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Algorithms for automated temperature controls to cure peanuts☆

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Abstract

The introduction of affordable control networks for peanut dryers has made it possible to easily vary the curing temperature based on ambient air conditions. Previous research has used ambient temperature, relative humidity, and humidity ratio as possible control parameters. Peanuts from the same field were cured using four 0.11 m^3 dryers to a moisture content of approximately 0.11 kg kg^{-1}. Four different algorithms, one for each dryer, were used to calculate the desired plenum temperature based on ambient conditions. They were: (1) conventional control (CC); (2) drying rate control (DRC1); (3) modified drying rate control (DRC2); and (4) relative humidity control (RHC). Peanuts cured significantly faster (0.42 kg h^{-1}) using DRC2 compared to peanuts cured using DRC1 (0.23 kg h^{-1}), RHC (0.29 kg h^{-1}), and CC (0.35 kg h^{-1}). Curing with DRC2 was not significantly faster than with CC (0.60% h^{-1}). No significant differences in milling quality, as indicated by percent splits, percent bald kernels, and shelled stock value, were found due to drying treatments. The percent split kernels averaged 9.8% over all temperature control methods and ranged from 8.7 to 10.2%. Shelled stock value ranged from 959.89 to 978.74 US$ t^{-1}. Peroxide values and free fatty acids were acceptable for all curing treatments and were not significantly different. Seed germination ranged from 83 to 87%, but was not significantly different. Flavor ratings determined by a flavor panel on a scale from 1 to 8, with 6 being acceptable and 8 being the best, were all greater than 7.1. Historical weather data from Dawson, GA indicated that DRC2 would result in a higher plenum temperature. These tests indicated that maximum recommended drying rates may be too conservative for efficient operation of commercial operations.

Keywords: Peanut; Curing; Drying; Controls; Milling quality

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1. Introduction

In the southeastern U.S., peanuts are usually allowed to partially cure in the windrow for 3–7 days, then harvested and placed in drying wagons with a perforated plenum floor. Each 4–6 t load is mechanically cured by forcing heated air up through the 1.5 m deep bed of peanuts until the moisture content of the peanut kernels is less than 0.11 kg kg^{-1}. Young et al. (1982) presented optimum plenum conditions for curing peanuts (Fig. 1). Temperatures in excess of 35 °C were shown to increase the risk of the development of off-flavor (Whitaker and Dickens, 1964) and removing moisture too rapidly increased the incidence of split kernels and loose skins (Beasley and Dickens, 1963; Troeger, 1989). The current recommendation for heating air 8–11 °C above ambient not to exceed 35 °C (Samples, 1984; Cundiff et al., 1991) is a practical implementation of this research. Butts (1996) manually controlled plenum temperatures to maintain a plenum relative humidity between 40 and 60%. Drying time increased 56% and energy consumption decreased 30% compared to conventional constant setpoint controls. Labor availability for commercial peanut drying facilities would prohibit manual manipulation of individual thermostat settings. Steele (1982) developed and implemented a microprocessor temperature control system for curing peanuts in Virginia that increased peanut drying time 10% and reduced consumption of liquified petroleum gas (LPG) and electricity by 49 and 33%, respectively, compared to conventional dryer controls. However, the complexity of the hardware and software prevented commercial adaptation of the technology. Baker et al. (1993) used regression analysis to fit three separate line segments to the upper limit of the preferred curing zone specified by Young et al. (1982). Using this DRC in Virginia reduced percent skin slippage approximately 30% with similar curing times and fuel costs as CC. Butts et al. (1998) reduced the DRC used by Baker et al. (1993) to a single equation (Fig. 1) and used a microprocessor to control a commercial peanut dryer. Under typical

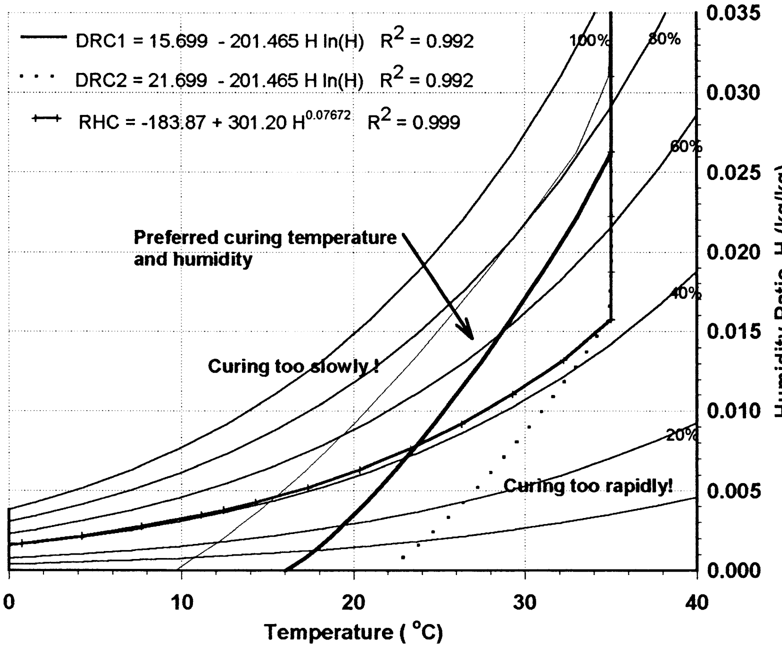

Fig. 1. Psychrometric chart showing preferred air conditions for curing peanuts (adapted from Young et al., 1982) and three temperature control algorrithms, DRC1, DRC2, and RHC.

weather conditions experienced in south Georgia during the peanut harvest, the plenum temperature remained fairly constant (± 2 °C) throughout any 24-h drying cycle.

The purpose of this research was to determine the optimum peanut curing temperature control algorithm to minimize drying time and detrimental effects on resulting peanut quality.

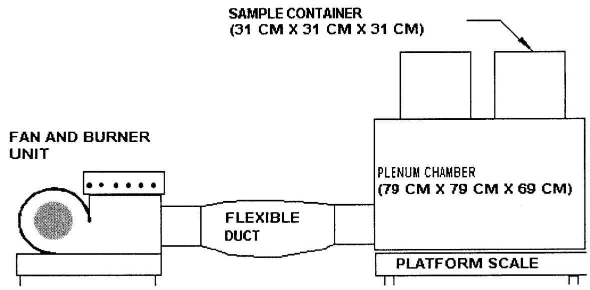

Fig. 2. Schematic of experimental-drying equipment.

2. Materials and methods

2.1. Algorithm description

Based on previous research (Baker et al., 1993; Butts, 1996; Butts et al., 1998) and conventional drying practice, four algorithms to control dryer temperature were developed. They were:

1. CC: $T_p = T_a + 8$ °C, ≤ 35 °C
2. DRC1: $T_p = 15.699 - 201.46H \ln(H)$, ≤ 35 °C
3. DRC2: $T_p = 21.699 - 201.46H \ln(H)$, ≤ 35 °C
4. RHC: $T_p = -183.867 + 301.20H^{0.07672}$, ≤ 35 °C

where: T_p is plenum air temperature (°C); T_a is ambient air temperature (°C); H is humidity ratio of ambient air (kg kg^{-1}).

CC is the method for determining the thermostat set point recommended in all peanut producing areas of the U.S. DRC1 is a regression fit to the upper limit of the preferred curing zone recommended by Young et al. (1982) shown in Fig. 1. Due to excessively slow curing in commercial applications (Butts et al., 1998), DRC1 was increased by 6 °C to obtain DRC2 for these tests. RHC is the temperature to which ambient air may be heated to achieve 45% relative humidity in the dryer plenum.

Five years of hourly weather data collected at Dawson, GA between 1995 and 1999 were analyzed to determine the expected plenum temperatures using each of the four control algorithms. Data from August through October each year were used in the analysis to correspond with the typical harvest in the southeastern U.S.

2.2. Drying test procedure

To determine the effect of each control algorithm on drying time and the resulting peanut quality, runner type peanuts (*Arachis hypogea* L.) were cured in laboratory scale dryers (Fig. 2). Peanut (*Arachis hypogea* L.) cultivar Georgia Green, grown by cooperating producers, were dug and allowed to partially cure in the windrow according to conventional practice. After windrow curing, peanuts were harvested and approximately 140–160 kg of peanuts were collected and divided into four, 35- to 40-kg subsamples. Each 40-kg subsample was poured into four, $31 \times 31 \times 31$ cm drying boxes and placed on a sample dryer (Fig. 2). This was repeated until all four 40-kg subsamples were on separate dryers. The initial moisture content was determined for the peanuts on each dryer. All dryers were started simultaneously and operated until the peanuts on that dryer reached the desired cutoff moisture content of 0.11 kg kg^{-1}. Each of the four dryers used a different one of the control algorithms previously described.

The peanuts cured from each bin on a dryer were transferred into separate mesh bags, labeled, and stored. Each sample was approximately 10 kg. As each batch was completed, the 16 10-kg samples from each batch were stacked on a pallet and held an average of 45 days until all drying tests had been completed. The average hourly temperature during the storage period was 18 °C and ranged from 13 to 32 °C. The relative humidity averaged 72% and ranged from17 to 100%. Samples were cleaned and shelled using a laboratory scale rotary sheller (McIntosh et al., 1971).

Peanut kernels were sized into five commercial categories for shelled runner peanuts: jumbo, medium, number 1, splits, and oil stock. 'Bald' kernels were manually sorted from the whole kernel market sizes (jumbo, medium, and number 1). A 'bald' kernel is a peanut kernel with more than 25% of the testa, or skin, removed during shelling and handling. A high percentage of bald kernels indicates excessive rates of moisture removal (Beasley and Dickens, 1963). The whole kernels were recombined and a 0.5-kg sample removed and analyzed for seed germination. A second 0.5-kg sample was removed and analyzed for peroxide values (Kelrich, 1990) and flavor by a commercial quality assurance laboratory. Peroxide values are indicators of storability or shelf life of peanuts and peanut products (Sanders et al., 1982) and tend to increase during storage especially under poor storage conditions (Sanders et al., 1995). Flavor was scored on a scale from 1 to 8 by a four-member taste panel. Ratings below 6 are generally unacceptable.

Data were analyzed by standard analysis of variance procedures. Least significant difference was used to show differences among means tested at the $P = 0.05$ level of probability when ANOVA F-test showed significance.

2.3. Equipment and controls

Each dryer unit consisted of a 79 cm × 79 cm × 69 cm plenum chamber with four 30 cm × 30 cm outlets. A centrifugal fan (Dayton Model 1C792) and LPG burner unit forced heated air up through the four boxes placed on the plenum (Fig. 2). Each fan supplied approximately 125–150 $m^3\ min^{-1}\ m^{-3}$. Each plenum was set on an electronic platform scale with a digital readout capable of serial communications. A four-junction thermopile constructed of ANSI Type T thermocouple was installed in each plenum to monitor air temperature in the plenum.

A programmable logic controller (PLC) controlled the temperature of each dryer. The PLC monitored and recorded ambient temperature (T_a), relative humidity (RH_a), plenum temperature (T_p), and mass of peanuts in each dryer. A PLC coprocessor module running BASIC calculated the desired plenum temperature for each of the four dryers based on one of the temperature control algorithms discussed earlier. The PLC coprocessor also performed the serial communications with the scales and a personal computer (PC). The PC was used to record the temperature, humidity, and mass data at a 15-min interval.

Initial moisture content was determined using an electronic moisture meter (Dickey-john, GAC II) and the oven method (ASAE, 1997). The PLC controlled dryer plenum temperatures and monitored the mass of peanuts while curing. Based on the initial kernel moisture content determined by the electronic moisture meter, the water loss necessary to reach a final kernel moisture content of 0.11 kg kg^{-1} was calculated. When the desired weight loss had occurred, the PLC automatically turned off the burner and the fan. A final moisture content was determined using the moisture meter and the oven method. All moisture contents reported are those determined using the oven method.

3. Results and discussion

Plenum temperatures calculated from historical weather data for Dawson, GA using the four temperature control algorithms were significantly different (Table 1). All temperature control methods resulted in dryer set point temperatures significantly greater than ambient. There were significant differences in set points among all control methods for every month, except during the month of September. The average hourly set point during September determined by CC and RHC were not significantly different. DRC2 resulted in the highest plenum temperature in each of the 3 months analyzed and over the entire drying season. The DRC2 plenum temperature averaged 32.6 °C, approximately 10 °C above ambient. DRC1 had the lowest average set point at 27.4 °C with an average 5 °C rise above ambient. Plenum temperatures calculated using both drying rate control methods, DRC1 and DRC2, had lower standard deviations than the ambient temperature and plenum temperatures calculated using RHC and CC. The air tends to get cooler and drier as the harvest season progresses from August through October. This trend is indicated by the decreased monthly average temperature from 26 to 18 °C and the decreased humidity ratio from 0.015 to 0.010 kg kg^{-1} from August to October.

Tests using the four temperature control algorithms were repeated six times between 17 September 1998 and 20 October 1998. Ambient temperatures during the drying tests (Table 2) averaged 26.6 °C and were slightly higher than the 5-year average data. The average absolute humidity during the tests was 0.0134 kg kg^{-1} and was within the range normally observed during September.

The average initial moisture content (oven) ranged from 0.309 to 0.317 kg kg^{-1} while final moisture contents ranged from 0.118 to 0.128 kg kg^{-1} (Table 2). In general, temperature set points for CC and DRC2 were greater than ambient temperature throughout each test cycle (Fig. 3). Set point temperatures for DRC1 and RHC were greater than ambient temperatures except for a period between 11:00 and 18:00 h. During that period, the ambient temperature was higher than the set point, therefore no heat was added. Set point temperatures for DRC1 and DRC2 were more stable throughout the curing cycle than those using CC and RHC. Set point temperatures for DRC1 and DRC2 varied by approximately 6 °C over the 4-week test period. The RHC set point varied 14 and 8 °C for CC. The average plenum temperatures over all tests ranged from 27.5 °C for DRC1 to 32.2 °C for DRC2. The average plenum temperatures for CC, DRC2, and RHC were not significantly different ($P \leq 0.05$). However, they were approximately 4 °C higher than the plenum temperature using DRC1. The average plenum relative humidity for DRC1 (57%) was significantly higher than for CC (47%), DRC2 (43%) and RHC (44%).

Peanuts cured using DRC1 had the longest average curing time of 30 h which was 57% longer than CC (Table 2). The average curing time for peanuts cured using RHC was 36% longer than CC. DRC2 cured peanuts 8% faster than CC. Moisture removal rates were calculated by dividing the difference between the initial weight and final weight by the elapsed time from dryer start to dryer stop as recorded by the PLC. The moisture removal rate ranged from 0.23 kg h^{-1} for DRC1 to 0.42 kg h^{-1} for DRC2. The average moisture removal rate for DRC2 was not significantly different from the 0.35 kg h^{-1} moisture removal rate using CC. However, it was significantly faster than 0.29 kg h^{-1} using RHC.

The airflow rate provided in the laboratory dryers (125–150 m^3 min^{-1} m^{-3}) exceeds the minimum recommended airflow rate for commercial

Table 1
Average ambient conditions and expected plenum temperatures[a] using hourly data at Dawson, GA from 1995 through 1999

	August		September		October		Season	
	Mean[b]	S.D.	Mean[b]	S.D.	Mean[b]	S.D.	Mean[b]	S.D.
Ambient Conditions								
Temperature (°C)	25.9a	4.1	23.5a	4.5	18.4a	5.7	22.6a	5.7
Rel. humidity (%)	75.5	18.1	72.8	20.5	72.9	20.2	73.8	19.7
Humidity ratio (kg kg^{-1})	0.015	0.002	0.013	0.003	0.010	0.003	0.013	0.004
Dryer set point								
CC (°C)	32.8b	2.3	31.1b	3.5	26.7b	5.6	30.2b	4.8
DRC1 (°C)	29.5c	1.9	27.9c	2.4	24.9c	2.6	27.4c	3.0
DRC2 (°C)	34.3d	1.0	32.9d	1.8	30.7d	2.6	32.6d	2.4
RHC (°C)	33.4e	1.8	31.2b	3.4	26.1e	5.8	30.4e	5.2

[a] Dryer control: conventional control (CC): $T_p = T_a + 8$ °C, ≤ 35 °C; drying rate control (DRC1): $T_p = 15.699 - 201.46H \ln(H)$, ≤ 35 °C; modified drying rate control (DRC2): $T_p = 21.699 - 201.46H \ln(H)$, ≤ 35 °C; relative humidity control (RHC): $T_p = T(RH_p = 45\%)$, ≤ 35 °C.

[b] Temperatures in the same column followed by the same letter are not significantly different at the $P \leq 0.05$ level.

Table 2
Summary of automated peanut dryer performance using four different temperature control algorithms

Parameter	Dryer control[a]				LSD
	CC	DRC1	DRC2	RHC	
Ambient temperature (°C)	26.7a	26.6a	26.6a	26.6a	0.6
Ambient relative humidity (%)	61.1a	60.2a	61.0a	59.8a	1.6
Ambient humidity ratio (kg kg^{-1})	0.0136a	0.0134a	0.0136a	0.0133a	0.0003
Plenum temperature (°C)	31.0a	27.5b	32.2a	31.8a	2.4
Plenum relative humidity (%)	48.7a	56.8b	43.7a	43.7a	6.2
Initial moisture content (kg kg^{-1})	0.317a	0.309a	0.311a	0.310a	0.012
Final moisture content (kg kg^{-1})	0.125a	0.128a	0.118a	0.118a	0.015
Curing time (h)	19.7a	30.4b	17.6a	24.3ab	10.2
Moisture removal rate (kg h^{-1})	0.35ab	0.23c	0.42a	0.29bc	0.12

Dryer control: conventional control (CC): $T_p = T_a + 8$ °C, ≤ 35 °C; drying rate control (DRC1): $T_p = 15.699 - 201.46H\ \ln(H)$, ≤ 35 °C; modified drying rate control (DRC2): $T_p = 21.699 - 201.46H\ \ln(H)$, ≤ 35 °C; relative humidity control (RHC): $T_p = T(RH_p = 45\%)$, ≤ 35 °C

[a] Values in the same row followed by the same letter are not significantly different at the $P \leq 0.05$ level of significance.

dryers of 10–15 $m^3\ min^{-1}\ m^{-3}$ ten-fold. These excessive airflow rates ensure that airflow is not the rate-limiting factor in these drying tests. Rather moisture migration within the peanut itself and drying air temperature become rate-limiting in the drying process. These airflow rates are high enough that the drying air does not become saturated. Therefore, moisture removal rates should be higher than those expected in a commercial application and should accentuate any quality differences caused by excessive drying rates.

Shelled peanut quality as indicated by the shelled kernel size distribution was not significantly different. The percent medium-sized kernels was the only size category that had significant differences among curing treatments (Table 3). DRC1 had 30.7% medium-sized kernels compared to 28.6 and 28.9% for CC and DRC2, respectively. The percent medium-sized kernels obtained from samples cured using RHC (29.8%) was not significantly different from the other control methods. The percent of split kernels obtained using all methods averaged 9.8% and were not significantly different. Average percent split kernels ranged from 8.7 to 10.2%. Bald kernels average 0.55% with no statistically significant differences due to temperature algorithms. The value per ton of peanuts was determined by multiplying the 5-year running average price and the percent of kernels of each size category of shelled peanuts. No significant differences in shelled stock value were observed. Similarly, no significant differences in seed germination rates due to temperature control algorithms were detected (Table 3).

Curing has been shown to influence oxidative stability of the lipid profile of peanuts (Pickett and Holley, 1960). Increased peroxide values are indicative of lipid oxidation during storage (Sanders et al., 1982). The peroxide values in these tests were measured approximately 3–4 months after curing (Table 3). The peroxide values for all temperature control regimes indicated no signifi-

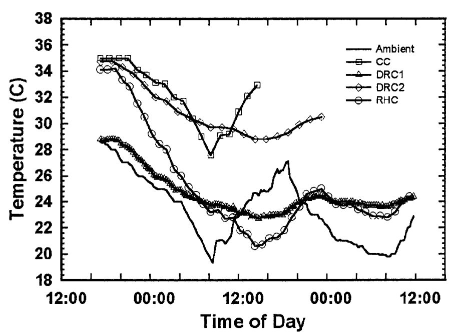

Fig. 3. Typical set point temperatures during 1998 peanut curing studies using four algorithms, conventional control (CC), drying rate control 1 (DRC1), drying rate control 2 (DRC2), and relative humidity control (RHC).

Table 3
Summary of automated peanut dryer performance using four different temperature control algorithms

Kernel size	Dryer control[a]				LSD
	CC	DRC1	DRC2	RHC	
Jumbo (%)	22.2a	22.6a	21.4a	21.3a	1.6
Medium (%)	28.6a	30.7b	28.9a	29.8ab	1.6
No. 1 (%)	6.3a	5.8a	5.8a	5.7a	1.1
Splits (%)	10.2a	8.7a	10.1a	10.2a	1.6
Oil stock (%)	9.3a	8.6a	9.9a	9.5a	1.8
Bald kernels (%)	0.6a	0.4a	0.6a	0.6a	0.3
Shelled value (US$ t^{-1})	972.79a	978.74a	959.89a	968.82a	23.24
Germination (%)	84.1a	87.3a	83.3a	82.8a	2.9
Flavor rating (1–8)	7.1a	7.3b	7.2ab	7.2ab	0.2
Peroxide value (cmol kg^{-1})	0.019a	0.015a	0.014a	0.019a	0.010

Dryer control: conventional control (CC): $T_p = T_a + 8$ °C, ≤ 35 °C; drying rate control (DRC1): $T_p = 15.699 - 201.46H \ln(H)$, ≤ 35 °C; modified drying rate control (DRC2): $T_p = 21.699 - 201.46H \ln(H)$, ≤ 35 °C; relative humidity control (RHC): $T_p = T(RH_p = 45\%)$, ≤ 35 °C.

[a] Values in the same row followed by the same letter are not significantly different at the $P \leq 0.05$ level of significance.

cant lipid oxidation. Therefore, none of the control regimes affected storability.

Average flavor ratings for all control method were greater than 7.0 which is above the minimum acceptable rating of 6. Flavor for peanuts cured using DRC1 rated slightly higher (7.3) than those cured using CC. The flavor rating for DRC1 was not significantly different than peanuts cured using DRC2 or RHC.

4. Conclusions

Four different temperature control algorithms were tested for their effect on moisture removal rate and subsequent peanut quality. All algorithms were based on ambient conditions and had a 35 °C upper limit. The DRC1 was based on peanut curing research conducted primarily in the Virginia–Carolina peanut growing region of the United States. DRC2 controlled 6 °C higher than DRC1. Peanuts cured using DRC1 took longer to dry than those cured using RHC, CC, and DRC2. No significant differences in peanut milling quality were detected. Based on analysis of historical temperature data, using the DRC2 algorithm in the southeastern U.S. would consistently implement higher dryer temperatures compared to the conventional control methods, thus increasing drying rates. Based on laboratory tests, using DRC2 would have minimal impact on peanut quality. Since DRC2 results in a higher plenum temperature, fuel consumption may be higher than for the other control algorithms. However, the higher fuel consumption rate may be offset by decreased curing times. Simulation studies using historical weather data from each peanut producing region of the U.S. could determine dryer performance under the different temperature control regimes discussed here.

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