A DYNAMIC MODEL FOR

CONTINOUS ADIABATIC DRYING

by

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Chairman, Departmental Committee

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Dedicated to my parents

I would like to thank Babu Joseph for his help in formulating this dynamic model. And a very special thanks to Joanne Rudinsky for the many long and late hours spent typing this manuscript.

I. ABSTRACT

In this thesis, I intend to find the dynamic equations which will predict the outlet temperature of a continuous dryer. Dynamic equations determine the steady state conditions and how quickly a new steady state is reached with small perturbations. The main purpose of this dynamic model is to know how to change the inlet conditions so that the desired outlet moisture content is continuously maintained. By knowing the temperature profile and the final outlet temperature, it will be possible to predict the outlet moisture content in the gas stream and in the product stream. As inlet temperatures change, this set of equations will predict the changes in the outlet conditions. That is, gas temperature, gas moisture content, and solid moisture content. The desired changes in the inlet conditions can be determined from the difference of the predicted outlet conditions and the desired outlet conditions. The dynamic equations predict both the change of the parameters at each position in the dryer and also the changes in each position with the change of time.

II. INTRODUCTION

Today with energy being a vital resource, engineers are looking for ways of conserving energy by making processes efficient. In a drying operation it would be ideal if just enough energy was used to dry a product to its desired moisture content. Just heating up a product until it is dry could be wasteful and disastrous. Some products can only be dried to a certain critical level. Beyond this level, the products would be ruined; but, if you didn't dry it enough, you have to dry it again. This is a waste of process, time, and energy for products that are sensitive to moisture content.

It will be possible to control the moisture content of the product stream to the desired level in the model that I am proposing. This model will be able to be used on adiabatic continuous drying operations. So far, only a co-current flow model has been developed. Essentially, this model comes from an overall energy balance and a moisture balance on the air stream and on the product stream.

Three dynamic equations are derived from these three balances. The dynamic temperature equation will make it possible to determine the temperature profile and how it changes with time. Then, the moisture content in the gas stream can be calculated. As the temperature changes with position and time, the evaporation rate will also vary with

Position and time. Using the dynamic temperature profile, the dynamic moisture content in the gas and solid stream can be determined. The moisture in the solid stream is calculated from the steady state equation derived from the solid stream moisture balance.

One of the problems in making this model is that the moisture content of the solid product stream cannot be measured directly. To get an exact measure on the dryness of the product, it would be necessary to analyze individual samples of the product stream. The time which it takes to analyze the exact moisture content of the product stream would make it impossible to maintain continuous operation. Under certain conditions and assumptions, the product moisture content can be measured indirectly.

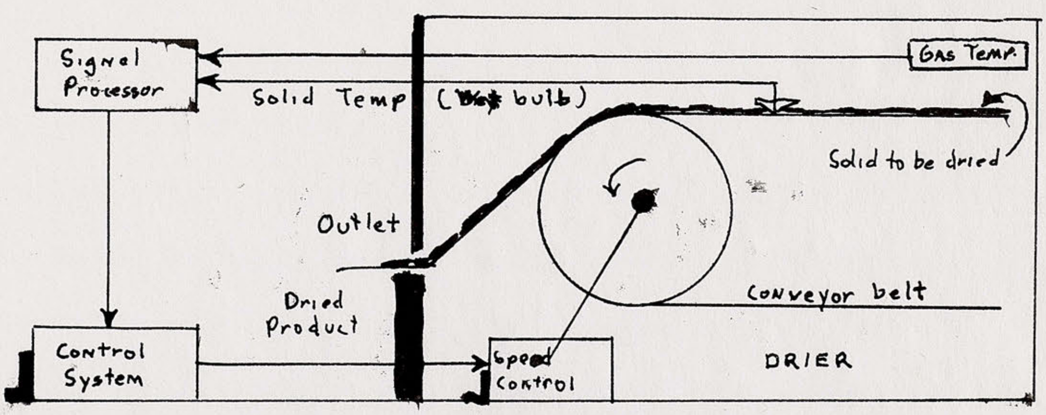
The indirect way of measuring the moisture content on solids is by knowing the temperature of the gas stream in which the solid is in equilibrium with. Through psychrometic considerations, the humidity of the gas stream can be calculated. The difference between the dry-bulb temperature and the wet-bulb temperature is proportionately related to the difference between humidity at saturation and the humidity of the gas. The dry-bulb and wet-bulb temperatures can be easily monitored in a continuous dryer. Thus, the moisture content of the gas stream can readily be measured. Then the moisture in the product stream can be estimated by using an overall moisture balance.

There are three different rate of drying zones. The first is the drying of excess water. This is when the solid particles are essentially floating in a stream of water. Water from both the particles and the liquid stream are being evaporated into the gas stream. The drying rate is independent of the solid particles and only depends on the heat of vaporization. The second zone is essentially known as the constant drying rate zone. This is when the complete surface of the particles are wet. Drying takes place evenly on all surface areas. The third zone is when parts of the surface are dry. Now the drying rate decreases since drying is taking place on the surface and through diffusion. This is known as the falling drying rate zone.

The transition between the constant rate zone and the falling rate zone takes place at the critical moisture content designated by (XC). The major concern of this model is the drying of particles to this critical moisture level. My proposed model deals with the adiabatic drying in the constant rate zone. Under adiabatic conditions, the wet-bulb temperature is constant. At equilibrium, the surface temperature of the particles is the wet-bulb temperature. It is at this temperature that evaporation takes place. The difference between the dry-bulb temperature and the wet-bulb temperature is the driving force of the evaporation.

III. THE BACKGROUND OF DRYING

In the paper industry, textile industry, food industry, and pharmaceutical industry there are many products which need to be dried to specific moisture content. In these fields, the product can be irreversibly damaged by over-drying. In 1973, the Sira Institute developed new techniques for measuring moisture content of materials continuous and batch drying processes. F. C. Harbert developed a controlling technique based on the measurements of temperature differences. His method is suitable for measuring any moisture content less than that to saturate the material. In the Harbert method, the temperature of the drying material and the wet-bulb temperature are compared. For each material, specific temperature differences were correlated to specific moisture contents. In a process developed for the continuous drying of cloth fabric the monitoring of the temperature difference between the fabric and the wet-bulb temperature determines at what speed the fabric is drawn through the dryer, (See fig. 1, below).



TEMPERATURE DIFFERENCE Control

figure 1

In any continuous drying operation, the inlet conditions will inevitably vary to some degree. This will cause the outlet conditions to also vary. It is desired to know how to adjust the inflowing air to account for the variance in the flow of the material being dried so the outlet moisture content will be constant. The purpose of a dynamic model is to know how to vary the adjustable inlet parameters so the product stream will be at the desired value. (See fig. 2, page 11.)

In continuous dryers the variable parameters are the flow of the material to be dried, the flow rate of the drying gas, and the temperature of the drying gas. Once a set of equations describing the drying process of a particular drying unit is known, the affect of varying the parameters can be determined. The flow rate of the gas and temperature of the gas are dependent on each other. Increasing the flow rate will cause the temperature of the gas to drop. This would depend on the air heating system and is not a concern of this model.

In order to control a drying process, some parameters must be monitored to determine how the inlet conditions must be varied. The desired result is a product with a particular moisture content. In many cases, this moisture content cannot be measured directly. Nor, can its temperature be measured directly. But, the properties of the air which it is in contact with can be measured and monitored. The two parameters that can be instantaneously measured are the dry-bulb temperature and the wet-bulb temperatures. From the dry-bulb and wet-bulb temperatures, the moisture content of the out flowing air can be determined. Calculating the differences between the incoming moisture of the solid and the outgoing moisture of the gas stream, will give a reasonable approximation of the moisture content of the solid product stream. Through the dynamic equations for the dryer, the degree in which the inlet parameters should be changed can be calculated.

DYNAMIC CONTROL

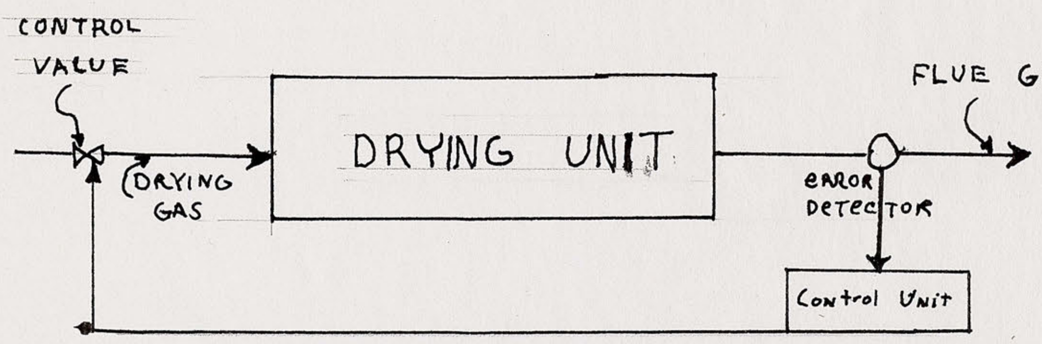
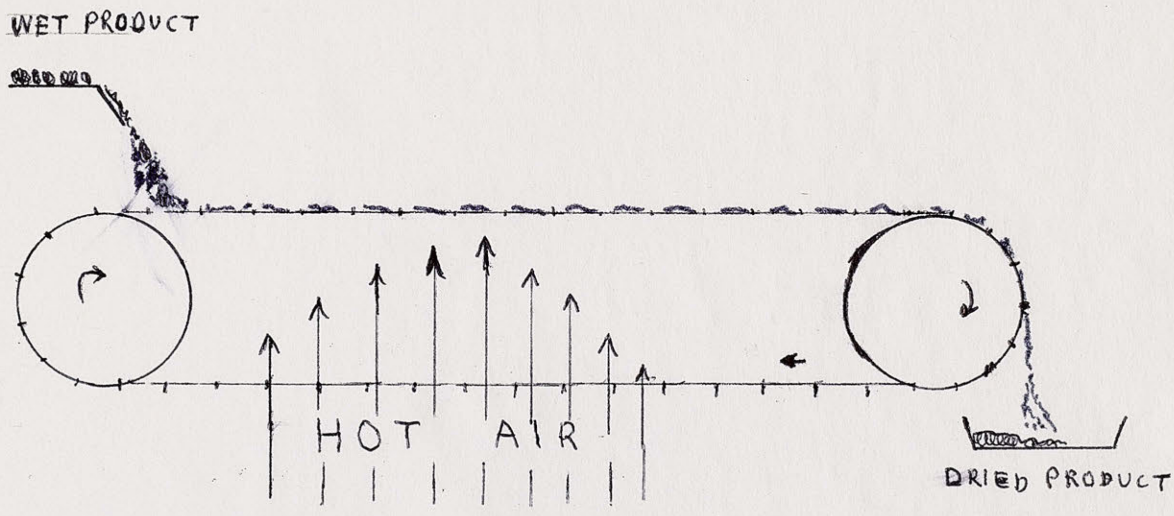


figure 2

IV. THE DYNAMIC MODEL

A model for drying solids moving on a conveyor belt or tray-type drier, is now proposed. (See fig. 3, page 12) The drying air is blowing in the same direction as the solid is moving. It is in this model that no energy is lost to the drying apparatus. All heat transfer is to the solid being dried. This model does not account for the pre-heating zone. Nor, does this model cover the falling rate drying zone past the critical moisture content. The rate of evaporation is related to the rate of heat transfer from the gas to the solid. The rate of drying can be given as a ratio of diffusion to heat transfer. In the model studied here, the main mode of heat transfer is conduction.

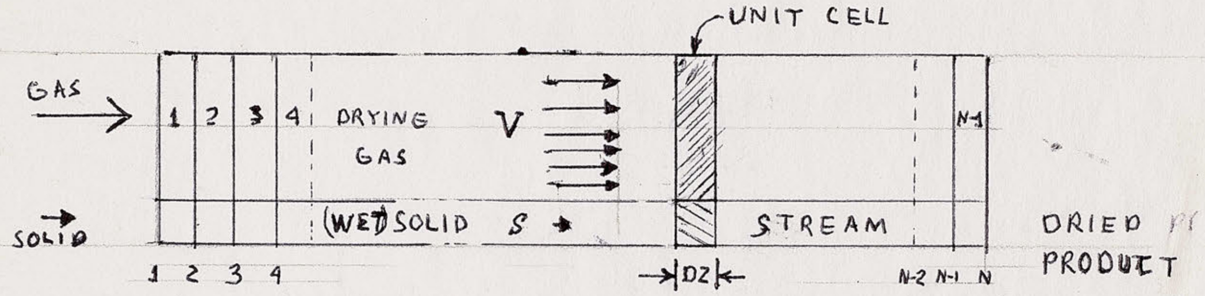


Conveyor Belt Drier

figure 3

The continous conveyor drier is represented by a gas stream flowing at a velocity V and a solid stream moving at a slower speed S. (See fig. 4) The length of the drier is divided into (N-1) compartments of equal size.

The Mathematical Model



V = Velocity of gas through drier (ft/hr)

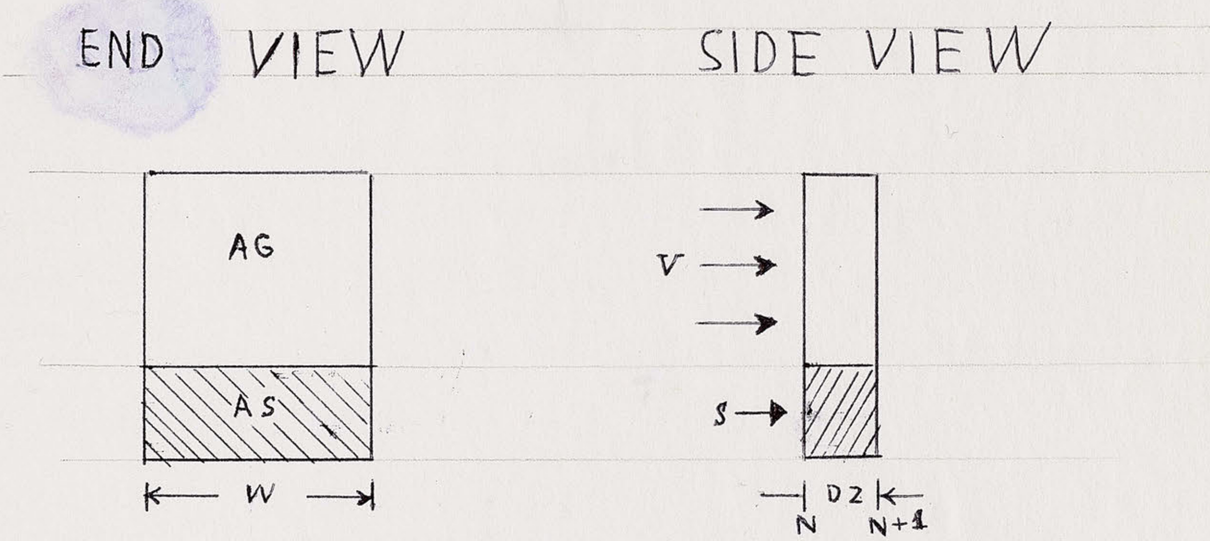
S = Speed which solid moves through drier (ft/hr)

(N-1)= Number of unit cells in the drier

DZ = Length of unit cell (ft)

figure 4

A mass and energy balance is written for one compartment to lead to a set of differential equations for the drier. The differential equations come from letting the limit of the length of each compartment go to zero. The imput of the compartment or unit cell is subscripted with N. The output side is subscripted (N+1). (See fig.5) The length is delta Z, represented by DZ in the computer program. The width is W. The area perpendicular to the flow of the gas and the solid are represented by AG and AS respectively.



\\\ Solid flowing into the page

/// Solid flowing to the right

AG Cross sectional area perpendicular to gas flow

AS Cross sectional area perpendicular to solid flow

W·DZ Area of gas-solid interface

figure 5

IVa. The Energy Balance on The Gas Stream

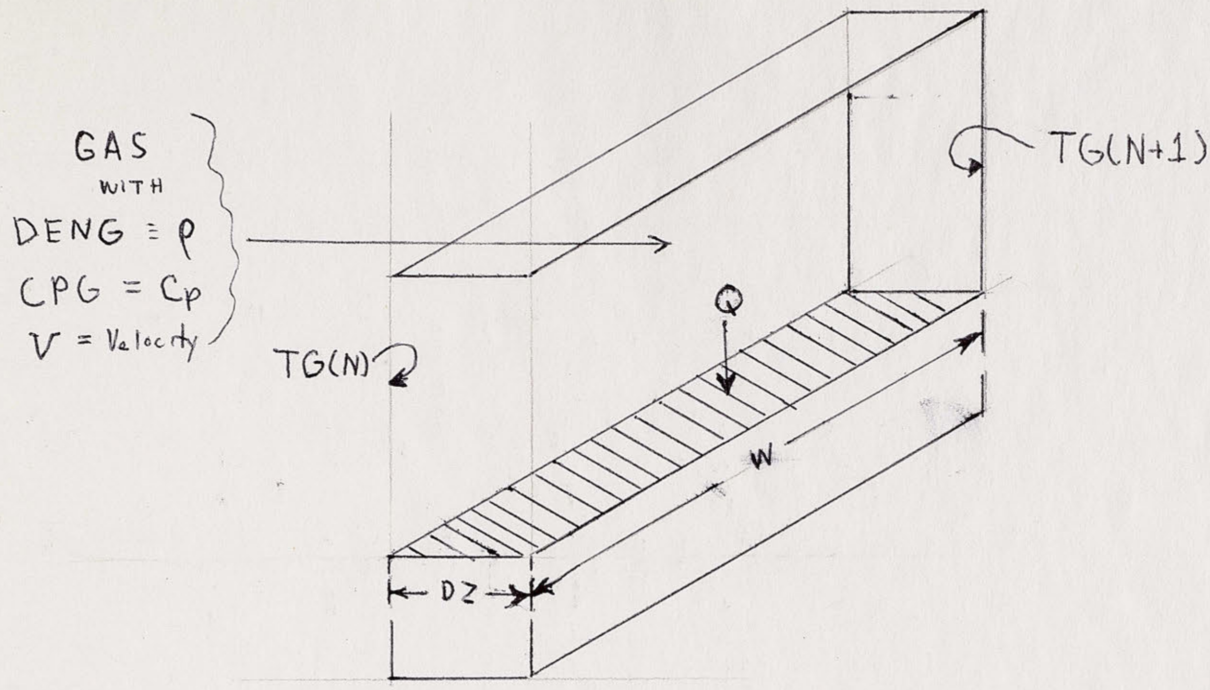
The gas is assumed to be in plug flow. The accumulation of energy in the unit cell per unit time is equal to the difference of the input and the output of energy. The heat content of the moisture is ignored here:

$$\text{Accumulation} = \text{Input} - \text{Output} \qquad (1)$$

Accumulation is equal to the change of heat content per unit time. The units are BTU's per hour. The volume of gas is the cross secional area times the length, (AG·DZ). The mass is the volume times the density of the gas, (DENG). The mass equals (AG·DZ·DENG). The heat capacity of the gas is CPG and the temperature is taken at the outlet of the unit cell. The partial derivitive equation for the accumulation of energy is:

$$\text{Accumulation} = (\text{AG}\cdot\text{DZ}\cdot\text{DENG}\cdot\text{CPG}\cdot\text{TG(N+1)}) \qquad (2)$$

The input of energy into the cell is from the gas flowing in. The volume per unit time is the velocity times the cross-secional area, V·AG. The temperature of the



TG(N) = Dry-bulb gas temperature at the inlet (^{o}F)

TG(N+1) = Dry-bulb gas temperature at the outlet (^{o}F)

DENG = Density of the gas (lb/cu.ft)

CPG = Heat capacity of the gas (BTU/lb^{o}F)

Q = Heat transfered per unit time (BTU/hr)

figure 6

incoming gas is TG(N). Volume times density times heat capacity times the temperature gives the energy per degree per unit time. (See fig. 6 above)

$$\text{Energy Input} = (V \cdot AG \cdot DENG \cdot CPG \cdot TG(N)) \qquad (3)$$

The output of energy is from the outflowing gas and the heat transfer to the solid stream. The flow output is similar to the input except the temperature is TG(N+1) which is lower than TG(N) since sensible heat has been transfered to the solid stream. The heat transfer per unit time is designated by Q. (See fig. 6, page 16)

$$\text{Energy Output} = (V \cdot AG \cdot DENG \cdot CPG \cdot TG(N+1)) + Q \qquad (4)$$

The heat transfer to the solid stream calculated by use of a heat transfer coefficient, h.[2] The rate of heat flowing across the solid-gas interface depends on the area of the interface and the driving force which is the temperature difference. The temperature difference is the gas temperature minus the temperature of the solid which is at the wet-bulb temperature, (TW). The area of the solid-gas interface is the length times the width, DZ·W. The units of the heat transfer coefficients are BTU per square feet per hour per degree Fahrenheit. The heat transfer to the drying solid:

$$Q = h \cdot DZ \cdot W \cdot (TG(N+1) - TW) \qquad (5)$$

The heat transfer coefficient can be correlated from the mass flow rate of the gas. The mass flow rate designated by G is equal to the velocity times the cross-secional area times the gas density, G = V·AG·DENG. The heat transfer coefficient is proportional to the mass flow rate raised to the eight tenths power (3)

$$h = 0.01 \cdot G^{0.8} \tag{6}$$

Substituting equation 5 into equation 4 and equations 2,3, and 4 into equation 1 forms the transient energy equation:

$$(AG \cdot DZ \cdot DENG \cdot CPG \cdot TG(N+1)) =$$

$$(TG(N)-TG(N+1))(V \cdot AG \cdot DENG \cdot CPG) - h \cdot DZ \cdot W(TG(N+1)-TW) \tag{7}$$

Dividing by constants on the left hand side, (AG·DZ·DENG·CPG), and taking the limit of delta Z as it approaches 0 as N approaches infinity leads to the following partial differential equation:

$$\frac{(TG(N+1))}{t} = \frac{(TG(N) - TG(N+1)) \cdot V}{Z} - \frac{h \cdot W(T(N+1) - TW)}{AG \cdot DENG \cdot CPG} \tag{8}$$

For non-adiabatic drying, which is not concerned in this model, the wet-bulb temperature (TW) would be calculated from the psychrometric equation. The dry-bulb temperature, the moisture content, and the moisture content in vapor pressure at saturation would have to be known.

The partial differential equation, (8), can be approximated by a finite different equation: From the finite different equation a FORTRAN equation for the gas temperature at each position along the dryer can be determined.

The partial differential of temperature with respect to time can be approximated by the finite difference of the temperature at the same location at the beginning and ending of a time unit divided by that time unit, DT. The superscript, i, is the beginning of the time unit, and the superscript, i+1, is the end of the time unit.

$$t(i+1) = t(i) + DT \qquad (9)$$

$$\frac{TG(N+1)}{t} = \frac{TG(N+1)^{i+1} - TG(N+1)^{i}}{DT} \qquad (10)$$

Now equation (8) becomes:

$$\frac{TG(N+1)^{i+1} - TG(N+1)^{i}}{DT} = \left(TG(N)^{i+1} - TG(N+1)^{i+1}\right)\frac{V}{DZ} + \frac{h \cdot W\left(TW - T(N+1)\right)^{i+1}}{AG \cdot DENG \cdot CPG} \qquad (11)$$

Solving for $TG(N+1)^{i+1}$ equals the following after re-arrangement and factoring to a common denomination:

$$TG(N+1)^{i+1} = \frac{(TG(N+1)^{i} \cdot GZ) + (TG(N)^{i+1} \cdot VT) + (TW \cdot ZW))}{(GZ+VT+ZW)} \qquad (12)$$

Where $GZ = AG \cdot DENG \cdot CPG \cdot DZ$

$VT = V \cdot AG \cdot DENG \cdot CPG + DT$

$ZW = DZ \cdot DT \cdot H \cdot W$

IVb. The Moisture Balance on The Gas Stream

The accumulation of moisture in the gas stream in the unit cell is equal to zero at all times since all moisture is carried out in the gas flow. The moisture carried in by the gas flow plus the amount evaporated into the gas stream is equal to the amount flowing out of the unit cell. The moisture flowing in equals the mass flow rate times the fraction of water to air, Y(N). The rate of evaporation corresponds to the heat transfer to the solid stream divided by the latent heat of evaporation at the wet-bulb temperature. The amount of water flowing along the solid-gas interface must also be taken into account. The conservation of moisture in gas stream and the solid-gas interface per unit time is:

$$G \cdot Y(N) + (S \cdot W \cdot h \cdot TEMP \cdot DT)/HV = G \cdot Y(N+1) \qquad (13)$$

$$TEMP = (TG(N)) + TG(N+1))/2 - TW \qquad (14)$$

Where TEMP is the average dry-bulb temperature of the cell minus the wet-bulb temperature which is the driving force for the evaporation rate. Rearrange the above equation and substituting for G leads to this equation which can be translated directly into FORTRAN.

$$Y(N+1) = Y(N) + \frac{(S \cdot W \cdot h \cdot TEMP \cdot DT)}{(HV \cdot VG \cdot AG \cdot DENG)} \tag{15}$$

The moisture in the solid stream can be calculated from the total moisture balance since the moisture on the gas stream is now known. The total moisture balance states that the difference of the moisture content in the gas stream equals the moisture difference in the solid stream. Mass is conserved. The flow of moisture in per unit time equals the mass flow rate times the fraction of water in the gasstream at the inlet. The fraction of water at the outlet in the gasstream is higher than the inlet. The moisture carried in the solid stream is the mass flow rate times the fraction of water per total amount water saturation. The mass fraction is designated by X(N) and X(N+1) at the inlet and outlet of the unit cell respectively. The mass flow rate for the solid stream is the mass velocity times the cross-sectional area perpendicular to the flow times the solids density. The mass flow rate equals S·AS·DENS. The conservation of moisture equation is:

$$(Y(N) - Y(N+1))(V \cdot AG \cdot DENG) = (X(N) - X(N+1))(S \cdot AS \cdot DENG) \tag{16}$$

The moisture at the outlet of the unit cell is:

$$X(N+1) = X(N) + (Y(N+1) - Y(N))\frac{(V \cdot AG \cdot DENG)}{(S \cdot AS \cdot DENS)} \quad (17)$$

Equations 12, 15, and 17, model the change of gas temperature, gas moisture content, and product moisture content---for each position in the drier as the time changes.

V. DYNAMIC SIMULATION AND THE RESULTS

With the aid of a digital computer, equations 12, 15, and 17, were used to simulate the values of the gas temperature, the gas moisture content, and the solid moisture content. The transient profiles for the gas temperature (TG) gas moisture content (Y), and solid product moisture content (X) were studied for three cases.

First, the variance of these profiles with time were determined at different fixed initial conditions. A description of this program is in section Va. Steady state was attained very quickly. From start up, the slowest that steady state was reached was 10 minutes. After 6 minutes, 85 percent of the steady state condition had been reached. In most cases, steady state was reached in under 5 minutes.

Next, the gas flow rate was optimized. The optimal gas velocity was found within 0.02 ft. per sec. From this study it is apparent that flucuations in gas flow rate will have very little effect on the steady state condition. The method of iteration is described in section Vb.

Third, the effect of flucuation of inlet temperature was simulated. A new steady state is reached in less than a minute. For an instantaneous change of 20°F causes the product moisture content to vary by 1.2 percent. This is a very drastic change in temperature and only a slight change in moisture content. Five degrees Fahrenheit only cause the product moisture content to vary by 0.5 percent. Section Vc describes how equations 12, 15, and 17, were grouped to simulate the flucuation of temperature. The optimized steady state condition from the second case was used as the initial condition at all locations on the drier.

From the three different simulations, the steady state was found to be stable. Small flucuations in the drying gas properties have very little effect on the steady state conditions.

Va. Time Dependents

At the beginning of all simulation, the initial conditions must be loaded. There are five types of constants which are unique for any drying process. There are the characteristics of the drier, physical properties of the gas, physical properties of the solid to be dried, the energy used, and the speed of operation of the drier.

The characteristic of conveyor driers are its length, cross-sectional area and its width.

The physical properties of the drying gas are its density, heat capacity, and initial moisture content. The density is used to calculate the mass flowing into the drier. The heat capacity is the amount of energy brought in per unit of mass. The moisture content is the ratio of the amount of water per mass to the amount at saturation.

The heat capacity for the solid is not needed. The energy balance was on the gas and water in the drier. Under the assumption that the solid is at the wet-bulb temperature and that the wet-bulb temperature is constant the energy balance on the solid stream is zero. The needed physical properties of the solid are its density and moisture content. The cross-sectional area perpendicular to the direction of flow is needed to calculate the mass flow rate.

The energy properties are the dry-bulb temperature and the wet-bulb temperature. The heat of vaporation is a function of the wet-bulb temperature.

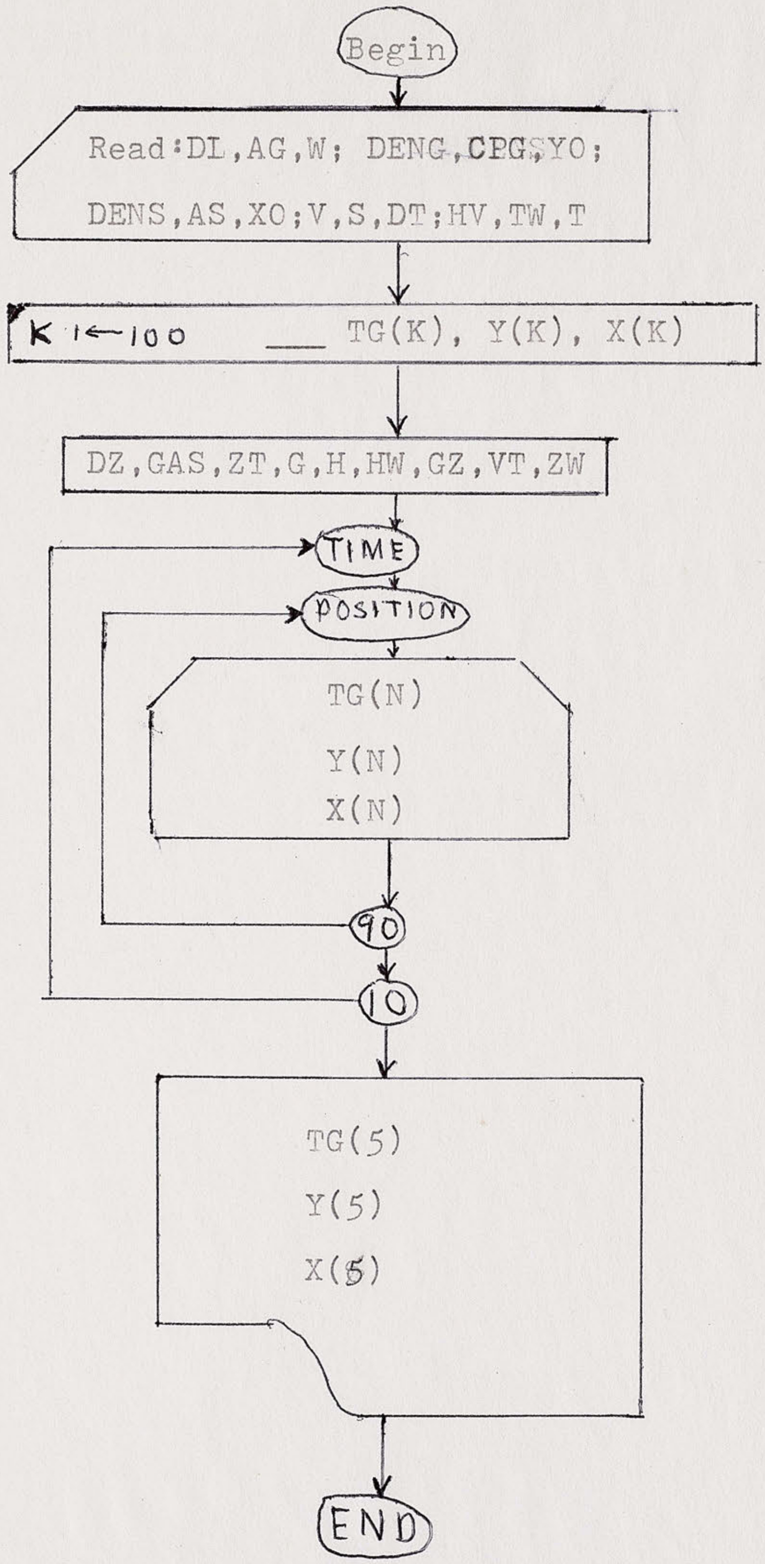
The time variables are the gas velocity, the solids feed speed, and the unit time set to be used in calculations.

The values for TG, Y, X, for each position in the drier need to be stored before calculation can be performed. The number of positions used was 100. This means there are 99 unit cells. At the starting time, all positions are given the initial values.

To save calculation time, the constant that arises from the mass and energy balances are performed.

Now, the transient calculation can be performed. For a more detailed description of these equations and how they are processed, see the Appendix. First the time counter is set. Then the position counter is set. Now the transient profile for temperature and moisture content are found. See flow chart A.

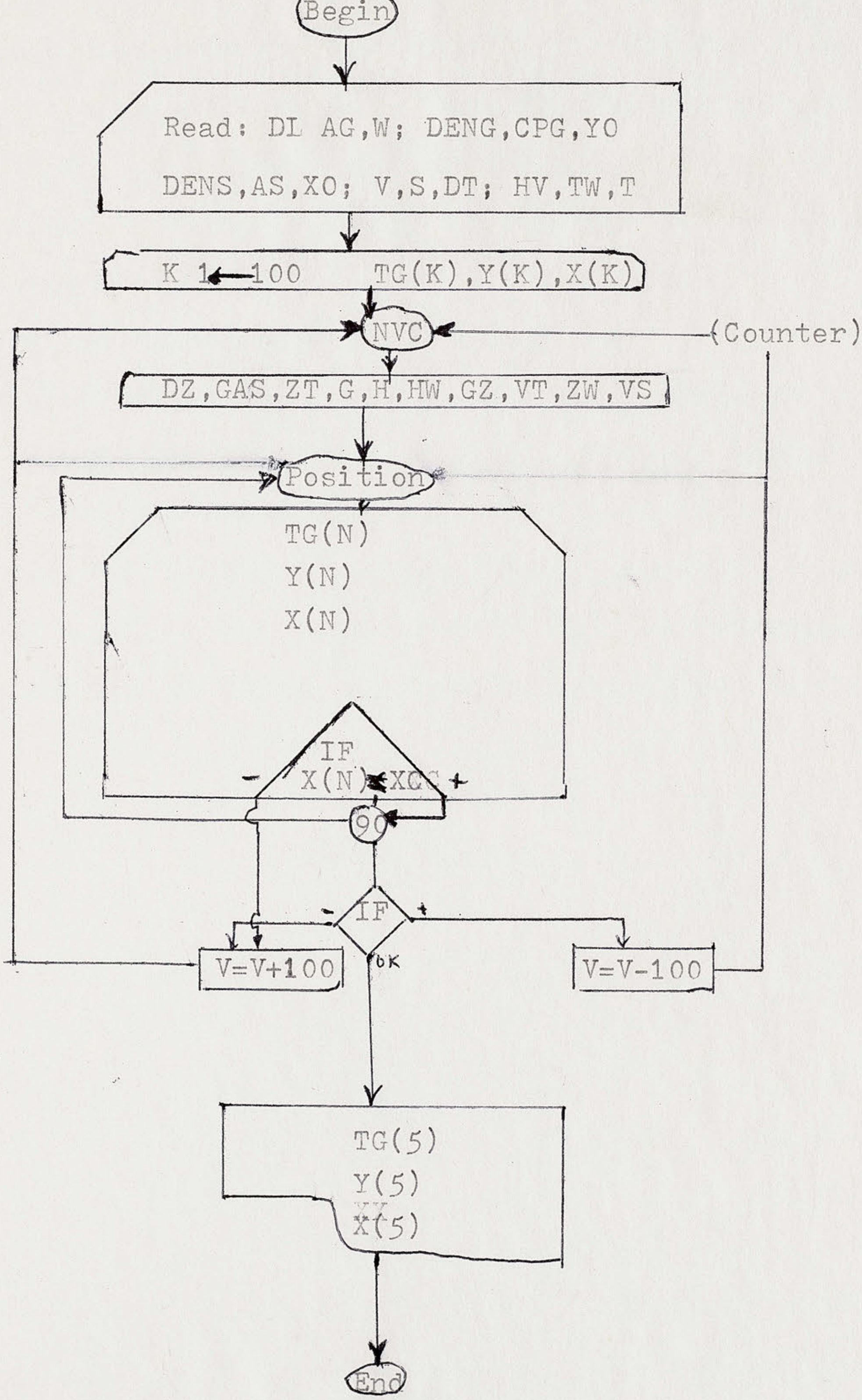
Flow Chart A Time dependence



Vb. Optimizing Velocity

A third iternative loop can be added before the time and position loop described in the previous section. A trial and error method is used to find the optimal gas flow velocity. The steady state for the new velocity is tested against the ideal case. The error determines whether a faster or slower velocity should be used. The ideal case is to have the desired moisture content on the solid stream attained in the last unit cell. The flow chart for this program is given on the following page. See flow chart B.

Flow Chart B Optimizing velocity

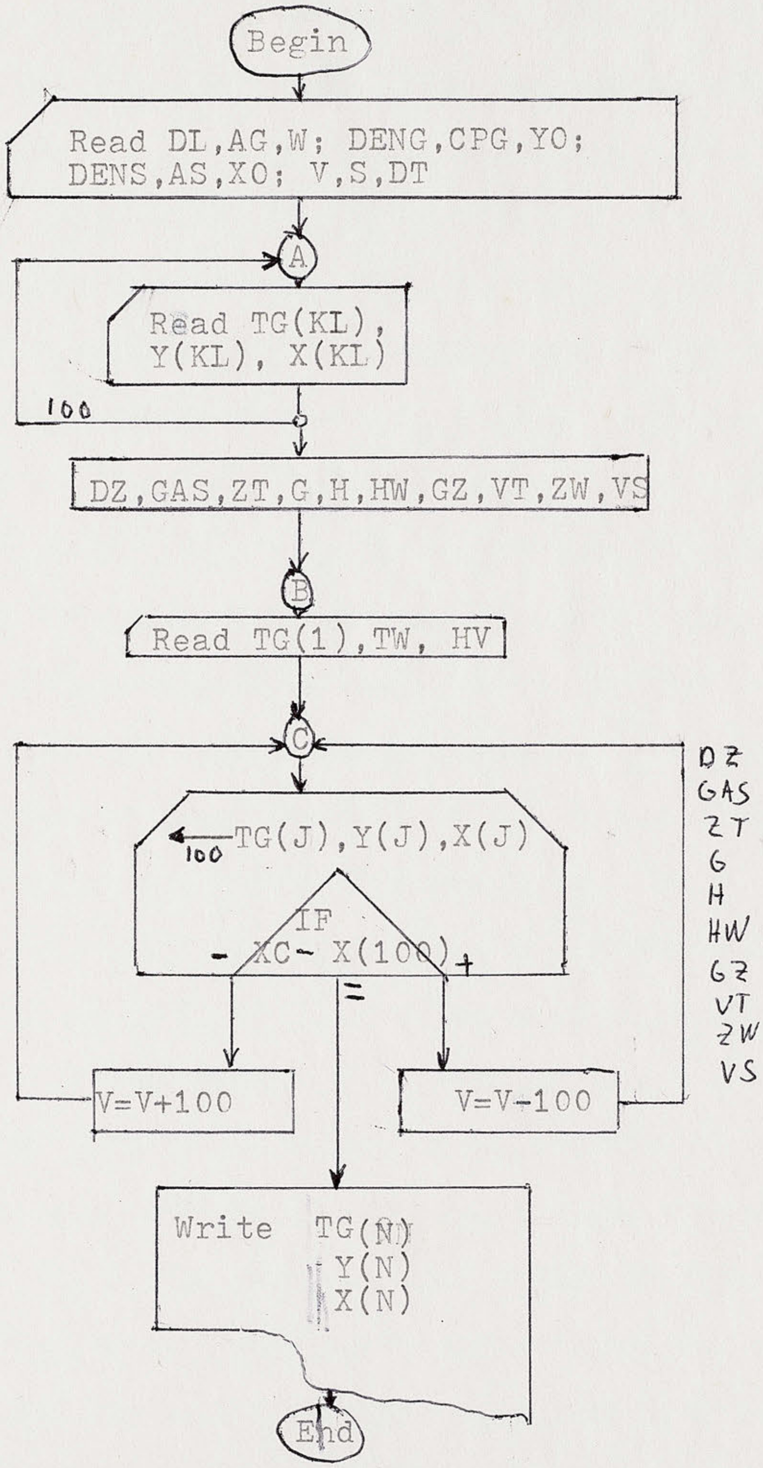


Vc. Temperature Flucuation

Now that optimal operating conditions are known, they can be used as the initial value at all locations in the drier. After this has been stored, new energy values are read. These are dry-bulb temperature, wet-bulb temperature, and the heat of vaporization at wet-bulb temperature.

The new temperature, TG, is read into the first unit cell. Then values for the next cell are calculated using the set of dynamic equations. After the values in the last cell are determined, the changes in the inlet conditions can be found using a similar approach as that given in section Vb. The flow chart for the dependence of temperature on steady state is given in flow chart C.

Flow Chart C Temperature Dependence



VI. CONCLUSION

Based on the stability of the steady state condition, it would be feasible to maintain a continuous conveyor-type dryer at a desired output be monitoring its temperature. When a flucuation in the temperature at a given point of the dryer is detected, the effect on the outlet moisture content can be calculated. The changes in inlet conditions which are needed to get the outlet conditions back to the desired level can be determined nearly instantaneously with the aid of a computer. These changes can be initiated almost immediately and with a second calculation can be compared to the observed values. In this matter, the desired outlet condition can be maintained at the desired values. Large flucuations in inlet conditions will be very small by the time they reach the end of the dryer with the aid of these continuous corrective measures. On a real dryer, terms for heat loss from the dryer and non-adiabatic drying would have to be determined experimentally. These terms would be incorporated to this proposed dynamic model, enabling continuous operation to be automatic.

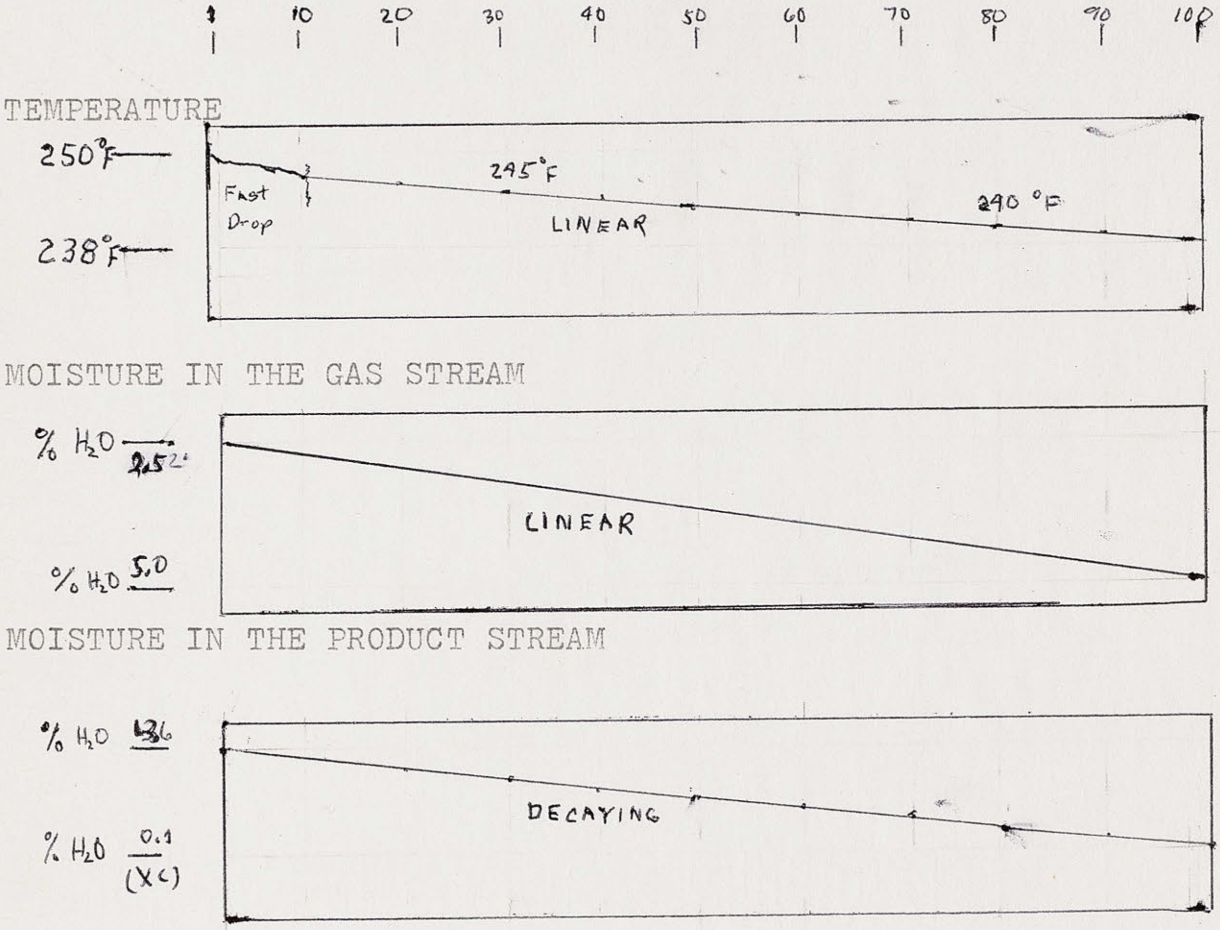
If there is flucuation in the incoming moisture content of the solid stream, this would cause changes in gas temperature and wet-bulb temperature that could be detected when the solid reaches equilibrium with the gas at some point in the dryer. This is assuming that the solid stream is in the dryer long enough to reach equilibrium with the gas stream. Monitoring the gas temperature and the wet-bulb temperature should make it possible for the dryer to be controlled automatically.

VII. NOMENCLATURE

AG	=	Cross-section area perpendicular to gas flow(sq.ft)
AS	=	Cross-section area perpendicular to solid flow(sq.ft)
CPG	=	Heat capacity of the gas stream(BTU/lb°F)
CPS	=	Heat capacity of the solid stream(BTU/lb°F)
DENG	=	Density of the gas(lb/cu.ft)
DENS	=	Density of the solid(lb/cu.ft)
DT	=	Time step(hr)
DZ	=	Length of unit cell(ft)
G	=	Mass flow rate(lb/hr)(V·AG·DENG)
h	=	Heat transfer coefficient(BTU/sq.ft.hr°F)
HV	=	Heat of vaporatization(BTU/lb. H_2O)
Q	=	Heat transfer per unit time(BTU/hr)
TG(N)	=	Dry-bulb temperature of gas at N.(°F)
TW	=	Wet-bulb temperature(°F)
S	=	Speed which solid moves through drier(ft/hr)
V	=	Velocity of drying gas through drier(ft/hr)
W	=	Width of drier(ft)

VIII. APPENDIX

STEADY STATE PROFILES



Steady state reached in 6 minutes.

V= 74800. ft./hr.

S= 100. ft./hr.

XC= 0.01 water/water at saturation

W= 1.0 ft. AS= 0.175 sq.ft. AG= 1.0 sq.ft.

DENG= 0.0107 lbs./ cu. ft. DENS= 84.1 lbs./cu.ft.

CPG= 0.24 BTU/lbs. DL= 10.0 ft.

TW= 110.°F HV= 1034.1 BTU/lbs water TG(1)=250.°F

PAGE 1

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// JOB T

LOG DRIVE   CART SPEC   CART AVAIL  PHY DRIVE
  0000        02CE        02CE        0000

V2 M12   ACTUAL  8K  CONFIG  8K

// FOR
*IOCS(TYPEWRITER,KEYBOARD,DISK,CARD,1132PRINTER)
*ONE WORD INTEGERS
*LIST SOURCE PROGRAM
C    *****************************************************************
C
C          PROGRAM  A        TIME   DEPENDENCE
C
C    *****************************************************************
C CONTINOUS DRYING UNDER ADIABATIC CONDITION
      DIMENSION  TG(100),Y(100),X(100)
C READ CHARACTERISTICS OF DRIER  W,DL,AG
C READ CHARACTERICS OF IN FLOWING GAS  DENG,CPG,YO
C READ CHARACTERICS OF IN COMING SOLID DENS,AS,XO
C READ CHARACTERISTICS OF TIME-VELOCITY   V,S,DT
C READ CHARACTERICS OF THE ENERGY (TEMPERATURE)   HV,TW,T
      READ  (2,100)  DL,AG,W
      READ  (2,100)  DENG,CPG,YO
      READ  (2,100)  DENS,AS,XO
      READ  (2,101)  V,S,DT
      READ  (2,100)  HV,TW,T
C INITIATE ARRAYS WITH INITIAL CONDITIONS
      DO  20 K=1,100
      TG(K)=T
      Y(K)=YO
      X(K)=XO
   20 CONTINUE
      XC=0.01
C CRITICAL MOISTURE CONTENT  XC
C CALCULATE NEEDED CONSTANTS FOR CALCULATIONS
      DZ=DL/99.
C PROPERTIES OF THE GAS STREAM  DENSITY ,HEAT CAPACTIY,AREA
      GAS=AG*DENG*CPG
      ZT=DZ*DT
      G=AG*V*DENG
      H=0.01*G**0.8
      HW=H*W
      GZ=GAS*DZ
      VT=DT*V*GAS
      ZW=ZT*HW
C RATIO OF MOISTURE IN GAS AND SOLID FLOWS
      VS=(V*AG*DENG)/(S*AS*DENS)
      WRITE (3,800)
      WRITE (3,400) DT,DZ
      WRITE (3,401) DL,AG,AS,W
      WRITE (3,402) DENG,CPG,YO,T,TW,HV
```

```
      WRITE (3,403) V,S,XO,XC,DENS
      WRITE (3,404) GAS,ZT,G,H,HW,GZ,VT,ZW,VS
      WRITE (3,405)
      DO  30 ITX=1,15
      DO  90  I=1,99
      J=I+1
      TG(J)=((TG(J)*GZ)+(TG(I)*VT)+(TW*ZW))/(GZ+VT+ZW)
      TEMP=(TG(I)+TG(J))/2.-TW
      Y(J)=Y(I)+((S*HW*TEMP*DT)/(HV*AG*DENG*V))
      X(J)=X(I)-((Y(J)-Y(I))*VS)
   90 CONTINUE
      DO 10 L=5,100,5
      WRITE (3,200) TG(L),Y(L),X(L)
      WRITE (3,201) L
   10 CONTINUE
   30 CONTINUE
  100 FORMAT (3F10.4)
  101 FORMAT (3F10.2)
  200 FORMAT (30X,F20.0,2F20.3)
  201 FORMAT ('+',I20)
  400 FORMAT ('0',' DELTA TIME =',F6.4,'      DELTA Z =',F6.4)
  401 FORMAT ('0','DRIER VARIBLES  DL=',F4.1,'    AG=',F4.2,
     $'   AS=',F4.2,'   W=',F6.4)
  402 FORMAT ('0','GAS PROPERTIES   DENG=',F6.4,'   CPG=',F6.4,
     $'   YO=',F6.4,'   T=',F4.0,'   TW=',F4.0,'   HEAT OF VAP=',F8.2)
  403 FORMAT('0','SOLID PROPERTIES    V=',F10.0,'   S=',F5.0,'   XO=',
     $F5.3,'   XC=',F5.3,'   DENS=',F6.1)
  404 FORMAT ('0','CALCULATED CONSTANTS',9E10.3)
  405 FORMAT ('0',24X,'GAS',7X,'ZT',8X,'G',9X,'H',9X,'HW',8X,'GW',
     $8X,'VT',8X,'ZW',8X,'VS')
  800 FORMAT ('1')
      CALL EXIT
      END

FEATURES SUPPORTED
 ONE WORD INTEGERS
 IOCS

CORE REQUIREMENTS FOR
 COMMON       0  VARIABLES     668  PROGRAM     654

END OF COMPILATION

// XEQ
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PAGE    1

// JOB T

LOG DRIVE   CART SPEC   CART AVAIL  PHY DRIVE
  0000        02CE        02CE        0000

V2 M12   ACTUAL  8K  CONFIG  8K

// FOR
*IOCS(TYPEWRITER,KEYBOARD,DISK,CARD,1132PRINTER)
*ONE WORD INTEGERS
*LIST SOURCE PROGRAM
C    **************************************************************************
C
C         PROGRAM B        OPTIMIZING VELOCITY
C
C    **************************************************************************
C CONTINOUS DRYING UNDER ADIABATIC CONDITION
      DIMENSION  TG(100),Y(100),X(100)
C READ CHARACTERISTICS OF DRIER  W,DL,AG
C READ CHARACTERICS OF IN FLOWING GAS  DENG,CPG,YO
C READ CHARACTERICS OF IN COMING SOLID DENS,AS,XO
C READ CHARACTERISTICS OF TIME-VELOCITY   V,S,DT
C READ CHARACTERICS OF THE ENERGY (TEMPERATURE)   HV,TW,T
      READ  (2,100)  DL,AG,W
      READ  (2,100)  DENG,CPG,YO
      READ  (2,100)  DENS,AS,XO
      READ  (2,101)  V,S,DT
      READ  (2,100)  HV,TW,T
C INITIATE ARRAYS WITH INITIAL CONDITIONS
      DO  20 K=1,100
      TG(K)=T
      Y(K)=YO
      X(K)=XO
   20 CONTINUE
      XC=0.01
C CRITICAL MOISTURE CONTENT  XC
C CALCULATE NEEDED CONSTANTS FOR CALCULATIONS
      DZ=DL/99.
      NVC=0
   60 CONTINUE
      NVC=NVC+1
      IF (NVC-10000) 1,1,99
    1 CONTINUE
C PROPERTIES OF THE GAS STREAM  DENSITY ,HEAT CAPACTIY,AREA
      GAS=AG*DENG*CPG
      ZT=DZ*DT
      G=AG*V*DENG
      H=0.01*G**0.8
      HW=H*W
      GZ=GAS*DZ
      VT=DT*V*GAS
      ZW=ZT*HW
C RATIO OF MOISTURE IN GAS AND SOLID FLOWS
```

```
      VS=(V*AG*DENG)/(S*AS*DENS)
      WRITE (3,800)
      DO  90  I=1,99
      J=I+1
      TG(J)=((TG(J)*GZ)+(TG(I)*VT)+(TW*ZW))/(GZ+VT+ZW)
      TEMP=(TG(I)+TG(J))/2.-TW
      Y(J)=Y(I)+((S*HW*TEMP*DT)/(HV*AG*DENG*V))
      X(J)=X(I)-((Y(J)-Y(I))*VS)
      IF (X(J)-XC) 95,95,90
   90 CONTINUE
   95 K=J
      IF (K-99) 1010,99,1001
 1001 IF (K-99) 99,99,1020
 1010 V=V-100.
      GO TO 60
 1020 V=V+100.
      GO TO 60
   99 CONTINUE
      WRITE (3,400) DT,DZ
      WRITE (3,401) DL,AG,AS,W
      WRITE (3,402) DENG,CPG,YO,T,TW,HV
      WRITE (3,403) V,S,XO,XC,DENS
      WRITE (3,404) GAS,ZT,G,H,HW,GZ,VT,ZW,VS
      WRITE (3,405)
      DO 10 L=5,100,5
      WRITE (3,200) TG(L),Y(L),X(L)
      WRITE (3,201) L
   10 CONTINUE
      WRITE (3,501) NVC
  100 FORMAT (3F10.4)
  101 FORMAT (3F10.2)
  200 FORMAT (30X,F20.0,2F20.3)
  201 FORMAT ('+',I20)
  400 FORMAT ('0',' DELTA TIME =',F6.4,'       DELTA Z =',F6.4)
  401 FORMAT ('0','DRIER VARIBLES  DL=',F4.1,'    AG=',F4.2,
     $'    AS=',F4.2,'    W=',F6.4)
  402 FORMAT ('0','GAS PROPERTIES   DENG=',F6.4,'    CPG=',F6.4,
     $'    YO=',F6.4,'    T=',F4.0,'    TW=',F4.0,'   HEAT OF VAP=',F8.2)
  403 FORMAT('0','SOLID PROPERTIES    V=',F10.0,'    S=',F5.0,'    XO=',
     $F5.3,'    XC=',F5.3,'    DENS=',F6.1)
  404 FORMAT ('0','CALCULATED CONSTANTS',9E10.3)
  405 FORMAT ('0',24X,'GAS',7X,'ZT',8X,'G',9X,'H',9X,'HW',8X,'GW',
     $8X,'VT',8X,'ZW',8X,'VS')
  500 FORMAT (' ',20X,'V=',F10.0,10X,I10)
  501 FORMAT (' ',I6)
  505 FORMAT ('0',45X,'TG',18X,'Y',19X,'X')
  800 FORMAT ('1')
      CALL EXIT
      END
```

UNREFERENCED STATEMENTS
 500   505

```
// JOB T

LOG DRIVE   CART SPEC   CART AVAIL  PHY DRIVE
  0000        02CE        02CE        0000

V2 M12   ACTUAL  8K  CONFIG  8K

// FOR
*IOCS(TYPEWRITER,KEYBOARD,DISK,CARD,1132PRINTER)
*ONE WORD INTEGERS
*LIST SOURCE PROGRAM
C    *****************************************************************
C
C          PROGRAM  C           TEMPERATURE DEPENDENCE
C
C    *****************************************************************
C CONTINOUS DRYING UNDER ADIABATIC CONDITION
      DIMENSION  TG(100),Y(100),X(100)
C READ CHARACTERISTICS OF DRIER  W,DL,AG
C READ CHARACTERICS OF IN FLOWING GAS  DENG,CPG,YO
C READ CHARACTERICS OF IN COMING SOLID DENS,AS,XO
C READ CHARACTERICS OF THE ENERGY (TEMPERATURE)   HV,TW,T
C READ CHARACTERISTICS OF TIME-VELOCITY   V,S,DT
      READ  (2,100)  DL,AG,W
      READ  (2,100)  DENG,CPG,YO
      READ  (2,100)  DENS,AS,XO
      READ  (2,101)  V,S,DT
C INITIATE ARRAYS WITH INITIAL CONDITIONS
      DO 12 KL=1,100
      READ  (2,700)  TG(KL),Y(KL),X(KL)
   12 CONTINUE
      XC=0.01
C CRITICAL MOISTURE CONTENT  XC
C CALCULATE NEEDED CONSTANTS FOR CALCULATIONS
      DZ=DL/99.
C PROPERTIES OF THE GAS STREAM  DENSITY ,HEAT CAPACTIY,AREA
      GAS=AG*DENG*CPG
      ZT=DZ*DT
      G=AG*V*DENG
      H=0.01*G**0.8
      HW=H*W
      GZ=GAS*DZ
      VT=DT*V*GAS
      ZW=ZT*HW
C RATIO OF MOISTURE IN GAS AND SOLID FLOWS
      VS=(V*AG*DENG)/(S*AS*DENS)
      WRITE (3,404) GAS,ZT,G,H,HW,GZ,VT,ZW,VS
      WRITE (3,405)
      WRITE (3,800)
      DO  40 NDT=1,5
C READ CHARACTERISTICS OF IN COMING TEMPERATURES   TG(1),TW,HV
      READ  (2,100)  HV,TW,T
      TG(1)=T
```

```
      WRITE (3,301) NDT
      WRITE (3,400) DT,DZ
      WRITE (3,401) DL,AG,AS,W
      WRITE (3,402) DENG,CPG,YO,T,TW,HV
      WRITE (3,403) V,S,XO,XC,DENS
      DO 90 I=1,99
      TG(J)=((TG(J)*GZ)+(TG(I)*VT)+(TW*ZW))/(GZ+VT+ZW)
      TEMP=(TG(I)+TG(J))/2.-TW
      J=I+1
      Y(J)=Y(I)+((S*HW*TEMP*DT)/(HV*AG*DENG*V))
      X(J)=X(I)-((Y(J)-Y(I))*VS)
   90 CONTINUE
      DO 10 L=5,100,5
      WRITE (3,200) TG(L),Y(L),X(L)
      WRITE (3,201) L
   10 CONTINUE
      NVC=0
   60 CONTINUE
      NVC=NVC+1
      IF (NVC-10000) 70,70,95
   70 CONTINUE
C RECALCULATE ALL VELOCITY DEPENDENT CONSTANTS
      G=AG*V*DENG
      H=0.01*G**0.8
      HW=H*W
      VT=DT*V*GAS
      ZW=ZT*HW
      VS=(V*AG*DENG)/(S*AS*DENS)
      WRITE (3,500) V,NVC
      DO 80 M=1,99
      N=M+1
      TG(N)=((TG(N)*GZ)+(TG(M)*VT)+(TW*ZW))/(GZ+VT+ZW)
      TEMP=(TG(M)+TG(N))/2.-TW
      Y(N)=Y(M)+((S*HW*TEMP*DT)/(HV*AG*DENG*V))
      X(N)=X(M)-((Y(N)-Y(M))*VS)
      IF (X(N)-XC) 81,81,80
   80 CONTINUE
      GO TO 1020
   81 K=N
      IF (K-98) 1010,85,85
   85 IF (K-99)95,95,1020
 1010 V=V-100.
      GO TO 60
 1020 V=V+100.
      GO TO 60
   95 CONTINUE
      WRITE (3,505)
      WRITE (3,801)
      WRITE (3,801)
      DO 20 KL=5,100,5
      WRITE (3,200)  TG(KL),Y(KL),X(KL)
      WRITE (3,201) KL
   20 CONTINUE
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      WRITE (3,501) NVC
   40 CONTINUE
  100 FORMAT (3F10.4)
  101 FORMAT (3F10.2)
  200 FORMAT (30X,F20.0,2F20.3)
  201 FORMAT ('+',I20)
  301 FORMAT ('1','THIS IS NEW DATA        SET',I10)
  400 FORMAT ('0',' DELTA TIME =',F6.4,'      DELTA Z =',F6.4)
  401 FORMAT ('0','DRIER VARIBLES  DL=',F4.1,'   AG=',F4.2,
     $'   AS=',F4.2,'   W=',F6.4)
  402 FORMAT ('0','GAS PROPERTIES   DENG=',F6.4,'   CPG=',F6.4,
     $'   YO=',F6.4,'   T=',F4.0,'   TW=',F4.0,'   HEAT OF VAP=',F8.2)
  403 FORMAT('0','SOLID PROPERTIES    V=',F10.0,'   S=',F5.0,'   XO=',
     $F5.3,'   XC=',F5.3,'   DENS=',F6.1)
  404 FORMAT ('0','CALCULATED CONSTANTS',9E10.3)
  405 FORMAT ('0',24X,'GAS',7X,'ZT',8X,'G',9X,'H',9X,'HW',8X,'GW',
     $8X,'VT',8X,'ZW',8X,'VS')
  500 FORMAT (' ',20X,'V=',F10.0,10X,I10)
  501 FORMAT (' ',I6)
  505 FORMAT ('0',45X,'TG',18X,'Y',19X,'X')
  700 FORMAT (F6.0,2F6.3)
  800 FORMAT ('1')
  801 FORMAT ('0')
      CALL EXIT
      END

FEATURES SUPPORTED
 ONE WORD INTEGERS
 IOCS

CORE REQUIREMENTS FOR
 COMMON      0  VARIABLES    672  PROGRAM   1016

END OF COMPILATION

// XEQ
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IX. B I B L I O G R A P H Y

Bird, R. Byron; Steward, Warren E.; Lightfoot, Edwin N.; Transport Phenomena, Copy. 1965, John Wiley & Son, Inc. New York

Carnahan, Brice; Cuther, H. A.; Wikes, James O.; Applied Numerical Methods, John Wiley & Son, Inc., New York, copy. 1969.

Chung, Sen F., "Mathematical Model and Optimization of Drying Process for a Through-Circulation Dryer", The Canadian Journal Of Chemical Engineering, Vol. 50 October, 1972

Harbert, F. C., "Temperature Differences Give Automatic Control of Process Plant Dryers", Process Engineer, Vol. 122 September, 1973

Keey, R. B., Drying Principles and Practice, Pergamon Press, New York, 1972

Nonhebel, G.; Moss, A. A. H., Drying of Solids in The Chemical Industry, Butterworth & Co., Ltd., London, 1971

Novak, Lawrence T.; Coulman, George A., "Mathematical Models for The Drying of Rigid Porous Materials", The Canadian Journal of Chemical Engineering, Vol. 53, February, 1975

Perry, Robert H., (Editor), Perry's Chemical Engineers' Handbook, McGraw-Hill Book Company, New York, 1963.

Shinskey, F. Greg, Humidity and Dryer Control, The Foxboro Co. Publication 413-6, Foxboro, MA

Treybal, Robert E., Mass-Transfer Operations, McGraw-Hill Book Co., New York, 1955