recycle ratio in the two stage drying of fixed bed red pepper trays at constant air flow rate of 49.9 m^3/min.m^2 (constraint of carotenoids retention: 195 mg/100g dry solid).

to 23.2 hours with step changing at 8.6 hours after start, which locates at about one third of the total drying time. Air temperature of 54.5 °C in the first stage rises to 72.1 °C and air recycle ratio of 0.76 increases to 0.88 in the second stage. Two stage drying adopts higher recycle ratio and longer total drying time than time invariable drying taking advantage of stagewise application of air temperature, which lowers energy consumption under the same quality retention. In the two stage drying at the same constraint energy consumption can be reduced from 8480 kJ/kg evaporated water of time invariable single stage drying to 6112 kJ/kg, which corresponds to 28.0% energy saving. This shows that stagewise operation of the red pepper dryer itself can improve the energy utilization in the drying of fixed bed trays considerably. As in the drying of the thin layer red peppers of Lee *et al.*(5) two stage drying of fixed bed trays could also give higher carotenoids retention than time invariable operation.

Lee *et al.*(5) have reported that for quality optimization of bistaged drying of red pepper air temperature should take low value at the first stage and higher value in the second stage both under low limit humidity. When the results of Lee *et al.*(5) are analyzed together with the above trend of control variable change in Fig. 4, it is reasoned that two stage drying can not only relax the quality constraint, but also reduce energy consumption by adopting the temperature profile improving carotenoids retention with reasonable high recycle ratio. In order to further investigate this the optimized two stage drying of Fig. 4 was simulated as in Fig. 5. When comparing with Fig. 3 variations in state variables among layers becomes markedly small with the extension of the drying period. In the first stage low temperature and relatively low recycle make moisture removal proceed smoothly with red pepper temperature maintained low in order to suppress the carotenoids destruction, whose rate is high at high moisture(9). In the second stage where the moistures of lower layers decrease below around 2.0 g water/g solid the applied high air temperature and a little higher recycle ratio reduce the moistures of upper layers sharply to the final dryness. Even though temperature of bottom layer is high in this stage, carotenoids retention is not affected so much probably because of relative inertness of carotenoids destruction at low moisture content(9). Energy consumption increases a little sharply in the latter stage following the average moisture removal pattern.

Stagewise drying optimization was also tried in the case of assumed product mixing. The optimal profiles of control variables under carotenoids constraint of 245 mg/100 dry solid and fixed optimal air flow of 38.7 m^3/min.m^2 are shown in Fig. 6. With step changing at the drying time of about one third of total drying time the trend of control variable change in product mixing is similar to Fig. 4 in drying of fixed bed trays, but higher air temperature and a little higher recycle ratio are used even for higher quality constraint. Two stage drying with product mixing lengthens the total drying time with reduction of energy consumption from 6956 kJ/kg water evaporated to 6503 kJ/kg compared with time invariable optimal drying in Table 2. This is 6.5% energy saving. Lower caro-

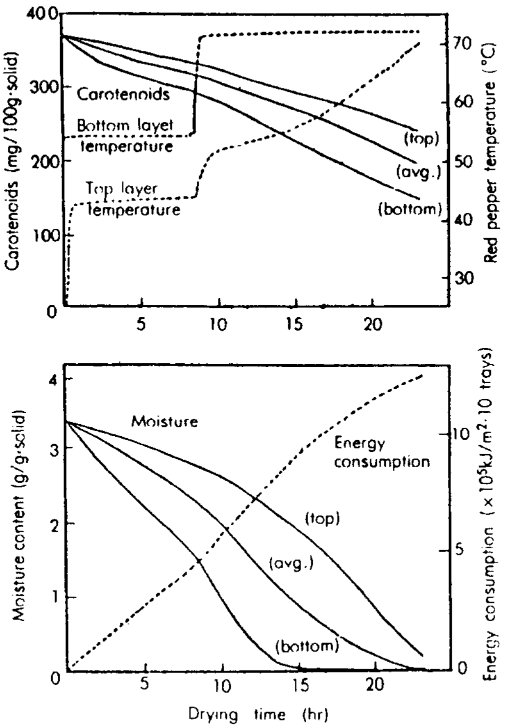

Fig. 5. Simulated state variables during the optimized two stage drying of fixed bed red pepper trays at constant air flow rate of 49.9 m^3/ min.m^2 (constraint of carotenoids retention: 195 mg/ 100g dry solid).

tenoid constraints were also tried in optimization and produced much lower energy saving. In these cases the trends of control variable change were the same as in Fig. 6 but with a little higher temperature and higher recycle ratio than those for higher carotenoids retentions. When the air flow rate below 10 m^3/min.m^2 was used, high carotenoids could not be obtained. The optimized energy consumption under lower retention of 220 mg/100g dry solid was not improved compared with that of optimal time invariable drying in Table 2. This again emphasizes the importance of air flow rate, which needs to be increased from the presently used one. Due to the change of control variables of Fig. 6 in the optimized two stage drying of product mixing, simulated moisture and carotenoids decrease slowly in the first stage and a little sharply in the second stage as shown in Fig. 7. Energy consumption seems to increase proportionally to the moisture removal.

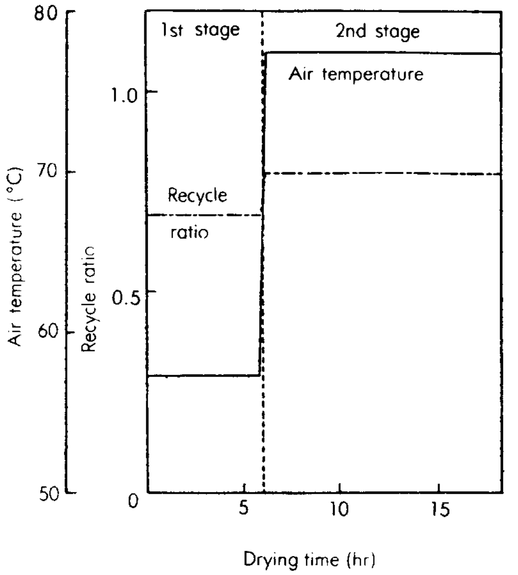

Fig. 6. Optimal profiles of air temperature and recycle ratio in the two stage red pepper drying at constant air flow rate of 38.7 m^3/min·m^2 when product is mixed through the drying (constraint of carotenoids retention: 245 mg/100g dry solid).

Conclusively product mixing is essential for the good quality red pepper in practical drying equipment. Two staged operation at constant optimal air flow rate can improve the energy efficiency appreciably with satisfying proper high quality retention. The advantage of staged operation is more pronounced in the drying of fixed bed trays. As for the control variable change the air temperature should be low at the first stage and increase to high value at the second stage starting at about one third of total drying time. Recycle ratio of air should be relatively low at first stage and then increase a little high for energy saving. For efficient utilization of dryer and proper quality retention the presently used air flow rate is assessed to need to be increased somewhat in both the time invariable optimal operation and optimized staged operation.

Our optimized results involve the valuable schemes of dryer operation which save the energy consumption and produce the required quality.

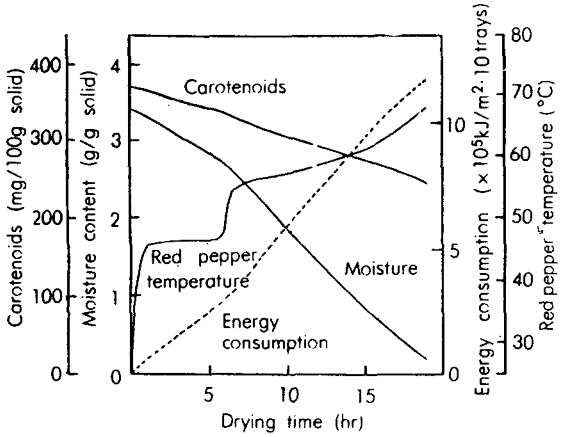

Fig. 7. Simulated state variables during the optimized two stage red pepper drying at constant air flow rate of 38.7 $m^3/min.m^2$ when product is mixed through the drying (constraint of carotenoids retention: 245 mg/100g dry solid).

These were accomplished from combination and application of the proper drying and quality destruction models confirmed by various authors$^{(7-9)}$. Established schemes themselves would be able to be used as a guideline for the dryer operation. However for the higher reliableness experimental confirmation of our simulation and optimization results is needed and suggested.

Nomenclature

C : Carotenoid concentration (mg/100g dry solid)
C_a : Specific heat of dry air (kJ/kg.K)
C_v : Specific heat of water vapor (kJ/kg.K)
C_p : Specific heat of wet red pepper (kJ/kg.K)
C_{pex} : Humid heat of exhaust air (kJ/kg dry air)
C_{pam} : Humid heat of ambient air (kJ/kg dry air)
C_{pmix} : defined by equation (11)
C_1 : $R_1(1 + m_o)C_p$
C_2 : $R_1(1 + m_f)C_p$
E : energy consumption (kJ)
E_{ac} : Activation energy of carotenoid destruction (cal/mol)
G : mass flow rate of air (kg dry air/min)
G_o : Food temperature before drying (°C)
H_o : Absolute humidity of input air (kg water/kg dry air)
H_f : Absolute humidity of output air (kg water/kg dry air)
H_{ex} : Absolute humidity of exhaust air (kg water/kg dry air)
H_{am} : Absolute humidity of ambient air (kg water/kg dry air)
H_{mix} : Defined by equation (12)
ΔH : H_f-H_o
i_g : Enthalpy of saturated water vapor at 0°C (kJ/kg water)
k : Rate constant of carotenoids destruction (min^{-1})
k_o : Frequency factor in carotenoids destruction (min^{-1})
m : Moisture (kg water/kg dry solid)
m_e : Equilibrium moisture content (kg water/kg dry solid)
m_o : Moisture content before drying (kg water/kg dry solid)
m_f : Moisture content after drying (kg water/kg dry solid)
R : Gas constant, 1.987 cal/mol.K
R_1 : Ratio of dry food to air flow (kg dry food/kg dry air)
r : Recycle ratio of exhaust air, decimal
RH : Relative humidity, decimal
t : Time (min. or hr.)
T_{db} : Drying air temperature (°C)
T_e : Equilibrium temperature (°C)
T_o : Air temperature before drying (°C)
T_s : Food or air temperature after drying (K or °C)
T_{am} : Ambient air temperature (°C)
T_{ex} : Temperature of exhaust air (°C)
T_{in} : Inlet air temperature into the dryer plenum (°C)
T_{mix} : Defined by equation (10)
λ : Latent heat of water (kJ/kg)

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(Received July 20, 1989)

고추건조기의 최적운전조건

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농가에서 현재 사용되고 있는 고추건조기의 운전조건을 고추의 건조 모델과 품질변화 모델을 수치해석적 최적화방법인 Box의 complex 방법과 연결하여 최적화를 시도하였다. 주어진 carotenoids 보존을 만족시키는 제한조건 하에서 에너지소비를 최소화하기 위한 열풍온도, 열풍재순환율, 풍량이 결정되었다. 품질제한조건이 엄격할수록 낮은 열풍재순환율과 높은 풍량이 사용되어 에너지소비는 증가하고 전체 건조시간은 짧아졌다. 건조 중 건조기내에서의 고추의 혼합이 에너지 사용효율과 제품품질을 향상시킬 수 있었다. 현재 사용되고 있는 풍량은 최적운전을 위해서는 증가되어야 하는 것으로 판단되었다. 풍량을 일정하게 적정조건으로 고정하고 열풍의 온도와 재순환율을 2단계로 변화시키는 건조방식이 에너지소비를 더욱 감소시킬 수 있었다. 이러한 2단계 최적건조에서는 단계이동은 전체 건조시간의 약 1/3 부근에서 이루어지고 열풍온도는 첫단계에서 낮다가 두번째 단계에서 증가하고 열풍재순환율은 단계변화에 따라 약간 증가하였다. 얻어진 최적제어변수는 건조기내에서의 건조과정과 carotenoids 파괴 kinetics에 의하여 해석될 수 있었다. 얻어진 결과의 실험적 확인이 요청된다.