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SOLAR GRAIN DRYING IN CANADA:
A SIMULATION STUDY

by

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ABSTRACT

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An inexpensive, efficient method of on-farm grain drying is low-temperature in-bin drying. Such a dryer is easily adapted to solar drying by the addition of a solar collector to warm the drying air. The purpose of this study was to investigate the feasibility of this method of solar drying in Canada.

Computer simulation models were used to determine the effects of variables and to study the economics of various drying systems. The computer drying model assumed that during drying the air and grain reached temperature and moisture equilibrium during each time interval. The grain deterioration models predicted grain quality during the drying period, based on laboratory results.

Minimum airflow rates were predicted by these models for 422 combinations of parameters. The minimum airflow rate was the lowest airflow which would dry the grain before it spoiled. The parameters investigated were

geographical location, initial moisture content of the grain, harvest date, weather conditions, grain type and amount of heat added. Weather data for the two most adverse years of weather were used for each location.

The geographical locations considered were Edmonton, Swift Current, Winnipeg and London. The predicted airflow rates were lowest at the driest and coolest locations, Edmonton and Swift Current, where airflows as low as 0.10 $m^3/(min \cdot t)$ (cubic metres per minute per tonne) could be utilized. The minimum airflow rates predicted for the warmest, most humid locations ranged up to 16 $m^3/(min \cdot t)$. The minimum airflow rates were approximately doubled for each 2% increase in initial moisture content of the grain, and each month's delay in harvesting reduced the minimum airflow rate by approximately 50%. Addition of solar heat also reduced the airflow rate by as much as 50%.

The performances of low-temperature dryers over periods of 10 or more years were simulated for 97 combinations of parameters. Solar collectors with average temperature rises of 1 to 2°C were also added to the simulation models. The addition of the collectors reduced the energy consumption by an average of 8% in the Swift Current area and 35% at London, Ontario.

Cost analyses as applied to a 5.7 m diameter bin dryer indicated that the addition of solar heat to the unheated air drying system, reduced the total drying cost in only a few instances.

The cost analysis was set up so that further price increases could be accommodated. The analysis showed that as electricity costs increase more rapidly than other costs, solar grain drying will become more economical than unheated air drying.

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LIST OF SYMBOLS

A	Solar collector area per unit mass of grain, m^2/t
a	Coefficient for a particular grain in ERH equation
AC_r	Revised annual equipment cost, \$/bin
AFC_r	Revised allowable first cost of the collector, $\$/m^2$
AFR	Airflow rate per unit mass of grain, $m^3/(min \cdot t)$
A_o	Original horizontal collector area of 50% efficiency, m^2
A_r	Revised collector area for a different orientation or efficiency required to deliver the same amount of energy, m^2
b	Coefficient for a particular grain in ERH equation
C	Specific heat of corn or wheat, $J/(kg \cdot K)$
c	Coefficient for a particular grain in ERH equation
C_{A_r}	Revised annual collector cost, $\$/(m^2 \cdot a)$
C_o	Collector depreciation cost, \$/t
d	Coefficient for a particular grain in ERH equation
Dep	Drying equipment depreciation cost, \$/t
Dep_A	Drying equipment depreciation cost for ambient air drying, \$/t
Dep_S	Drying equipment depreciation cost for solar drying, \$/t
DM	Dry matter decomposition, %
D_r	Revised bin diameter, m
e	Base of natural logarithm
E	Electricity cost, \$/t

E_A	Electricity cost for ambient air drying, \$/t
Eff	Average solar collector efficiency, related to total radiation on a horizontal surface, decimal fraction
E_r	Revised electrical rate, \$/MJ
ERH	Equilibrium relative humidity of the air, decimal fraction
E_S	Electricity cost for solar drying, \$/t
exp	Exponential e
F	Sum of products to be minimized in determining ERH
F_r	Revised annual cost factor, fraction of first cost, decimal
G_o	Grain temperature at the beginning of the time interval, °C
G_r	Revised grain value, \$/t
H	Daily solar radiation on a horizontal surface, MJ/m^2
H_f	Absolute humidity of the air at the end of the time interval, kilograms of water per kilogram of dry air
H_o	Absolute humidity of the air at the beginning of the time interval, kilograms of water per kilogram of dry air
i	Sample number
M_D	Mechanical damage multiplier
M_f	Moisture content of the grain at the end of the time interval, % dry mass basis
M_i	Moisture content of sample i, % dry mass basis
M_M	Moisture content multiplier
M_o	Moisture content of the grain at the beginning of the time interval, % dry mass basis
M_T	Temperature multiplier
M_W	Moisture content, % wet mass basis

n	Number of samples or data points
OD	Overdrying cost, \$/t
OD_A	Overdrying cost for ambient air drying, \$/t
OD_S	Overdrying cost for solar drying, \$/t
P_i	Vapor pressure of the air in equilibrium with sample i, kPa
P_s	Saturation vapor pressure of the air, kPa
P_{s_i}	Saturation vapor pressure of the air at the temperature of sample i, kPa
R	Dry matter-to-air ratio, kilograms of dry matter per kilogram of air
R'	Grain-to-air ratio, kilograms of grain per kilogram of air
RH_{air}	Relative humidity of the air
S_e	Standard error of estimate
SC	Solar collector coefficient, °C
T	Grain temperature, °C
TDC_r	Revised total drying cost, \$/t
T_f	Air temperature at the end of the time interval, °C
T_o	Air temperature at the beginning of the time interval, °C
Δt	Temperature rise produced by a solar collector, °C
θ	Estimated allowable storage time, h or d
θ_{eq}	Equivalent storage time, h
θ_R	Reference storage time for corn, 230 h
$\Delta\theta$	Simulation or drying time interval being considered, h

I. INTRODUCTION

Grain crops grown in Canada are sometimes harvested in a tough or damp condition. The reasons may be to speed up the harvest, to reduce field losses or because the grain will not dry in the field.

It is not necessary to dry this grain immediately. It may be fed to livestock, mixed with dry grain, sold or utilized in other ways. The grain quality is best preserved by drying, however. Also, dry grain requires less energy for transportation, because it contains less water. Although off-farm drying may be desirable, it is often precluded by marketing constraints and limited drying capacities. Whatever action is taken, it is normally based on economics and the availability of the various options. On-farm drying is therefore necessary in some circumstances.

Escalating energy costs have emphasized the need of developing grain drying methods which are energy efficient. The use of solar energy may be one way of meeting this goal.

Farmers who annually dry large quantities of grain normally use a high-temperature high-speed grain dryer. Drying is achieved in this type of dryer by forcing heated air at a relatively high velocity through the grain. Combination drying is one method of energy saving in such a dryer (Morey and Cloud, 1977). This combines rapid high-temperature drying for high moisture content grain with low-temperature drying for the final drying stages. Solar heating may be used in this second stage.

Farmers who dry grain infrequently or in small amounts cannot usually justify the high capital cost of a high-temperature dryer. An alternative is the in-bin dryer which is cheaper to purchase and uses less energy (Friesen, 1974). It consists of a grain bin with a perforated floor, a fan and possibly a heater. For batch-in-bin drying, air temperatures of 30°C or more, airflow rates of 10 $m^3/(min \cdot t)$ (cubic metres per minute per tonne) or more and limited grain depths are used (Friesen, 1974). The grain is dried within one or two days.

When the drying time can be extended, energy savings are realized by using a smaller fan and heater. This is low-temperature drying. Heated or unheated air may be used, but the addition of heat lowers the relative humidity of the air. This ensures that drying will occur during periods of high relative humidity. Usual drying times range from a few weeks to several months. The extended drying times and small heat requirements make it possible to collect solar energy with reasonably small and inexpensive collectors. Thus energy can be saved and heating costs may be reduced. Two questions remain.

Is sufficient solar energy available when required, and is the use of solar energy economical?

The objective of this study was thus to determine the cost-effectiveness of utilizing solar energy in a low-temperature drying system in Canada. Such a system appeared to be most suitable for on-farm solar grain drying.

The method of investigation was a computer simulation model. This model predicts the drying of grain based on the initial moisture content, harvest date, airflow rate and weather conditions. Such a technique cannot exactly duplicate the processes occuring in nature. It can, however, produce useful results for a fraction of the cost and time required for field studies. The results of this study provide guidelines for the future of grain drying in Canada.

II. LOW-TEMPERATURE GRAIN DRYING WITH SOLAR ENERGY

2.1 Solar Collectors

Solar collectors for grain drying are generally simple and low-cost. They consist of a surface to intercept the sun's rays and to absorb some of the energy, plus an adjacent passage to move the air. The air collects the heat energy as it passes the absorbing surface before being blown through the grain. The absorbing surface may be metal, wood, paper or plastic and may be flat, corrugated or V-shaped. Best performance results from a slightly rough surface with a dull, black finish (Foster and Peart, 1976).

Solar collectors are normally constructed according to the bare plate, covered plate or suspended plate design. The bare plate collector (Fig. 2.1) is usually the least expensive to build but is also least efficient (Schoneau and Besant, 1976). For grain drying, metal sheets may be fastened to the southern wall of a bin, leaving a few centimetres of space for the air passage.

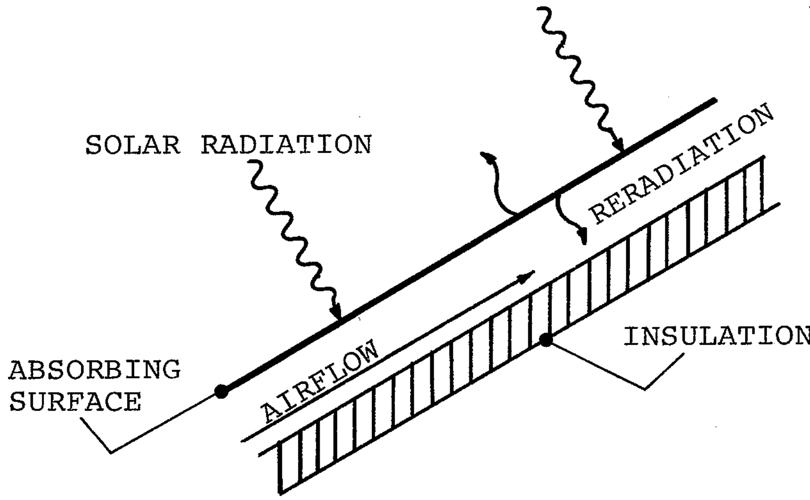

Fig. 2.1 Bare plate solar energy collector (Shove, 1977; Foster and Peart, 1976).

The covered plate collector has a transparent cover to reduce heat loss (Fig. 2.2). This collector is usually more efficient than the bare plate collector and may be low priced if a plastic cover is used. It has the lowest cost per unit of heat collected (Schoneau and Besant, 1976). For grain drying, a transparent cover can be fastened over a bin wall with the wall painted black. During storage when no air is moved to cool the collector, the black wall may cause increased grain temperatures. This is undesirable because warm grain has a greater potential for deterioration. To avoid this problem an adjacent structure may be used to mount the collector.

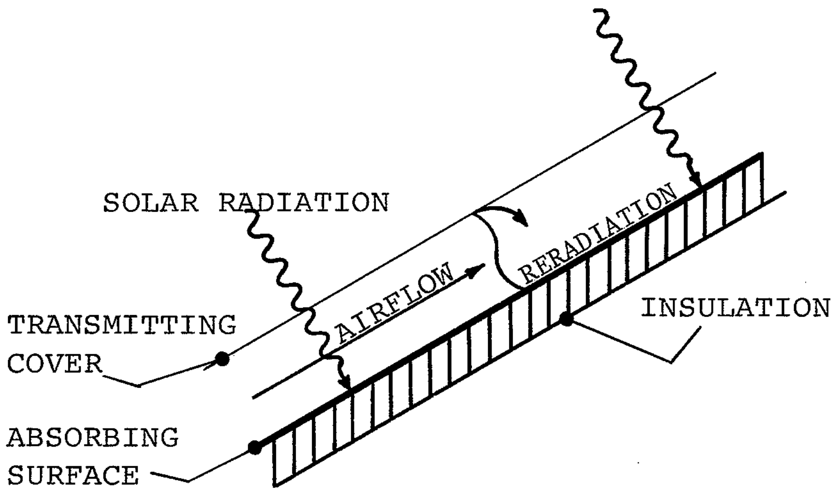

Fig. 2.2 Covered plate solar energy collector (Shove, 1977; Foster and Peart, 1976).

The suspended plate collector has a suspended absorbing surface to provide two air passages (Fig. 2.3). This increased heat transfer area results in highest efficiency but also highest cost compared to the other types (Schoneau and Besant, 1976). For grain drying it may be mounted at any convenient location.

The slope of a solar collector determines the amount of heat collected. Maximum heat is collected with the

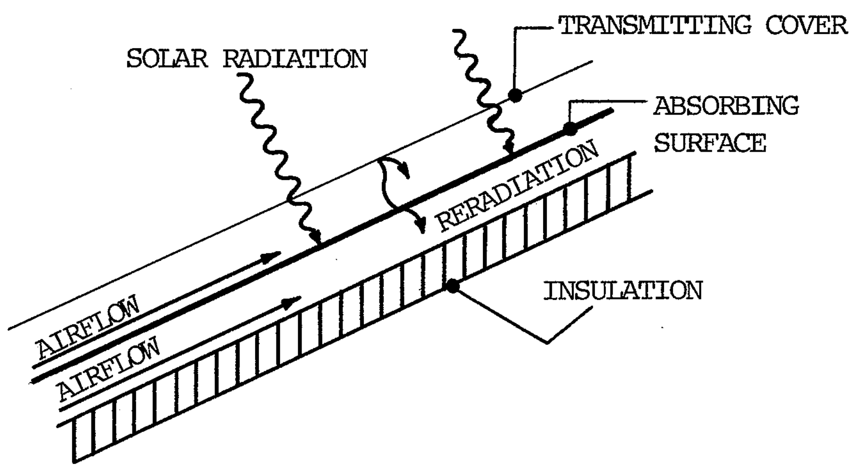

Fig. 2.3 Suspended plate solar energy collector (Shove, 1977; Foster and Peart, 1976).

collector at the optimum slope, perpendicular to the sun's rays. During the fall when most grain is dried the optimum slope is between 40 and 70 degrees from horizontal depending on the location and date (Fig. 2.5). To collect an equal amount of heat, a collector at the optimum slope is smaller than one at any other slope (Fig. 2.4). Similarily, a vertical collector is smaller than a horizontal collector. During the fall a south-facing wall would therefore be better than a horizontal surface for mounting a collector.

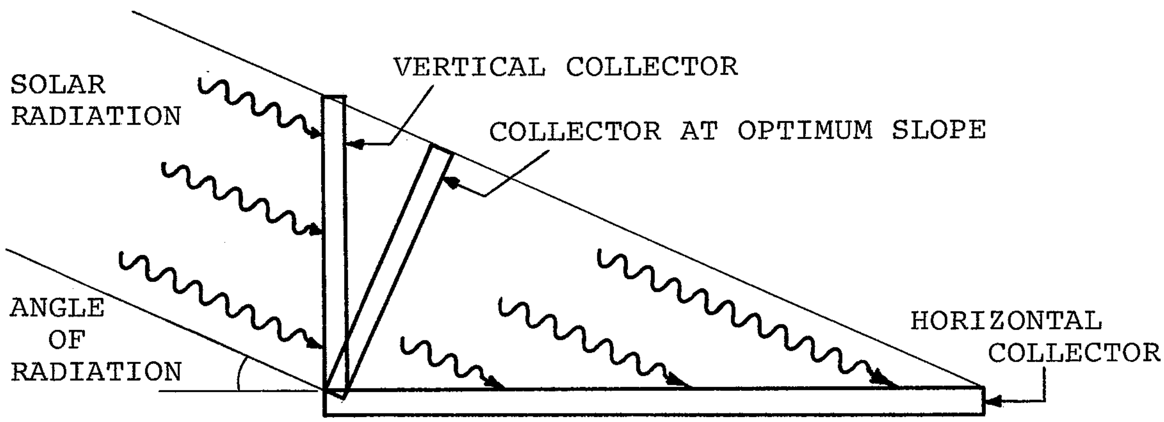

Fig. 2.4 Relative collector areas required to intercept an equal amount of solar radiation during the fall drying period. Exaggerated for illustration.

A variation on the basic solar collector is the use of an intensifier to concentrate and reflect the sun's rays onto a collector (Saienga et al. 1977). The collector is smaller than normal and the intensifier is cheaper per unit area than a collector.

Another variation is a portable collector designed for multiple use (DesChenes et al. 1976). Spreading the cost

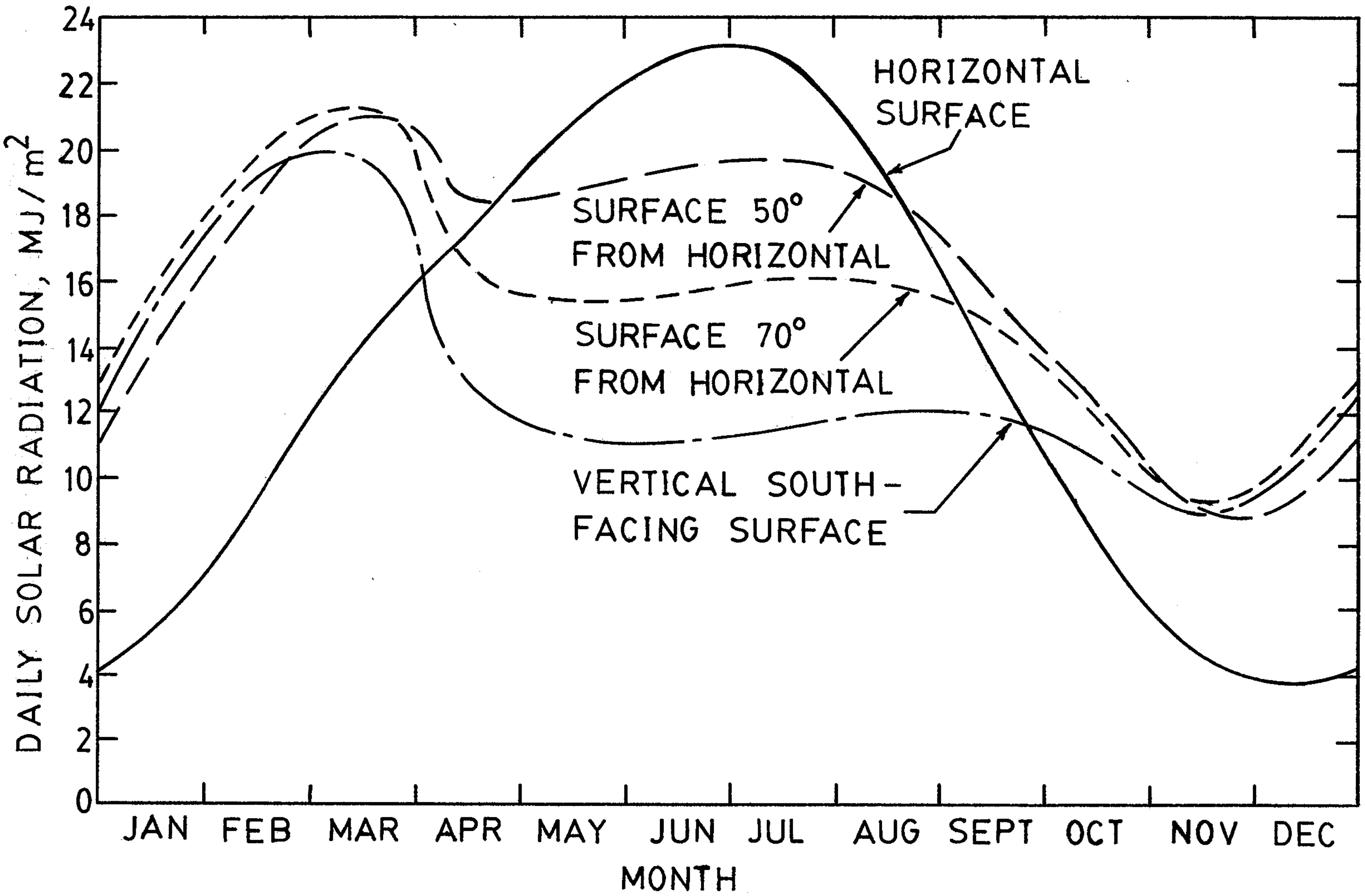

Fig. 2.5 Amounts of radiation received on various surfaces at Winnipeg. Data for radiation on a horizontal surface are averages for 1957 to 1975 (Environment Canada). Other data were calculated from these data as shown in Appendix A.

over several applications improves the economics and allows a more efficient and durable design. Possible conflicts in use may limit the number of applications.

2.2 Heat Storage

Many solar applications require heat to be stored for use when no radiation is available. In low-temperature grain drying the grain itself acts as a storage medium. During the daytime the bottom layers of grain tend to become overdried. At night the overdried grain picks up moisture from the high humidity air. This reduces over-drying and lowers the air relative humidity. This air continues to dry the grain above (Foster and Peart, 1976).

Other methods of heat storage for grain drying, suggested by Eckhoff et al. (1976), are -

1. Seasonal storage.

   The storage unit is heated during the summer, using the collectors. During the fall the hot air from the collectors is used directly for drying. When there is no radiation, heat from storage is used. This increases the rate of drying over non-storage methods but a large storage is expensive.

2. Collector storage.

   The hot air from the collectors is used to heat the storage unit during the day. At night the stored heat is used to warm the drying air. This provides a more constant heat source than non-storage methods of drying.

3. Ambient storage.

   The collectors heat the drying air directly, as in conventional systems. The storage unit is heated by the ambient air.

4. Natural storage.

   Ambient air is used both to dry the grain during the day and to heat the storage unit. No collectors are used.

In all of these cases, the storage medium may consist of phase-change materials, rocks, soil or other materials. According to Eckhoff et al. (1976) the three media holding the most promise are sodium sulphate decahydrate, rock and water-saturated-soil.

2.3 Reported Results of Solar Grain Drying

2.3.1 Field Studies

Lipper and Davis (1959) found that solar energy was most suitable for use with low-temperature dryers where slow drying was adequate and where the cost of fuels was high or their availability limited. They suggested that supplemental heating would be necessary to avoid spoilage of high moisture grain during drying. Buelow (1958) suggested that a solar drying system would be most profitable for farmers with small volumes of grain to dry.

In recent years, solar drying of corn has been compared with unheated air and electrically heated air drying in low-temperature drying systems (Bauman et al. 1975; Converse et al. 1976; DesChenes et al. 1976; Foster and Peart, 1976; Hammond and Winsett, 1976; Heid, 1978; Kranzler et al. 1975; Meyer et al. 1975; Morey et al. 1975; Morrison and Shove, 1975; Peterson and Hellickson, 1976; Saienga et al. 1977; Shove, 1977; Smit and Shove, 1976; Williams et al. 1976). In all cases the grain was dried without significant spoilage. Drying rates with solar energy were faster than unheated air drying but slower than heated air drying with a temperature rise of 4 to 5.5°C. Similarly the final moisture contents were lower with solar heating than with unheated air and higher with heated air drying. Although energy was conserved by using solar energy, the economics were not favorable for solar drying.

An economic study of eight solar drying systems showed that solar corn drying may be economical under some conditions. If an additional dryer is needed, if a conventional dryer needs replacing or if fossil fuels are not available, a solar system should be considered (Heid, 1978).

Only one report of solar drying in Canada has been published to date. At Melfort, Saskatchewan, an experimental bin dried wheat from 16.5 to 14.5% moisture content in 47 h of operation (Brad et al. 1977).

2.3.2 Simulation Studies

Mathematical simulation models have been used to evaluate the potential for solar corn drying at different locations and for different crop conditions. Using a prediction of the corn deterioration, these models could evaluate whether or not the corn would spoil before drying.

Results of Pierce and Thompson (1976) showed that selecting a sufficiently high airflow rate was the most important requirement to assure that the grain did not spoil before it was dried. Yearly variations in weather made as much as a threefold difference in this minimum airflow rate. The addition of supplemental heat reduced the drying time and increased the probability that drying would be completed in the fall. Moving from a cool and dry climate to a warm and humid climate resulted in higher airflow rates being required. Solar energy was more effective in reducing the airflow requirements in the warm and humid areas. Grain with an early harvest date and high initial moisture content required the highest airflow rate. Supplemental energy requirements were lowest for solar supplemented systems and highest for systems using continuous supplemental heat. Total drying costs were highest with the solar systems due to the cost of the collector.

Overdrying was more of a problem when supplemental heat was added.

Results of Morey et al. (1977) showed that the effect of solar heat could be obtained by an increased airflow rate of 10% using unheated air. Solar drying was found to be uneconomical in most cases. However, conditions were economically most favorable for solar drying of corn with initial moisture contents of 20 to 22%. It was concluded that strictly low-temperature drying methods were not feasible at moisture contents above 22 to 24%. Constant-source supplemental heat was found to have essentially the same effect as solar heat. When the average temperature rise was the same, the minimum airflow requirements and hours of fan operation were the same for both types of heat.

Peart (1977) simulated the growing as well as drying of corn. He concluded that it was important to design for the earliest possible harvest date. This would ensure that the grain would not spoil some years due to early maturity and harvest.

Simulation results for Missouri and Michigan (Bakker-Arkema et al. 1977) showed that solar drying and unheated air drying were equally feasible. For the same airflow and initial moisture content the quality of the corn dried in both systems was similar. Energy requirements were reduced