

# THEORETICAL RATES OF FLOW OF AIR AT NEAR-AMBIENT CONDITIONS REQUIRED TO DRY RAPESEED

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Tentative guidelines for the design and operation of systems for drying rapeseed with air at near-ambient conditions in the Canadian Prairies were developed using mathematical simulations. Drying from three initial moisture contents; 11, 13 and 15% wet mass basis and three harvest dates; 15 Aug., 1 and 15 Sept. were simulated with 15 yr of weather data for four locations. Predicted rates of airflow required to dry the top layer of a bin of rapeseed to 10% within 15–20 days were lowest for Swift Current followed by Winnipeg, Fort St. John and Edmonton. By allowing drying to continue to 31 Dec., required airflows are reduced by 30–40%. Suspension of drying when the mean moisture content of the grain bulk is 10% rather than all grain below 10% can reduce energy consumption by 30–60%.

## INTRODUCTION

### Purpose

The most important decision in designing ventilation systems to dry grain with air at near-ambient conditions is to select the rate of airflow. Tentative guidelines for this selection have been developed for drying wheat and corn in Canada (Fraser and Muir 1981). The purpose of this project was to develop tentative guidelines for the drying of rapeseed in western Canada with air at near-ambient conditions.

### Problem

In Canada during 1972 to 1981 the average annual production of rapeseed was 2 Mt, worth about 430 million dollars to farmers each year (Anonymous 1982). Frequently freshly harvested rapeseed is stored in farm bins at moisture contents conducive to fungal growth and infestation by mites. Both types of pest organisms can readily grow at water activities above 0.65–0.70 (Beuchat 1978; Sinha et al. 1981) which is equivalent to a moisture content in rapeseed of about 8% at 15–35°C (Pixton and Henderson 1981). In Canada, rapeseed is stored at moisture contents higher than 8% because of such factors as: (i) the maximum moisture content for straight grade is set at 10% by the Canadian Grain Commission; (ii) mechanical damage and shelling losses during combining decrease with increasing moisture content of the crop and (iii) much of the rapeseed is grown in northern regions where weather conditions at harvest frequently do not result in complete drying of the crop in the field.

One method of drying is to blow atmospheric air at near-ambient conditions through the stored crop. Fraser and Muir (1980, 1981) showed that selecting the lowest airflow required to dry the grain

resulted in the lowest fixed and variable costs. In selecting this minimum airflow the system designer must determine the acceptable grain spoilage in those years having poor drying weather. Factors influencing spoilage include initial moisture content, date of harvest, daily temperature and relative humidity of the ambient air and fan control method. Because of the number and range of these variables and the possibility of numerous interactions among them it is economically impractical to develop guidelines by experimental procedures only. The only feasible method is to simulate the drying and deterioration processes in the ventilated rapeseed by repetitive calculations of mathematical models on a digital computer.

### Scope

Simulations described in this paper have been conducted so as to give designers some practical preliminary guidelines until better models can be developed. The designer or operator must modify these guidelines according to his knowledge of other major factors such as deterioration of the grain before harvest, nonuniformity of airflow through the grain and possible changes in future weather conditions.

Components of the model were developed from previous experimental and mathematical work and the completed model was compared with data collected from one rapeseed drying experiment.

Simulations were made following the procedure used by Metzger and Muir (1983b) using weather data from four locations across western Canada. The drying of rapeseed harvested at three initial moisture contents — 11, 13 and 15% — on three harvest dates — 15 Aug., 1 and 15 Sept. — were simulated up to 31 Dec.

(Moisture contents are expressed on a wet mass basis except in the equilibrium moisture content equation.) Repeated simulations with different airflow rates were conducted to determine minimum rates of airflow that resulted in the top layer being dried to 10% moisture content without excessive deterioration; (i) in 15–20 days in the median year; i.e. predicted drying times for one-half of the simulated years were greater than 15–20 days with this airflow, or (ii) dried before 31 Dec. in the median year.

## MATHEMATICAL MODEL Simulation Parameters

The mathematical model of wheat storage and ventilation described by Metzger and Muir (1983a) was used in this project. Mathematical relationships for the physical properties and deterioration of rapeseed were developed and inserted into the program. These relationships are described in following sections.

Simulations to predict minimum rates of airflow were based on a circular bin, 5.82 m in diameter filled to a level depth of 4.60 m on a completely perforated floor. The fan was assumed to be centrifugal with the motor not in the air stream. Temperature rise of the air was set equal to that calculated for isentropic compression (Metzger et al. 1981). Moisture contents were simulated for 10 equal layers and 1-h time increments. Hourly weather data stored on magnetic tape were used from four locations (years of data in parentheses): Winnipeg, Manitoba (1961–1978); Swift Current, Saskatchewan (1961–1976); Edmonton, Alberta (1961–1976); Fort St. John, British Columbia (1961–1978). These locations represent the four general climatic regions — Humid Prairie, Semi-arid, Sub-humid and Sub-boreal — which

encompass most of the grain-producing areas of the Canadian Prairies (Putnam and Putnam 1970).

### Specific Heat of Rapeseed

Four different forms of equations were fitted to the specific heat data reported by Moysey et al. (1977). Linear equations determined with the data divided into three sets of temperature and moisture content conditions were:

$$\text{for } t > 0^\circ\text{C and } W < 10\%, (R^2 = 0.71): \\ c = 1290 + 33W + 0.24t \quad (1)$$

$$\text{for } t \leq 0^\circ\text{C and } W \geq 10\%, (R^2 = 0.44): \\ c = 1270 + 34W - 1.33t \quad (2)$$

$$\text{for } t > 0^\circ\text{C and } W > 1\%, (R^2 = 0.87): \\ c = 1265 + 30W + 5.95t \quad (3)$$

where  $c$  = specific heat (J/(kg °C)),  $W$  = moisture content, wet-mass basis (%), and  $t$  = temperature (°C).

This equation form and division of the data resulted in the highest coefficient of determination ( $R^2$ ) for the set of conditions ( $t > 0^\circ\text{C}$  and  $W > 1\%$ ) most frequently applicable in the simulation model.

### Airflow Resistance

Different forms of equations were fitted to the data of Burrell and Armitage (pers. commun.) on the resistance of airflow through bulk rapeseed. Their data covered a range of airflows from 10 to 315 (L/s)/m<sup>2</sup> through rapeseed at a moisture content of 8% and a bulk density of 690 kg/m<sup>3</sup> in a column 0.15 m in diameter and 1.83 m high. The equation with the highest  $R^2$ , 0.998, was:

$$\Delta P = 2.263 F^{1.237} \quad (4)$$

where  $\Delta P$  = pressure drop per unit distance along flow path (Pa/m), and  $F$  = airflow rate ((L/s)/m<sup>2</sup>).

### Equilibrium Moisture Content

Equilibrium moisture content data most relevant to present Canadian rapeseed cultivars was that of Pixton and Henderson (1981) for the desorption of the cultivar Candle in the temperature range 5–35°C and the moisture content range 4–18%. Forms of equations given by Pfost et al. (1976) were compared using a nonlinear regression procedure and the asymptotic correlation matrix of the parameters as the criteria. The equation chosen was:

$$W_d = [\ln(1-RH)/(-C_1t - C_2)]^{C_3} \quad (5)$$

where  $W_d$  = equilibrium moisture content, % dry mass basis, RH = relative humidity, decimal fraction,  $C_1$  = constant = 0.000577,  $C_2$  = constant = 0.0270, and  $C_3$  = constant = 0.6990.

### Deterioration

In developing a deterioration or safe storage life relationship three sets of data were considered. Kreyger (1972) presents storage times until germination drops to 95% during storage at constant temperatures between 5 and 25°C and constant moisture contents between 6.5 and 17%. For rapeseed stored at 5–25°C and 6.7–17% moisture content Burrell et al. (1980) published data on the storage times required for: (i) seed clumps to form, (ii) fungi growth to be visible, and (iii) germination to decrease. Mills and Sinha (1979) present data on the maximum storage life for a limited number of varying conditions between 10 and 40°C and 7 and 12% moisture content.

Different forms of equations including linear, log-log, natural log and log were fit to each of the data sets. The highest correlation coefficients occurred with the following equations and the germination data of Kreyger (1972);

$$\text{for } W < 11\% (R^2 = 0.994): \\ \log \Theta_a = 6.224 - 0.302W - 0.069t \quad (6)$$

$$\text{and for } W \geq 11\% (R^2 = 0.999): \\ \log \Theta_a = 5.278 - 0.206W - 0.063t \quad (7)$$

where  $W$  = moisture content, wet-mass basis (%),  $\Theta_a$  = maximum allowable storage time (days), and  $t$  = temperature (°C).

These equations predict allowable storage times that are much longer than those given by Burrell et al. (1980) for germination decrease and seed clumping. But these equations were chosen because they predict shorter storage times than those measured under Canadian conditions (Mills and Sinha 1980) and are similar to those given by Burrell et al. (1980) for development of visible colonies of fungi.

### DRYING EXPERIMENT

A cylindrical, galvanized steel bin, 4.3 m in diameter, equipped with a fully perforated floor and a 5.4-kW axial-flow fan was used to dry 26 t of freshly harvested rapeseed (cv. Regent) at an initial moisture content of 14.4%. Airflow rate through the rapeseed was 17.7 (L/s)/m<sup>3</sup> measured by a Pitot tube traverse across a plane of an inlet duct attached in front of the fan (Anonymous 1979). Measured temperature of the air as it passed through the fan into the plenum under the rapeseed increased 3.8°C.

Rapeseed samples were obtained with a torpedo probe inserted from the leveled top surface of the bulk which had an initial depth of 2.7 m and a final depth after drying of 2.4 m. Samples were taken along vertical lines 0.1 m and 1.8 m southwest of the center line of the bin. Samples were

taken 11 times at 2- to 4-day intervals during the first 4 wk of drying. Samples were taken monthly for the next 5 mos. Final samples were taken before the bin was emptied on 17 June 1981.

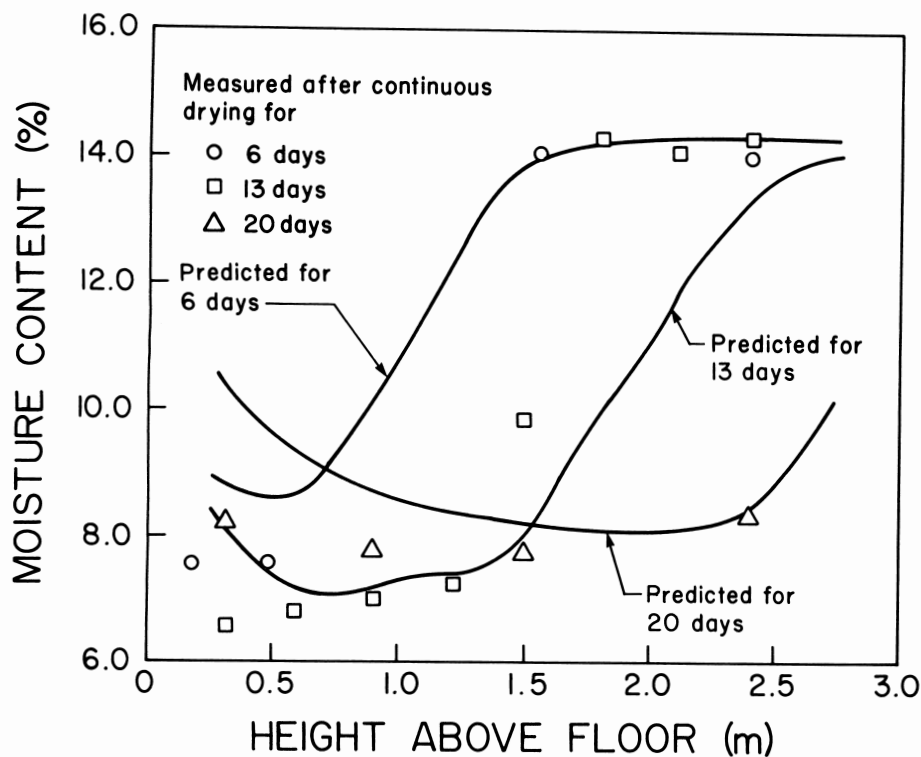
Moisture contents were determined by a whole-seed oven-drying method (Anonymous 1980). Insects and mites were extracted from 300-mL samples placed in Berlese funnels for 24 h. The amount of free fatty acids, expressed as fat acidity values (FAV) were determined using the AACC general method AACC 02-01 (Anonymous 1962). Seed-borne microflora and seed germination were measured by placing 25 randomly selected unsterilized seeds on sterile filter paper saturated with 4.5 mL of sterile water in a petri dish (Wallace and Sinha 1962). Rapeseed samples were graded according to Canadian grading standards and oil content was measured by nuclear magnetic resonance by inspectors of the Canadian Grain Commission, Winnipeg.

## RESULTS AND DISCUSSION

### Comparison of Measured and Predicted Results

The drying front was defined as being where the moisture content of the rapeseed was 11.2% which was the mean of the measured initial and final moisture contents during the drying period. Based on this definition both the measured and predicted times for the drying front to pass through the rapeseed were 20–21 days. Moisture content measurements 9 and 13 days after the start of drying indicated that the drying front near the center of the bin was lagging the drying front near the wall of the bin by about 0.3 m. This suggests that the airflow at the center of the bin was restricted although drying was completed throughout the bin at about the same time. Because the moisture contents measured near the wall are representative of more of the bin than those near the center only those from near the wall are shown in Fig. 1.

The model predicted much more reabsorption during late October, November and December than was measured. With continuous operation of the fan for 53 days the mean measured moisture content was 8.3% compared with the predicted 9.8% for 19 Nov. 1980. After 86 days on 22 Dec. 1980 the mean measured moisture content was still 8.3% ranging from 8.2% at the bottom to 8.5% at the top. The predicted moisture contents ranged from 12.8% at the bottom to 10.9% at the top with a mean of 11.4%. Because measured reabsorption was less than that predicted by the model the minimum airflows predicted by the



**Figure 1.** Measured and predicted moisture contents (wet mass basis) in 26 t of rapeseed dried with a continuous flow of air at near-ambient conditions with an airflow rate of 17.7 (L/s)/m<sup>3</sup>.

computer simulations are probably greater than may be necessary.

The freshly harvested rapeseed put into the bin was infested with four species of stored-product mites: *Aeroglyphus robustus* Banks, *Lepidoglyphus destructor* (Schrank), Tydeidae and *Acarus siro* L. *Aeroglyphus robustus* was in five of the six samples with a maximum number of 130 per 300-g sample. It was unusual to find this species in freshly harvested grain and in such high numbers. It is commonly found in aged stored wheat (Sinha 1976). By 10 Oct. there were no *A. robustus* with only one to three per sample of *Cheyletus eruditus*, *G. destructor* and *Acarus siro*. No mites were found in samples taken on 27 Mar. 1981. No harmful storage fungi grew on the seeds before or after the drying period.

The mean free fatty acid value (FAV, expressed as mg/KOH required to neutralize oil from 100 g of dry seed) determined on six samples decreased from 43 (range, 39–48) initially on 27 Sept. 1980, to 36 (range, 27–44) by 10 Oct. and 32 (range, 29–37) by 31 Mar. 1981. Thus, the FAV of the dried rapeseed was near the upper limit of 30 defined for high quality rapeseed (Mills and Sinha 1980).

Samples of the rapeseed taken during the transfer of the crop into the drying bin were graded "Damp No. 1 Canada" with 2½% dockage and 14.1% moisture content. Samples taken from the bin in

December graded "No. 1 Canada", with 1.5 to 2.0% dockage, 8.1% moisture content and 47% oil content, dry basis. Thus drying and storing the rapeseed did not cause a reduction in quality as measured by storage fungi infection, FAV and commercial grade. This result was predicted by the simulation model. The portion of allowable storage time elapsed, averaged for the bin, was only 22% and the maximum, which is for the top layer, was 36% when simulated drying was completed on day 20. The average allowable storage time elapsed was predicted to increase to

27% and the maximum to increase to 40% by 31 December.

### Theoretical Airflow Requirements

Predictions based on the top layer dried to 10% within 15 to 20 days. The minimum rates of airflow required to dry the top layer of rapeseed in a bin to 10% within 15–20 days after harvest in the median year were predicted (Table I). The median year is defined such that at the indicated airflow, drying times for one-half the simulated years were longer and one-half were shorter than those for the median year. At these airflows maximum drying times were usually before 31 Dec. (for example see Table II for rapeseed harvested on 1 Sept. at 13% moisture content). In only 1 yr with two sets of conditions at Winnipeg and Fort St. John and three sets of conditions at Edmonton was drying incomplete by 31 Dec.

Except for two situations required airflow rates increased as harvest time was delayed (Table I). This general pattern of increasing airflow rates was opposite to that for wheat (Fraser and Muir 1981). The simulations for wheat allowed for continued drying in the spring. Thus, for wheat, the limiting factor was the reducing temperature at later harvest dates resulting in lowered rates of spoilage and longer allowable drying periods. For the rapeseed simulation where drying was to be completed within a given time the limiting factor was usually the amount of good drying weather available in the fall after harvest. At Fort St. John the reduction or equal airflow requirements for harvest on 15 Sept. compared with the earlier harvest on 1 Sept. suggest that drying conditions for the years simulated were similar throughout the month of September. The

**TABLE I. THEORETICAL MINIMUM RATES† OF AIRFLOW (L · s<sup>-1</sup> m<sup>-3</sup>) AT NEAR-AMBIENT CONDITIONS TO DRY RAPESEED TO 10% IN 15–20 DAYS IN THE MEDIAN YEAR‡ AT FOUR CANADIAN PRAIRIE LOCATIONS**

Harvest date	Initial moisture content (%)	Location			
		Winnipeg	Swift Current	Edmonton	Fort St. John
15 Aug.	11	11	10	14	14
	13	15	13	19	17
	15	28	16	22	21
1 Sept.	11	13	13	18	19
	13	20	16	22	21
	15	23	20	25	25
15 Sept.	11	17	14	19	15
	13	20	19	22	22
	15	24	22	25	25

† In any future application of these airflow rates the rates must be modified according to major factors such as initial deterioration of the rapeseed before ventilation begins, nonuniformity of airflow through the rapeseed and trends in future weather conditions.

‡ The median year is defined such that at the indicated airflow drying times for one-half the simulated years were longer and one-half were shorter than those for the median year.

**TABLE II. PREDICTED TIME REQUIRED TO DRY RAPESEED HARVESTED AT 13% MOISTURE CONTENT (WET BASIS) ON 1 SEPT. WITH AIR AT NEAR-AMBIENT CONDITIONS**

Location	Drying time criteria†	Airflow ((L/s)/m <sup>3</sup> )	Year‡	Time (days) to dry§		
				Average to 10%	Top layer to	
					10%	8%
Winnipeg	15–20 days	20	Min.	4	10	11
			Med.	11	16	34
			Max.	14	23	*4
	31 Dec.	9	Min.	17	26	53
			Med.	38	47	**
			Max.	*4	*5	*16
Swift Current	15–20 days	16	Min.	4	11	12
			Med.	8	17	29
			Max.	34	44	*1
	31 Dec.	8	Min.	10	28	70
			Med.	28	46	**
			Max.	*1	*1	*10
Edmonton	15–20 days	22	Min.	4	9	11
			Med.	11	17	43
			Max.	31	39	*5
	31 Dec.	9	Min.	16	30	**
			Med.	46	68	**
			Max.	*5	*7	*15
Fort St. John	15–20 days	21	Min.	7	13	17
			Med.	12	17	32
			Max.	20	26	*3
	31 Dec.	10	Min.	17	29	**
			Med.	36	53	**
			Max.	*2	*4	*17

† Airflows were selected for completion of drying in the median year within the time indicated without spoilage.

‡ Min. = minimum, Med. = median, Max. = maximum.

§ The asterisk and number (\*4) indicate that drying was incomplete by 31 Dec. in the indicated number of years. The double asterisk (\*\*) indicates that drying was not complete by 31 Dec. in the median year.

other exception was for 15% wheat at Winnipeg where airflow requirements decreased from harvest on 15 Aug. to 15 Sept. In this situation spoilage was the limiting factor requiring high airflows for the two early harvest dates.

Airflow rates were lowest at Swift Current (Table I) where the climate is classified semi-arid. With few exceptions airflow rates were highest for Edmonton (sub-humid to sub-boreal climate) followed by Fort St. John (sub-boreal) and Winnipeg (humid prairie).

*Predicted requirements based on drying by 31 December.* Required airflow rates reduce by an average of 40% when the criterion is to dry the top layer to 10% by 31 Dec. without spoilage at Swift Current, Edmonton and Fort St. John. The average reduction of 30% is less at Winnipeg. The reductions are smallest where spoilage is the major criterion which is the case for 15% moisture content rapeseed harvested on 15 Aug. and 1 Sept. at all locations and 11 and 13% moisture content rapeseed harvested on 15 Aug. at Winnipeg. The increased drying times (Table II) due to the reduced airflow rates would reduce the opportunity to use the drying equipment for more than one filling and could delay marketing of the crop. Thus, these airflow

rates are probably of little interest to most operators therefore only one set of conditions is reported in Table II.

*Predicted times required to dry to an average moisture content of 10%.* Drying may be stopped when the average moisture content of the bulk has been reduced to 10% rather than continue drying until the top layer is dried to 10%. Such a management procedure may be beneficial if the undried rapeseed at the top of the bin can be thoroughly mixed with the overdried rapeseed at the bottom of the bin before spoilage of the undried rapeseed becomes unacceptable. The predicted airflows for drying the top layer to 10% in 15–20 days in the median year (Table I) were used to simulate the time to bring the average moisture content to 10% (see Table II for one set of conditions). The mean reduction in drying times for the median year for the four locations and three harvest dates were 10 days for an initial moisture content of 11%, 6 days for 13% and 5 days for 15%. The greatest effect was for Swift Current.

Suspension of drying when the average moisture content reaches 10% reduces drying time and energy consumption for the median year by 61% for 11% initial moisture content, 37% for 13% and 31% for 15%. By reducing the drying time it

may be possible to empty the drying bin and dry more grain for the same capital cost in drying fans and floors. An important economic advantage in stopping drying at an average moisture content of 10% is that the maximum economic value of the crop is obtained with the maximum amount of wet mass at the top limit of moisture content for straight grade. (Under some conditions this may not be true if a reduced moisture content increases bulk density sufficiently to increase the grade.)

*Predicted times required to dry top layer to 8%.* To reduce the potential for deterioration during long-term storage the moisture content must be reduced to 8% or lower (Mills and Sinha 1980). Computer simulations were continued until the top layer was dried to 8% using the airflows required to dry the top layer to 10% in 15–20 days for the median year (Table I). The extra days required to remove the additional 2% moisture content decreased as initial moisture content increased because airflow rates increased. At an initial moisture content of 11%, 6 of the 12 sets of conditions of location and harvest date did not dry to 8% before 31 December in the median year. The mean number of additional days required to dry to 8% was 21 for an initial moisture content of 13% and 7 for 15%. Similarly additional days required decreased with later harvest dates. For an initial moisture content of 13% the mean number of additional days for the four locations was 33 for 15 Aug., 18 for 1 Sept. (Table II) and 13 for 15 Sept. The number of additional days was lowest for Swift Current with a mean of 7 days for the three harvest dates and 13% initial moisture content. The other three locations required 24 to 29 additional days for the same conditions.

## CONCLUSIONS

A mathematical model of rapeseed dried with air at near-ambient conditions was developed using the available experimental data on rapeseed drying and deterioration. The model was used to predict minimum rates of airflow required to dry rapeseed in the Canadian Prairies. Until more experimental research is conducted to improve the computer model, designers and operators of rapeseed drying systems may find the simulation results presented in this paper a useful starting point to be modified according to their own conditions and experience.

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