GRAIN DRYING MODEL FOR A DEEP LAYER

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The STOREDRY Grain Drying Model, which has its origin in Silsoe Research Institute in the early eighties, has been substantially improved in 1993 by J. Jílek during his stay in the Silsoe Research Institute in Silsoe. It can simulate grain drying in a deep bed of up to 6 metres for up to twenty years. Historical weather data for simulated years have to be available. Historical weather data are read from weather data file. It is also possible to set constant weather conditions. The model works in constant weather time steps. But drying subroutines DMODEL and DRSB are working in smaller time steps. Two drying models are available within STOREDRY. DMODEL is the near equilibrium model and DRSB is four equation model. In every time step the working point of the fan is calculated. It is possible to add fan characteristics and duct characteristics of a simulated drying arrangement. Simulation in every year ends when both target average moisture content and target wettest moisture content are met. There are several options for reporting the simulated results. 16 policy options have been written and tested. Success or failure of a policy can be judged on the basis of the achievement of the target average or wettest moisture contents, grain spoilage index, grain germination, germination index, grain dry matter loss, energy consumption, total costs etc. Any other policy can be easily added. Program is written in Microsoft FORTRAN, version 5.1.

near ambient grain drying; modelling; deep bed; fan characteristics; duct characteristics; shrinkage; grain policy

INTRODUCTION

The Silsoe Research Institute grain drying model is a simulation of the drying of a deep bed of grain with ambient (unheated) or slightly heated air. Two drying models are available within STOREDRY. DMODEL is a near equilibrium model and DRSB is four equations model. The near ambient grain drying model DMODEL is a version of the Morey equilibrium model (M o r e y et al., 1979) with a thin-layer check (S h a r p , 1983). It can be used for ambient or slightly heated air. The four equations model DRSB is a simulation of the drying of a deep bed of grain with both ambient and heated air (N e l l i s t , 1987). The same four equations model is for simulation of heated air dryers.

The drying is driven by historical weather data, currently available for 20 years at Waddington in England. The simulation model includes 16 policy options for controlling the operation of a fan, electrical resistance heater, fuel heater and heat pump for dehumidification of the drying air. Additional policies can be added to the simulation model.

The near-ambient simulation model was originally written by S h a r p (1981, 1982, 1983, 1984a), validated by S h a r p (1984b), transferred to VAX FORTRAN by M c K e e v e r (1985), and then further modified and documented by B r o o k (1987) and H o d g e s et al. (1988). The model has been used to simulate grain drying by N e l l i s t and B r o o k (1987) and N e l l i s t (1988) to compare control policies by N e l l i s t and B a r t l e t t (1988) and to find optimum strategy for near-ambient drying by R y n i e c k y and N e l l i s t (1989, 1991a, b). The author of this report added Nellist's four equation model (N e l l i s t , 1987), calculation of the fan working point on the basis of fan and duct characteristics, shrinkage, the shape of input and output files, thorough programme comments and he did general overhaul of the program including control policies rewriting and their subsequent careful checking.

INPUT AND OUTPUT PARAMETERS

The main data used for the simulation are the input through the file INFILE.DAT. Its purpose is to specify crop data, bin and fan data, price and energy data, year and time data, weather data and model data including selection of the control policy and its parameters.

The amount and location of output is controlled through the input variable IOUTPUT. The output information depends on IOUTPUT:

IOUTPUT = 1 time steps of DTW in HOURLY1.CSV and HOURLY2.CSV, annual final moisture and damage profiles and end summaries in SUMMARY.OUT

= 2 time steps of DTW for year given by JOUTYR, annual moisture and damage final profiles and end summaries in SUMMARY.OUT

= 3 annual moisture and damage final profiles and end summaries in SUMMARY.OUT

= 4 end summaries in SUMMARY.OUT

The output file SUMMARY.OUT contains three parts:

– output of simulation input data

– output of annual moisture and damage final profiles

– output of end summaries.

Structure of output of simulation input data is similar to INFILE.DAT. There are also data about the working point of fan and duct characteristics at the beginning of the simulation - initial airflow, initial duct pressure, initial grain pressure, initial fan/motor efficiency, initial fan energy consumption. Output of annual moisture and damage final profiles contains data for the first ten and the last ten layers. Profiles contain data about spoilage index, germination calculated on the basis of probit analysis, germination index, dry matter loss. There are also hours from the beginning of simulation when maximum spoilage index, minimum allowed germination and maximum dry matter loss (all three parameters are the input from INFILE.DAT) have been reached. Output of end summaries has 3 sets of tables. The first set corresponds to results for drying to the target average moisture content. The second set corresponds to results for drying to the target wettest moisture content. The third set corresponds to results for drying when both the target wettest moisture content and the average moisture contents have been met. The first and second sets correspond to the first reach of the target average and wettest moisture contents respectively. Take in mind that there can be grain rewetting! Every set contains four summary tables:

1. grain data
   – time of simulation, fan, heater, and heat pump, h
   – average, minimum and maximum final moisture content through the final profile, %wb
   – average, minimum and maximum spoilage index through the final profile, dec
   – average, minimum and maximum dry matter loss through the final profile, %
   – dry matter loss, $kg_g.t^{-1}$
   – overdrying, $kg_w.t^{-1}$

2. weather data
   – average weather conditions through the whole time of simulation
   – average weather conditions through the time when fan is ON
   – average weather conditions through the time when heater of heat pump is ON
   – average plenum conditions through the time when fan is ON
   – used drying potential, $g.kg^{-1}$

3. energy data
   – fan energy consumption during on-peak, off-peak and total hours, $MJ.t^{-1}$, $MJ.kg_w^{-1}$
   – heater energy consumption during on-peak, off-peak and total hours, $MJ.t^{-1}$, $MJ.kg_w^{-1}$

– heat pump energy consumption during on-peak, off-peak and total hours, $MJ.t^{-1}$, $MJ.kg_w^{-1}$
– fan and heater and heat pump energy consumption during on- peak, off-peak and total hours, $MJ.t^{-1}$, $MJ.kg_w^{-1}$

4. costs data – on-peak electricity, off-peak electricity, dry matter loss, overdrying and total costs, $GBP.t^{-1}$, $GBP.kg_w^{-1}$ for the case of electric heater
– on-peak electricity, off-peak electricity, dry matter loss, overdrying and total costs, $GBP.t^{-1}$, $GBP.kg_w^{-1}$ for the case of fuel heater

Every line in end summary tables represents one year. In addition there are four more lines in every table for the average, deviation and maximum and minimum values of every parameter through all years when target average and/or wettest moisture contents have been reached.

The output files HOURLY1.CSV and HOURLY2.CSV contain grain moisture content and grain temperature profiles respectively for every time step DTW. They are created by STOREDRY for every year. In addition to grain moisture content profile, HOURLY1.CSV contains:

– average moisture content of the bed, %wb
– bed height (varies due to shrinkage), m
– maximum dry matter loss through the profile, %
– dry matter per square meter, $kg_g.m_{-2}$
– water in grain per square meter, $kg_w.m^{-2}$
– evaporation rate, $kg_w.m^{-2}.h^{-1}$
– relative humidity cut value, %
– state of the fan, either ON or OFF
– heater output, kW.

In addition to grain temperature profile, HOURLY2.CSV contains:

– plenum temperature, °C
– plenum relative humidity, %
– airflow, $m^3.s^{-1}.t^{-1}$, $m.s^{-1}$, $m^3.s^{-1}$
– duct pressure, Pa
– grain pressure, Pa
– total pressure, Pa
– fan/motor efficiency, %
– fan energy consumption, $W.m^{-2}$, kW

The data in line are separated by commas so that they can be easily read by the program EXCELL for plotting.

Tab. I gives the list of input and output files.

I. Input and output files

File Assigned	Purpose
INFILE.DAT	main input data for simulation
WEATHER.DAT	weather data input file to be used for simulation
KREYGER.DAT	spoilage table input file of Kreyger damage data
SUMMARY.OUT	there are three parts: – output of simulation input data – output of annual moisture and damage final profiles (if IOUTPUT = 1 or 2 or 3) – output of end summaries
HOURLY1.CSV	output of grain moisture content profiles for every time step and for every year (if IOUTPUT = 1) or for year given by JOUTYR (if IOUTPUT = 2)
HOURLY2.CSV	output of grain temperature profiles for every time step and for every year (if IOUTPUT = 1) or for year given by JOUTYR (if IOUTPUT = 2)

DESCRIPTION OF THE SIMULATION MODEL

Grain quality

The routines available for estimating spoilage are self contained, with the exception of the one based on data of Kreyger (1972). More details about the routines can be found in Hodges (1989). The probit approach to germination (Nellist, 1978) is included in the simulation model.

Simulation of one time step

If fan is on for the time step given (as set by subroutine POLICY) then the subroutine DMODEL or DRSB is called and later the accumulated fan hours, heater hours and heat pump hours are updated. Energy use is accumulated separately for Economy 7 hours and for the rest of the day. Both are used to compute the total energy values and costs values. Then RESPIR is called to calculate the respiration heat (and increase of temperature) and released moisture. Subroutine SPOIL updates deterioration in grain quality through mold growth. The spoilage index for each layer is calculated. In case of spoilage index higher than maximum spoilage index SPLGMX, the first time of such a case is stored for printing in profile moisture and spoilage summaries.

II. List of control policies

Policy No.	Policy description
1	continuous run of fan and heater inputs: HEATERKW(1) heater power, kW
2	fan is ON and heater is OFF if plenum rh = RHCUT fan is OFF if plenum rh > RHCUT and HEATERKW(1) = 0 fan is ON and heater is ON if plenum rh > RHCUT and HEATERKW(1) > 0 inputs: POLADJ relative humidity set point, % HEATERKW(1) heater power, kW
3	fan is ON and heater is OFF if plenum rh =< erh [pl. temp.; mean mc + POLADJ] fan is OFF if plenum rh > erh [pl. temp.; mean mc + POLADJ] and HEATERKW(1) = 0 fan is ON and heater is ON if plenum rh > erh [pl. temp.; mean mc + POLADJ] and HEATERKW(1) > 0 inputs: POLADJ - moisture content set point, %wb HEATERKW(1) - heater power, kW
4	fan is ON and heater is OFF if plenum rh =< erh [pl. temp.; wettest mc + POLADJ] fan is OFF if plenum rh > erh [pl. temp.; wettest mc + POLADJ] and HEATERKW(1) = 0 fan is ON and heater is ON if plenum rh > erh [pl. temp.; wettest mc + POLADJ] and HEATERKW(1) > 0 inputs: POLADJ - moisture content set point, %wb HEATERKW(1) - heater power, kW
5	fan is ON and heater is OFF if plenum rh =< erh [pl. temp.; target mean mc + POLADJ] fan is OFF if plenum rh > erh [pl. temp.; target mean mc + POLADJ] and HEATERKW(1) = 0 fan is ON and heater is ON if plenum rh > erh [pl. temp.; target mean mc + POLADJ] and HEATERKW(1) > 0 inputs: POLADJ - moisture content set point, %wb HEATERKW(1) - heater power, kW

Continuation of Tab. II

Policy No.	Policy description
6	fan is ON and heater is OFF if mc of the top layer => initial mc - POLADJ fan is OFF if mc of the top layer < initial mc - POLADJ and HEATERKW(1) = 0 fan is ON and heater is ON if mc of the top layer < initial mc - POLADJ and HEATERKW(1) > 0 inputs: POLADJ - moisture content set point, %wb HEATERKW(1) - heater power, kW
7	fan and heater of power HEATERKW(1) are ON only between the hours of 0600 and 2100
8	fan is ON if plenum rh =< RHCUT1 and the mean mc => SETMCWB fan is ON if plenum rh =< RHCUT2 and the mean mc < SETMCWB inputs: RHCUT1 - first phase relative humidity set point, % SETMCWB - changeover mc for second phase, %wb RHCUT2 - second phase relative humidity set point, %
9	fan is ON if plenum rh =< RHCUT1 and mc of the top layer => initial mc - POLADJ fan is ON if plenum rh =< RHCUT2 and mc of the top layer < initial mc - POLADJ inputs: RHCUT1 - first phase relative humidity set point, % RHCUT2 - second phase relative humidity set point, % POLADJ - moisture content set point, %wb
10	fan is ON if absolute humidity of weather air =< absolute humidity of exhaust air + + HUMSET (kg/kg) input: HUMSET - moisture content set point, %wb
11	Myson A (fan control) example for SETMA(7) = 22. 20. 18. 16. 0. 0. 0. SETHA(7) = 100. 83. 72. 62. 0. 0. 0. run fan if mc of the wettest layer >= 22. and plenum rh <= 100. mc of the wettest layer <20.;22.) and plenum rh <= 83. mc of the wettest layer <18.;20.) and plenum rh <= 72. mc of the wettest layer <16.;18.) and plenum rh <= 62. inputs: SETMA(7) - moisture content set points, %wb SETHA(7) - relative humidity set points, %

Continuation of Tab. II

Policy No.	Policy description
12	Myson B (fan and heater control) example for SETMB(7) = 22. 20. 18. 16. 0. 0. 0. SETHB(7) = 100. 83. 72. 62. 0. 0. 0. HEATERKW(7) = 4. 8. 12. 16. 0. 0. 0. run fan if mc of the wettest layer >= 22. and plenum rh <= 100. mc of the wettest layer <20.; 22.) and plenum rh <= 83. mc of the wettest layer <18.; 20.) and plenum rh <= 72. mc of the wettest layer <16.; 18.) and plenum rh <= 62. if plenum rh > than the value set above, switch on such a number of heater steps so that plenum rh <= the value set above if it can't be reached, switch off the fan inputs: SETMB(7) - moisture content set points, %wb SETHB(7) - relative humidity set points, % HEATERKW(7) - heater power stages, kW
13	Myson C (fan and heater control) example for SETMB(7) = 22. 20. 18. 16. 0. 0. 0. SETHB(7) = 100. 83. 72. 62. 0. 0. 0. HEATERKW(7) = 4. 8. 12. 16. 0. 0. 0. run fan if plenum rh is below 62 % if plenum rh > 62 %, switch on such a number of heater steps so that plenum rh <= 62 % if it can't be reached then switch on the last heater step and run fan if mc of the wettest layer >= 22 % and plenum rh <= 100 % mc of the wettest layer <20; 22) % and plenum rh <= 83 % mc of the wettest layer <18; 20) % and plenum rh <= 72 % mc of the wettest layer <16; 18) % and plenum rh <= 62 % if it can't be reached, switch off the fan inputs: SETMC(7) - moisture content set points, %wb SETHC(7) - relative humidity set points, % HEATERKW(7) - heater power stages, kW
14	Myson A (fan control) during normal hrs Myson B (fan and heater control) during economy 7 hrs
15	Myson A (fan control) during normal hrs Myson C (fan and heater control) during economy 7 hrs
16	Myson B (fan control) during normal hrs Myson C (fan and heater control) during economy 7 hrs

Reporting and stop conditions

There are two intermediate reporting conditions as the drying progresses and two conditions used to terminate the drying for the year. The two reporting conditions are:

1. The first time period the average moisture falls below the target average moisture content TGAMCW.
2. The first time period the moisture of the wettest layer falls below the target wettest moisture content TGWMCW.

The two stop conditions are:

1. Both the average moisture and the moisture of the wettest layer are below their respective target points TGAMCW, TGWMCW.
2. Drying has continued through the finishing day and month specified in IFINISH.

At each of the reporting conditions and when one of the stop conditions has been satisfied, the subroutines are called to save and print the drying conditions.

End of reporting

At the end of every year of simulation, information about grain conditions at every reporting time, and grain and average air conditions at the end of drying are stored in the first and/or second and/or third set of end summary tables. The first set corresponds to the state when target average moisture contents have been reached. The second set corresponds to the state when target wettest moisture contents have been reached. The third set corresponds to the state when both states have been met. Subroutine STATS computes for every parameter through the years with data: the average, standard deviation and maximum and minimum values. These are then written as the last four lines in the end summaries tables.

Control policies

Tab. II summarizes the control policies which have been rewritten and tested.

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Model pro sušení zrnin v silné vrstvě.

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Matematický program STOREDRY je určen k simulaci procesu sušení zrnin v silné vrstvě. Původní model vznikl na počátku osmdesátých let ve Výzkumném ústavu v Silsoe (Anglie). Autor tohoto článku tento model v roce 1993 podstatně zdokonalil.

Model může simulovat sušení zrnin ve vrstvě silné až 6 m, a to až po dobu 20 let. K dispozici musí být záznam o počasí za dobu, po kterou chceme sušení simulovat. Jeden vstupní soubor obsahuje záznam o počasí (teplota, relativní vlhkost a tlak vzduchu). Simulovat je možné i průběh sušení za konstantních parametrů vstupního prostředí.

Program pracuje metodou konstantního časového kroku, který je shodný s krokem záznamu hodnot o počasí. Avšak sušicí procedury DMODEL a DRSB pracují při menším časovém kroku. V současné době jsou v programu obsaženy dvě sušicí procedury. DMODEL představuje model, který je založen na postupné rovnováze mezi sušicím materiálem a sušicím prostředím. DRSB je model, jehož základem je řešení čtyř parciálních diferenciálních rovnic přenosu tepla a hmoty a zachování vlhkosti a energie.

V každém časovém okamžiku se počítá pracovní bod ventilátoru, který se postupně mění, neboť zrno se smršťuje a ubývá v něm vody. Proto je nutné do programu vložit charakteristiku použitého ventilátoru a charakteristiku vzduchovodů. Simulace v každém roce končí, jestliže je dosaženo jak cílové průměrné měrné vlhkosti materiálu, tak cílové maximální měrné vlhkosti materiálu (měřeno podél vlhkostního profilu). Do výstupních souborů lze ukládat výsledky simulace různé úrovně podrobnosti.

Dosud bylo sestaveno a odzkoušeno 16 strategií použití ventilátoru a ohřívače vzduchu. Na úspěšnost strategie je možné usuzovat na základě dosažení cílové průměrné a cílové maximální měrné vlhkosti materiálu, poškození zrna (např. plísněmi), klíčivosti zrnin, ztráty sušiny, měrné spotřeby energie a dílčích a celkových nákladů na sušení. Program je napsán v jazyce Microsoft FORTRAN 5.1.

Výstupní údaje jsou strukturovány do čtyř bloků:

1. údaje o zrnu
   - doba simulace, doba chodu ventilátoru, doba zapnutí ohřívače vzduchu, doba zapnutí tepelného čerpadla, h
   - průměrná, minimální a maximální vlhkost zrna podél vlhkostního profilu na konci simulace, %
   - průměrný, minimální a maximální index poškození zrna podél vlhkostního profilu
   - průměrná, minimální a maximální ztráta sušiny podél vlhkostního profilu, %
   - ztráta sušiny, $kg_g.t^{-1}$
   - přesušení, $kg_w.t^{-1}$

2. údaje o počasí
- průměrné údaje o počasí během celé doby simulace
- průměrné údaje o počasí během doby zapnutí ventilátoru
- průměrné údaje o počasí během chodu tepelného čerpadla
- průměrné údaje vstupního prostředí (tj. po průchodu ventilátorem, ohřívačem a ev. tepelným čerpadlem) během doby zapnutí ventilátoru
- využitý sušicí potenciál, $g.kg^{-1}$

3. údaje o spotřebě energie
- spotřeba elektřiny ventilátoru během dne, během noci a za celý den, $MJ.t^{-1}$, $MJ.kg_w^{-1}$
- spotřeba energie ohřívače během dne, během noci a za celý den, $MJ.t^{-1}$, $MJ.kg_w^{-1}$
- spotřeba energie tepelného čerpadla během dne, během noci a za celý den, $MJ.t^{-1}$, $MJ.kg_w^{-1}$
- spotřeba energie ventilátoru, ohřívače, tepelného čerpadla během dne, během noci a za celý den, $MJ.t^{-1}$, $MJ.kg_w^{-1}$

4. údaje o nákladech
- náklady na denní elektřinu, noční elektřinu, ze ztráty sušiny a z přesušení a celkové náklady, $GBP.t^{-1}$, $GBP.kg_w^{-1}$ pro případ elektrického ohřívače vzduchu
- náklady na denní elektřinu, noční elektřinu, ze ztráty sušiny a z přesušení a celkové náklady, $GBP.t^{-1}$, $GBP.kg_w^{-1}$ pro případ ohřívače vzduchu pracujícího na základě spalování paliv.

sušení zrnin okolním vzduchem; modelování; silná vrstva; charakteristika ventilátoru; smrštění zrnin

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