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ABSTRACT

High intensity paper drying is defined as any drying process in which the web is at or above the thermodynamic saturation temperature corresponding to the ambient pressure. Rapid generation of vapor under these circumstances causes the drying process to be driven by a gradient of total pressure and not by a gradient of partial vapor pressure. Therefore, the generated vapor leaves the web by a bulk (convective) flow mechanism rather than a slower diffusion mechanism. The vapor pressure build-up in the web also offers the opportunity for removal of moisture in liquid form, since the fast flowing vapor can displace and/or entrain liquid as it moves through the web. This can result in significantly lower energy usage relative to conventional drying, since only a fraction of the moisture has to be evaporated.

The thesis objective is a mathematical model simple enough to be easily modified or expanded but comprehensive enough to be applicable to a wide variety of process conditions and sheet variables.

Early experiments suggested that the high intensity drying process could be described effectively by a discrete "zone" model. The process is idealized by picturing the sheet as composed of different zones which contain various amounts of fiber, liquid water, and water vapor. The model is based on sets of equations which account for the heat and moisture transfer within and among the zones during three regimes: heatup, transition, and quasi-static. Once the hot surface temperature, boiling point temperature, basis weight, Canadian Standard Freeness, initial moisture ratio, and mechanical pressure pulse are specified, the equations may be solved to predict the moisture content as a function of time.

Comparisons between experimental data and the model's predictions demonstrate that the model qualitatively and quantitatively describes high intensity drying
behavior and provide indirect evidence that the mechanisms on which the model is based actually are in effect under high intensity conditions. An exploratory parametric study shows that the predicted drying behavior is most sensitive to changes in hot surface temperature and sheet basis weight. Peak pressure and freeness have a more moderate effect, and initial moisture ratio has almost no effect. Comparisons to laboratory data show that the model tends to overpredict the extent of liquid moisture removal and underpredict the heat flux. Changing the values of constants in the model modifies the predictions and suggests that a mathematical optimization of all constants, constrained by experimental data, would improve the predictive capability of the model.
INTRODUCTION

Low heat transfer rates, low drying rates, and low mechanical pressures characterize conventional can drying of paper. Moisture removal is dominated by a vapor diffusion mechanism, and average sheet temperatures are well below the boiling point.

In contrast, high intensity drying occurs at high surface temperatures and high mechanical pressures. Heat transfer rates and drying rates are orders of magnitude above those in the conventional process (see Fig. 1 and 2). Moisture removal is dominated by bulk (convective) vapor flow and liquid displacement or entrainment, and sheet temperatures frequently exceed the boiling point.

Mathematical modeling provides a convenient and comprehensive means for exploring the effects of temperature, pressure, freeness, and other factors on high intensity drying behavior. Mathematical modeling complements experimental study by identifying incomplete areas in knowledge of the physical system and suggesting areas for further research. Finally, mathematical modeling offers the opportunity for blending and balancing theoretical and empirical relationships to provide a fast, low-cost investigative tool.

Early experiments indicated that high intensity drying could be described effectively by a discrete "zone" model, since the drying behavior is consistent with other examples of phase change problems involving the development of zones. Initially, two zones of different moisture content were assumed to be present. As more information became available, additional zones were added to the model. Fundamental mass and energy balances for the zones are linked by the boundary conditions and the conditions at the interfaces between the zones. Solving the system of equations allows a prediction of the temperature distribution within
the sheet, the positions and rates of advance of the interfaces, and the moisture content of the sheet as functions of time.

![Diagram of water removal rates at different applied mechanical pressures for various drying methods.](image)

**Figure 1.** Water removal rates at different applied mechanical pressures for various drying methods.

This thesis presents the objective, experimental background, theoretical background, assumptions, and equations of the model. A parametric study details changes in the model's predictions resulting from changes in process variables. A sensitivity analysis shows the effects of varying certain model constants, and direct comparisons to experimental data demonstrate that the model qualitatively and quantitatively describes high intensity drying behavior.
Figure 2. Water removal rates at different hot surface temperatures for various drying methods.
OBJECTIVE

The objective of this thesis is the creation of a mathematical model of high intensity drying simple enough to be easily modified or expanded but comprehensive enough to be applicable to a wide variety of process conditions and sheet variables. The mechanisms of bulk vapor flow and liquid displacement are analyzed within the framework of a moving boundary model, and comparisons to experimental data are used to verify that the model describes high intensity drying behavior.
EXPERIMENTAL BACKGROUND

INTRODUCTION

High intensity paper drying occurs when the web is at or above the thermodynamic saturation temperature corresponding to the ambient pressure. This definition encompasses press drying, where the web is heated from both sides symmetrically, and the "one-sided" drying methods: thermal/vacuum drying, where the web is dried in a reduced pressure environment; impulse drying, where the web is dried in a heated press nip; and one-sided drying where temperatures and mechanical pressures are elevated above conventional conditions. The conventional conditions are a reference state of surface temperatures from about 127 to 171°C (260 to 340°F) and mechanical pressures from 1.2 to 7 kPa (0.17 to 1 psi). High intensity conditions are on the order of 177 to 399°C (350 to 750°F) and 7 to 4826 kPa (1 to 700 psi).

Experimental investigations into high intensity drying are extensions of the mechanistic studies of conventional paper drying. Within the range of conventional operating conditions, increases in surface temperature and/or mechanical pressure lead to increases in drying rate. Recent publications cite several references in this area, provide data at higher temperatures and pressures, and cite an example of press drying work at very high temperatures and pressures that shows the trend of increasing drying rate continues well beyond conventional conditions. It is clear that a dramatic increase in the drying rate is observed whenever the sheet temperature can be brought to or above the boiling point.
EXPERIMENTAL RESULTS

Figure 3 shows the configuration for the high intensity drying process modeled in this thesis. The paper contacts an impermeable heated surface directly. A felt, wire, or other highly porous material provides an escape path for the vapor and liquid to be removed from the paper, and another impermeable surface is used to exert mechanical pressure on the system. This arrangement causes one-sided heating of the paper. The overall heat and mass transfer are one-dimensional in the direction away from the hot surface. For experimental purposes, thermocouples are placed at various locations in the sheet so that the temperature distribution can be monitored throughout the course of drying.

Figure 3. Configuration for one-sided high intensity drying.

Figure 4 depicts a typical sheet temperature history from several types of high intensity drying experiments.\textsuperscript{6-8} It is important to note that all thermocouples reach a plateau value equal to or above the boiling point at approximately the same time and that this time is much shorter than the time needed to
simply conduct heat to the far thermocouples. The square roots of the times when the temperatures begin to rise above their plateaus are proportional to the distances of the thermocouples from the hot surface. When the temperature exceeds the boiling point, the vapor pressure exceeds the ambient pressure. The extent of the rise is related to the flow resistance of the sheet. The peak pressure is much higher in the high flow resistance cases than in the low flow resistance cases.\(^9\)

Figure 4. Internal sheet temperatures during high intensity drying.
Figure 5 shows a qualitative comparison between drying rates for conventional and high intensity drying. Four outstanding features differentiate the processes. In high intensity drying the peak drying rate is much greater than in conventional drying. In high intensity drying the peak rate is achieved (almost) instantaneously, but there is a significant heatup time required in conventional drying. The high intensity drying time is much shorter than the conventional drying time, and most importantly from a mechanistic point of view, high intensity drying does not exhibit a "constant rate" period as conventional drying does.

![Graph comparing drying rates](image)

Figure 5. Comparison of high intensity and conventional drying rates.

Figure 6 depicts the results of a study designed to track the liquid distribution in the sheet. A nonvolatile LiCl tracer is incorporated into the sheet during formation. This tracer moves with liquid water movement. After drying,
a cross section of the sheet is analyzed with the EDAX electron microscope technique to determine the location of the tracer. For conventional drying, most of the tracer is found near the side of the sheet which was adjacent to the hot surface. High intensity drying shows an opposite tracer distribution.

![Diagram showing tracer distributions for conventional and high intensity drying.]

Figure 6. Comparison of tracer distributions for high intensity and conventional drying.

The experimental results lead to the postulation of three dominant mechanisms operative during high intensity drying: bulk vapor flow, liquid displacement and/or entrainment, and the development of zones within the sheet.

BULK VAPOR FLOW

Simple visual observation of a high intensity drying experiment is enough to suggest convective vapor flow. Vapor is forcibly ejected from the sheet. Even under impulse conditions where the nip residence time is as short as 0.005 second, a vapor pulse exiting the sheet is clearly visible. The rapid temperature rise
of thermocouples far from the hot surface supports this mechanism (see Fig. 4). The drying rate is insensitive to ambient air flow rate, and this would not be true if diffusion were dominant since a diffusion mechanism would depend on convective transport external to the sheet. Finally, direct experimental evidence of vapor flow under a vapor-pressure-gradient driving force comes from a study of steady state heat transfer in a granular porous medium and work involving heat pipes. Darcy's law can be used to model the vapor flow in these cases, and while they are not examples of "drying," the fundamental transport mechanisms are identical.

**LIQUID DISPLACEMENT**

Liquid in the larger pores of a fibrous material can be displaced by a flowing gas. Devices for dewatering paper by passing air through the wet web were described in a patent filed for in March, 1963 and granted November 8, 1966. Extensions of this concept have shown that pressure differentials across the sheet on the order of 7 to 210 kPa (1 to 30 psi) can raise solids content from the 10 to 30% range up to the 40 to 45% range. For textile materials, steam pressurized at up to 700 kPa (100 psi) can be used to preheat the web, displace liquid, and raise solids content from around 20% to nearly 80%.

High intensity drying achieves its pressure driving force by vaporizing some liquid in the vicinity of the hot surface. As the vapor tries to escape, it pushes or entrains interfiber liquid out of the sheet. Figure 6 indicates the flow of liquid away from the hot surface. Heat flux determinations reveal that the actual thermal energy input can be on the order of 50% or less than the energy which would be required to raise the sheet to the boiling point and then evaporate all the liquid at that temperature.
Therefore, water has to be removed in liquid form. High intensity, vapor-induced expulsion of liquid droplets has been observed for other porous materials as well.\textsuperscript{22} Note that since the necessary condition for liquid displacement is a vapor pressure differential across the web, the symmetrical heating of the press drying process precludes this mechanism.

**Mechanical Dewatering**

High-pressure, short-duration mechanical pressing of paper is a fundamental water removal method used prior to conventional drying. The extent of the dewatering is controlled by the relationship between the applied pressure and time and by either the flow resistance or compressibility of the sheet (or both). In addition to bulk vapor flow and vapor-induced liquid displacement, the temperature and pressure levels in impulse drying encourage effects similar to those found from pressing at higher than normal temperatures.

Pressing at up to \(90\,^\circ\text{C} (194\,^\circ\text{F})\) can take a sheet at ingoing solids content of \(38\%\) and raise it to nearly \(50\%\), depending on temperature, basis weight, and freeness.\textsuperscript{23,24} Additionally, hot pressing offers the possibility for moisture profile control.\textsuperscript{25} Hot pressing and impulse drying use temperature to decrease the viscosity and surface tension of the water and to decrease the sheet compression resistance. Lower viscosity allows the liquid to flow more easily; this factor should be of key importance in a flow controlled situation. Lower compression resistance allows the sheet to be deformed more easily and should therefore be of key importance in a compression controlled case, particularly when a high percentage of lignin is present. Lower surface tension should benefit both cases by reducing capillary pressure and the possibility of rewetting.
ZONE DEVELOPMENT

Figure 6 indicates the presence of two main zones within the sheet at the end of drying: a zone of lower moisture content close to the hot surface and a zone of higher moisture content, created by liquid flow, far from the hot surface. This in itself is no guarantee of a uniform moving front that progresses through the sheet, but when there is no constant rate drying period (see Fig. 5) and the external boundary layer does not affect the drying, then a simple approach to modeling the phenomenon is with a moving boundary or zone model. The proportionality of the square roots of plateau rise times to thermocouple distances in Fig. 4 is compatible with the classical moving boundary problem called the Neumann problem and suggests that an elementary model of high intensity drying might be based on a Neumann-like analysis.

SUMMARY

There is experimental evidence to indicate that high intensity drying might be conveniently described by a moving boundary or zone model based on the bulk vapor flow and liquid displacement mechanisms. In the case of impulse drying, the additional effects of high temperature pressing may contribute to the overall moisture loss by changing the physical properties of the liquid water and/or the sheet compressibility. The similarities between high intensity drying behavior and a classical moving boundary problem suggest a logical starting point for the mathematical modeling.
INTRODUCTION

Muehlbauer and Sunderland\textsuperscript{28} present a brief summary of the Neumann problem and an excellent review of the mathematical investigations of moving boundary problems up until 1965. Substantial work in this area since then has centered on obtaining solutions to moving boundary problems with boundary and/or initial conditions or assumptions about key thermal properties which are different than those in the original and early analyses. Generally, the problems deal with one-dimensional heat transfer through one phase of a material to the interface with a different phase of the same material. The models usually treat melting or solidification problems, and mass transfer is not considered except in rare cases of convection in the liquid phase. The models either calculate the temperature or enthalpy distribution and position of the interface within the material or track the positions of isotherms that progress through the material.

TEMPERATURE-BASED MODELS

The original temperature-based model was formulated by Neumann. Details of the model are in.\textsuperscript{27} Heat conduction equations for each phase or "zone" coupled with appropriate initial, boundary, and interface conditions allow a prediction of the temperature distribution and interface position within a semi-infinite medium. Extensions of this model allow for phase transitions over a range of temperatures\textsuperscript{29,30} and a modified rate of interface advance due to the different densities of the two phases.\textsuperscript{31} Simple dependence of thermal conductivity on temperature is treated analytically,\textsuperscript{32} and clever numerical schemes handle more complicated dependencies of conductivity and density.\textsuperscript{33,34}
The primary problems with these methods, with reference to drying, are that they deal only with semi-infinite media and that they deal only with the presence of a one-component (multiphase) system. Paper behaves as a finite medium with regard to heat transfer during drying and contains two or more components (fiber, water, air, etc.). Integral transform methods have been applied to solve the problem in finite media of various geometries and with boundary conditions of the first, second, and third kinds, but the problem of multiple components remains.

ENTHALPY-BASED MODELS

When knowledge of the exact position of a phase change interface is not required, modeling the system in terms of an enthalpy equation often leads to greatly simplified (numerical) solution methods. In elementary cases, the solution of the enthalpy-based analysis is identical to that of the analytical temperature-based problem. In this method, the temperature-based model is formulated and then converted to an enthalpy-based model by using a relationship between temperature and enthalpy. This relationship describes the latent heat effect as a large jump in heat capacity over a very narrow temperature range. The advantages of this approach are: there are no conditions to be satisfied at the phase change boundary; there is no need to track the position of the phase change boundary accurately; there is no need to consider the regions on either side of the boundary separately; and it is possible to vary the range of temperatures over which the transition takes place. It is also relatively easy to extend this technique to more than one dimension.

The disadvantage of this method is that it can lead to problems when convective effects need to be considered. In a model of high intensity drying,
convection of vapor and liquid is a key mechanism, and so an enthalpy-based method is not directly applicable.

POSITION-BASED MODELS

The Isotherm Migration Method (IMM) and its modifications are alternatives to the temperature- and enthalpy-based approaches. IMM tracks the position of a given isotherm within the medium, and distance replaces temperature as the dependent variable. It is another attempt to avoid calculating the exact position of the phase change front.

While IMM is flexible and capable of handling more than one moving front, it is limited because it requires some analytical solution to "start" the process. This analytical solution is an exact solution for very short times, places all isotherms in the slab, and sets an initial temperature profile to start the finite difference numerical scheme. Thus, IMM is somewhat limited in that an analytical solution may not exist to start the process. The lack of an analytical starting solution, however, is a relatively minor shortcoming compared to its inability to handle convective aspects of problem.

DRYING MODELS

Drying differs significantly from simple moving boundary problems, since drying involves simultaneous heat and mass transfer. Furthermore, drying takes place within a matrix of solid material from which a volatile component is evaporated. The strong coupling of heat and mass transfer in drying thus requires a careful extension of the general concepts of moving boundary problems.

An exact solution of an evaporation problem in porous media has been known since 1975. This is the most elementary case involving constant surface
temperature, constant evaporation temperature, and a semi-infinite medium. Penetrating front models for finite media have evolved, generally for freeze drying applications. The geometry of the models is such that the medium is heated either symmetrically or with one face perfectly insulated and impermeable. The heat and mass transfer occur in opposite directions, and therefore these models are directly applicable only to press drying or to drying in which the heated surface is permeable.

Most models do not account for the hygroscopic nature of the matrix, but models for drying of wood and other materials do include this factor. However, these also involve opposite heat and mass transfer.

Models which calculate the pressure rise inside the porous medium are not applicable because they either use a diffusion mechanism for vapor transport or they assume a constant evaporation temperature but calculate the vapor flux based on a total pressure gradient. These are also opposite heat and mass transfer cases.

Strek and Nastaj have used the moving boundary concept to model the falling rate period in vacuum drying of a bed of granular material. Heat and mass transfer are in the same direction, but the experimental conditions are drastically different than those in high intensity paper drying. Mild temperature gradients and large bed thicknesses lead to very long drying times. The nature of the granular material is unlike that of cellulose papermaking fibers; the bed is not compressible and thickness is not sensitive to changes in moisture content.

Baines used a moving boundary concept to model a conventional drying process, and Ahrens used the concept in modeling high intensity drying. The Ahrens model is highly simplified and based on descriptions of the physical
processes dominant in high intensity conditions. The model is mathematically identical to an elementary analysis of the one-dimensional freezing of water. The Ahrens model gives reasonable agreement with experimental data and serves as the starting point from which this thesis has been developed.

SUMMARY

Moving boundary models in general prove unsatisfactory for the description of high intensity drying because: they deal with only one component; they assume a constant phase transition temperature equal to the normal phase transition temperature of the one component; they model processes with heat and mass transfer in opposite directions; they usually deal only with boundary conditions of the first kind; they do not account for vapor-pressure-induced liquid convection; and/or they present analytical solutions only for semi-infinite media.

Of the drying models, an elementary one possesses the required characteristics to be used as a starting point for further development. The Ahrens model, which is mathematically identical to a simplified analysis of a freezing water problem, is the starting point of this thesis.
THE MATHEMATICAL MODEL

INTRODUCTION

For modeling purposes, the high intensity process is pictured as a series of linked mechanisms. As the sheet is brought into contact with the hot surface, heat flow into the sheet through a finite contact resistance raises its temperature in a "heatup" regime. The contact resistance depends on the mechanical pressure and on the degree of saturation of the sheet next to the hot surface. Because of the high thermal diffusivity of the (metal) hot surface, its temperature does not change much in reality and remains constant in the mathematical model.

If the sheet surface temperature adjacent to the hot surface becomes incrementally greater than the thermodynamic saturation temperature corresponding to the ambient pressure, then the vapor pressure difference across the sheet is assumed to cause slug flow of the interfiber liquid and air. The position of this slug flow interface defines the limit of linear temperature gradients and thermodynamic saturation so that no vapor flows into the outer zone until the temperature gradient there becomes linear due to heat transfer by conduction and liquid convection within the sheet.

If the sheet becomes saturated before the inner surface temperature exceeds the boiling point, liquid water starts to be mechanically expressed from the sheet and vapor induced liquid flow does not begin until the inner surface temperature exceeds the thermodynamic saturation temperature corresponding to the hydraulic pressure at the inner surface.

Once vapor induced liquid flow starts, the sheet is in the "transition" regime where zones of different moisture content develop inside the sheet. A dry zone is created by evaporation. A zone with water trapped inside the fibers is created
when interfiber water is pushed ahead and the evaporative front has not yet reached the trapped water. If the heat transfer is such that the sheet's outer surface temperature exceeds the boiling point, then a second evaporative front can move into the sheet if the rate of liquid flow toward the cool side is less than the rate of evaporation there.

The "linear" or quasi-static regime begins when all temperature gradients become linear due to heat transfer or when they become linear because all interfiber water has been removed (and the interface defining the limit of linear gradients no longer exists).

ELEMENTARY MODELS

The Ahrens model is formulated to describe macroscopic trends and is based on a few of the physical processes judged to be controlling under high intensity conditions. Figure 7 diagrams the configuration considered.

The paper is divided into a dry zone (devoid of liquid water) adjacent to the hot surface and a wet zone with stagnant liquid adjacent to the dry zone. \( \delta \) is the time-varying dry zone thickness and \( \delta_T \) is the total thickness of the fully dry sheet. The wet zone is assumed to be at the boiling point temperature \( (TB) \) that corresponds to the ambient pressure. Thus, there is no heatup or transition regime.

The process is considered to be controlled by the rate of heat transfer from the hot surface (at constant temperature \( TH \)) to the paper. The vapor generated at the dry-wet interface flows through the partially saturated wet zone and out of the sheet. The flow resistance of the wet zone is considered to be negligible so that the vapor is generated essentially at \( TB \). (In any case, the difference between the interface temperature and \( TB \) would be much less than the
difference between TH and TB). The state of the system is described by an equation for heat flux

\[ Q = U(TH - TB) \]  

(1)

where Q is the heat flux and U is the overall heat transfer coefficient. As a consequence of assuming a linear temperature gradient in the dry zone, U is defined by

\[ \frac{1}{U} = \frac{1}{Hc} + \frac{\delta}{Kd} \]  

(2)
where \( H_c \) is the thermal contact coefficient between the hot surface and the sheet and \( K_d \) is the thermal conductivity of the dry zone (both assumed constant). The interface energy balance is

\[
Q = \varepsilon * S * \rho_w * \Delta h * \frac{d\delta}{dt}
\]  

(3)

where \( \varepsilon \) and \( S \) are the porosity and saturation of the wet zone, \( \rho_w \) is the density of water, \( \Delta h \) is the latent heat (all assumed constant), and \( t \) is time; and the relative mass of water removed is

\[
M_{REL} = \frac{\delta}{\delta_T}
\]  

(4)

Equations (1) through (3) can be combined to solve for \( \delta \) as a function of time by separating the variables and using the initial condition that \( \delta = 0 \) at time \( t = 0 \). The moisture removal (drying curve) is then given by:

\[
M_{REL} = \sqrt{\frac{1}{B_I^2 + \tau}} - \frac{1}{B_I}
\]  

(5)

where \( B_I \) is the dimensionless Biot number defined by:

\[
B_I = \frac{H_c * \delta_T}{K_d}
\]  

(6)

and \( \tau \), a dimensionless time variable, is defined by:

\[
\tau = \frac{2 * K_d * (T_H - T_B) * t}{\Delta h * M_0 * \delta_T}
\]  

(7)

where \( M_0 \) is the initial mass of water present per unit area.
The limiting case of "perfect" thermal contact between the sheet and hot surface (BI = ∞) reduces to a zone model with the interface location being directly proportional to the square root of time. Figure 8 graphs the results and gives some comparisons to experimental data.

Figure 8. Moisture removal as a function of dimensionless time with Biot number as a parameter for the Ahrens model.

If the permeability of the wet zone were zero, heat transferred by conduction would cause an evaporative front to move into the sheet from the cool side
toward the hot side. Making the same assumptions as in the Ahrens model (stagnant liquid, constant properties, etc.) allows a calculation of moisture loss from:

\[
\text{MREL} = 1 + \frac{1}{B_I} - \sqrt{1 + \frac{2}{B_I} + \frac{1}{B_I^2} - \tau}
\] (8)

where \(B_I\) and \(\tau\) are calculated based on the wet zone thermal conductivity and \(\delta_T\) is the initial sheet thickness. Figure 9 shows the drying curves for this model.

Figure 9. Moisture removal as a function of dimensionless time with Biot number as a parameter for the second limiting case.
DESCRIPTION OF THE ADVANCED MODEL

This thesis is developed from the Ahrens model of high intensity drying. The elementary analysis is extended by accounting for flowing liquid, elevated phase transition temperatures resulting from sheet flow resistance, and hygroscopic effects on latent heat at zone interfaces. The advanced model idealizes the high intensity paper drying process by picturing the sheet as composed of different zones which contain various amounts of fiber, liquid water, and water vapor. The model is based on sets of equations which account for the heat and moisture transfer within and among the zones during three regimes: heatup, transition, and quasi-static. Once the hot surface temperature, boiling point temperature, basis weight, Canadian Standard Freeness (CSF), initial moisture ratio, and mechanical pressure pulse are specified, the equations may be solved to predict the moisture content as a function of time.

The heat and mass balance equations are combined with supplementary equations that describe the nature of the pressure pulse; the liquid and vapor physical properties; and the thermal, compression, and permeability properties of the sheet. The complete model is converted to a FORTRAN program called HIDRYER1.

The program is used to run simulations of various drying conditions by calculating the rates of interface advance, multiplying the rates by a small time increment, and adding to the old values to obtain updated estimates of interface position, zone basis weight, and sheet moisture content.

ASSUMPTIONS

The fundamental assumptions of the model are listed in this section. Other assumptions are listed as they are invoked.
A1. Heat is transferred to the sheet from the hot surface by conduction only.

A2. The hot surface is an impermeable boundary.

A3. There is no conductive heat flux from the sheet to the felt.

A4. The vapor pressure at the sheet-felt interface is equal to the ambient pressure because of the negligible felt flow resistance.

A5. Heat and mass transfer occur only in one dimension.

A6. In the continuity equation, vapor and liquid storage terms within a zone are negligible.

A7. Change of phase occurs only at the zone interfaces.

A8. Porosity, saturation, and physical properties are uniform within a zone, but can differ from one zone to another and vary with time.

A9. Darcy's law is sufficient to describe liquid and vapor flow.

A10. The fiber flow can be described by a compression equation such that the fiber velocity at any point in a zone is linearly related to the velocities of the interfaces bounding the zone.

A11. Potential and kinetic energy contributions to the energy equation are negligible compared to thermal energy transfer.

A12. Conversion of mechanical energy to thermal energy is negligible.

A13. In energy calculations, the density, thermal conductivity, and specific heat of water vapor are negligible compared to those quantities for liquid water and fiber.

A14. Local thermal equilibrium exists at all points.

A15. Gravity effects are negligible.

A16. A representative value for the vapor and liquid physical properties of a zone may be obtained by calculating the values of
these properties at the temperatures of the interfaces bounding the zone and averaging the results.

A17. There is no net capillary force on a zone and there is no capillary pressure gradient within a zone.

A18. Fibers have a zero lumen volume and, in zones where water is present, a constant apparent cell wall density equal to 1.0 g/cc.\textsuperscript{59}

A19. Hygroscopic effects on vapor pressure reduction and moisture distribution in the zones are neglected.

A20. As the inner zones develop, air is pushed ahead of the progressing interfaces so that the gas in zones with linear temperature gradients is composed of vapor only.

Assumptions A1 through A4 are the overall boundary conditions on the sheet. A1 simply states that radiation heat transfer to the sheet from the hot surface is negligible. Paper emissivity is low and the hot surface-to-sheet temperature difference declines rapidly after contact. A2 means that the hot surface is solid, not porous, and no mass is transferred through it. A3 indicates that the thermal contact from the sheet to the felt is minimal compared to the contact between the hot surface and sheet. A4 means that there is no substantial pressure differential across the felt. Note that this is a condition on the pressure at the outer surface, not a condition on the temperature there.

A5 is an approximation to the overall direction of heat and mass transfer because the thickness of the sheet is much less than the lateral dimensions.

A6 through A8 pertain to the continuity equations for the model. A6 is an assumption of slug flow to simplify the transport calculations. A7 and A8 allow each zone to be characterized by its own unique value of moisture content and
state that this moisture content is not altered by vapor condensing within the zone.

A9 and A10 are for the momentum equations. Darcy's law is the momentum equation for flowing liquid and vapor. Calculations show that the Reynolds number is well within the appropriate regime for suitable application of Darcy's law. A10 allows the momentum equation for the deforming fiber bed to be replaced by a simple compression equation and states that each zone undergoes its own uniform compression.

Assumptions All through A15 pertain to the energy equation. All are standard assumptions used in drying models. A16 is made so that unique values can characterize a zone's vapor and liquid properties and variations with position in the zone can be neglected.

A17 might appear to be the most questionable approximation. The capillary pressure is typically calculated with the Laplace equation

\[
P_{\text{cap}} = \frac{2 \gamma \cos \theta}{r}
\]

where \( P_{\text{cap}} \) is the capillary pressure, \( \gamma \) is the liquid surface tension, \( \theta \) is the contact angle, and \( r \) is the pore radius. First, this applies to pores of circular cross section and therefore should NOT apply to paper since it has irregularly shaped pores. Second, at high drying temperatures the surface tension of water is drastically reduced and this serves to decrease \( P_{\text{cap}} \). Third, even at elevated mechanical pressure there are still many pores in the sheet with large radii. Fourth, the equation applies to a SATURATED pore, and it requires very
large mechanical pressures to achieve interfiber saturation. Therefore, at least in the initial stages of drying, the larger pores remain unsaturated.

When the sheet does become saturated, then a significant capillary pressure might be expected. However, it is exactly in this regime (wet pressing) that moisture loss by liquid expression dominates water removal and so the "drying" (evaporative) aspect becomes a secondary process. Thus, A17 may not be as bad an approximation as it would first appear to be. The net result is that the liquid pressure (and its gradient) is identical to the vapor pressure (and its gradient).

A18 is a means of trapping a certain fraction of liquid inside the fibers, thereby making it unavailable for vapor-induced displacement. Since the actual density of cellulose is about 1.55 g/cc, an apparent cell wall density of 1.0 g/cc means that roughly one-third of the fiber volume can contain liquid. Given the density of water and a "typical" fiber cross-sectional area, it is possible to determine the moisture ratio at which the fibers just become saturated.

Furthermore, by holding the apparent cell wall density fixed, a limit is placed on the minimum porosity attainable. Compressing the sheet is equivalent to moving the fibers closer together. The porosity of the zone can be no lower than the fiber wall porosity (about 0.33). In dry zones, A18 allows the porosity to go to zero by removing the apparent cell wall density restriction. Since there is no water there to occupy the space, the fiber wall can collapse.

A19 is made so that the moisture distribution in a zone can be treated as uniform and so that the vapor pressure is simply a function of the temperature. However, the hygroscopic effect on the heat of desorption is accounted for, since it strongly influences heat transfer calculations. This is detailed later in the thesis.
A20 is a convenience to simplify the mass and energy equations in zones of linear temperature gradient (zones where vapor flow is handled by Darcy's law) and to eliminate the need for a detailed gas continuity equation in the outer zone during the transition regime.

ADVANCED MODEL EQUATIONS

Continuity and energy equations determine the temperatures and rates of change of position of the interfaces and describe the heat and mass transfer within each zone. The interfaces separate zones of different moisture content. Figure 10 shows each kind of zone that may be present and the terminology for the zones, interfaces, and temperatures. Interface 1 separates zone 1 (no liquid moisture), which is adjacent to the hot surface, from zone 2 (liquid moisture only inside the fibers). Interface 2 separates zone 2 from zone 3 (liquid moisture inside and outside the fibers), or zone 2 from zone 4 (no liquid moisture), which can develop if heat is transferred to the far side of the sheet faster than interfiber liquid can flow there. Interface 3 separates zone 3 from zone 4. If zone 3 does not exist, either because there is initially not enough moisture present to saturate the fibers or because all the interfiber liquid is pushed out or evaporated, HIDRYER1 places interface 3 at $\delta_T$.

The reasonable assumption of linear temperature gradients in zones 1 and 2 because of the low moisture contents and the porosities, and because of the low specific heat of cellulose, introduces a considerable simplification to the required calculations. For example, the energy equations for these zones are converted from partial differential equations to algebraic ones (which are easily solved provided the interface temperatures can be determined). Thus, the zone concept is a means of simplifying a more "continuous" type of model by limiting the regions over which detailed calculations have to be performed.
Figure 10. Zone, interface, and temperature designations for advanced model equations.

**Zone Continuity and Momentum Equations**

Consider the one-dimensional flow of a mixture of fibers, liquid water, and a gas composed of water vapor. Consider further that a certain fraction of the liquid water is trapped within the fibers and moves at the fiber velocity. The continuity equation is:

\[
\frac{\partial}{\partial t} (\rho_F \ast (1-\varepsilon) + \rho_w \ast (1-a) \ast \varepsilon \ast S + \rho_w \ast a \ast \varepsilon \ast S + \rho_v \ast \varepsilon \ast (1-S)) = \\
- \frac{\partial}{\partial z} (\rho_F \ast (1-\varepsilon) \ast V_f + \rho_w \ast (1-a) \ast \varepsilon \ast S \ast V_f) \\
+ \rho_w \ast a \ast \varepsilon \ast S \ast V_{\text{water}} + \rho_v \ast \varepsilon \ast (1-S) \ast V_{\text{gas}})
\]  

(10)
where $\rho_F$, $\rho_W$, and $\rho_V$ are the fiber, water, and vapor densities; $a$ is the fraction of liquid water external to the fibers; $V_f$, $V_{water}$, and $V_{gas}$ are the fiber, water, and vapor velocities relative to the fixed origin; $z$ is the position coordinate and $t$ is time.

Darcy's law, the momentum equation for the flowing gas and liquid, is used to describe the velocities of the flowing gas and liquid relative to the moving fibers.\(^6\)

$$V_v = \varepsilon * (1-S) * (V_{gas}-V_f) = -\frac{Ka * K_v}{\mu_v} * \frac{\partial P_v}{\partial z} \quad (11)$$

$$V_w = a * \varepsilon * S * (V_{water}-V_f) = -\frac{Ka * K_w}{\mu_w} * \frac{\partial P_w}{\partial z} \quad (12)$$

where $V_v$ and $V_w$ are the vapor and liquid superficial velocities relative to the moving fibers; $K_a$ is the absolute permeability; $K_v$ and $K_w$ are the vapor and liquid relative permeabilities; $P_v$ and $P_w$ are the vapor and liquid pressures; and $\mu_v$ and $\mu_w$ are the vapor and liquid viscosities.

With these definitions, the continuity equation can be written as:

$$\frac{\partial D}{\partial t} = -\frac{\partial}{\partial z} (D * V_f + \rho_w * V_w + \rho_v * V_v) \quad (13)$$

where

$$D = \rho_F * (1-\varepsilon) + \rho_w * \varepsilon * S + \rho_v * \varepsilon * (1-S) \quad (14)$$

However, $\rho_v \ll \rho_w < \rho_F$, and with

$$S = \frac{(1-\varepsilon) * MR * \rho_F}{\rho_w * \varepsilon} \quad (15)$$
then

\[
D = \rho_f \ast (1-\varepsilon) \ast (1+MR) \tag{16}
\]

where MR is the moisture ratio.

The momentum equation for each zone of the fiber matrix is replaced by a power law compression equation:

\[
C = M \ast P^N \tag{17}
\]

where \(C\) is the dry fiber concentration (mass/total volume), and where each zone has its own compression constants (\(M\) and \(N\)) and effective mechanical pressure \(P\); the assumption of uniform zone compressibility gives

\[
V_f = \frac{\bar{L}}{L} \ast \frac{\partial L}{\partial t} + V_f' \tag{18}
\]

where \(\bar{L}\) is the distance inside the zone measured from the zone's interface closer to the origin, \(L\) is the zone thickness, \(\partial L/\partial t\) is the "compression velocity" or change in zone thickness caused by \(P\), and \(Vf'\) is the compression velocity of the zone interface closer to the origin with respect to that (fixed) origin.

For an unsaturated medium during the heatup regime, make the approximation that \(V_{\text{water}} = V_f\) so that \(V_w = 0\). (This is a compression model, not a wet pressing model.) For this case, and for an unsaturated or saturated zone in the transition or linear regimes, use assumption A6 so that the continuity equation becomes

\[
\frac{\partial}{\partial t} \left( \frac{\partial}{\partial z} \right) (D \ast V_f) \tag{19}
\]
If the sheet becomes saturated during heatup, its compression is significantly affected by the buildup of a substantial internal hydraulic pressure.

The overall continuity equation can be separated into its fiber and water components and combined with Darcy's law to produce:

\[
\frac{\partial}{\partial t} \frac{3}{2} \frac{MR}{L} = \frac{\rho_w}{(1-\varepsilon)} \cdot \frac{K_a \cdot K_w}{\mu_w} \cdot \frac{\partial^2 P_w}{\partial z^2}
\]  

(20)

Write \(\partial MR/\partial t\) as \((\partial MR/\partial L) \cdot (\partial L/\partial t)\) and when \(S = 1\), \(\partial MR/\partial L = \rho_w/\beta W\) where \(\beta W\) is the sheet basis weight. With \(\beta W/L = (1-\varepsilon) \cdot \rho_F\) and \(K_w = 1\) when \(S = 1\), Eq. (20) becomes

\[
\frac{1}{L} \frac{\partial}{\partial t} \frac{3}{2} L = \frac{K_a \cdot 2}{\mu_w} \frac{\partial^2 P_w}{\partial z^2}
\]  

(21)

Let

\[P_w = A_1 + A_2 \cdot z + A_3 \cdot z^2\]  

(22)

so that

\[
\frac{\partial P_w}{\partial z} = A_2 + 2 \cdot A_3 \cdot z
\]  

(23)

and

\[
\frac{\partial^2 P_w}{\partial z^2} = 2 \cdot A_3
\]  

(24)

At \(z = 0\), \(\partial P_w/\partial z = 0\) and therefore \(A_2 = 0\). Integrating Eq. (22) from \(z = 0\) to \(z = L\) and noting that at \(z = L\) \(\partial P_w/\partial z = 2 \cdot A_3 \cdot L\) and \(P_w = \beta atm\) (the ambient pressure) allows a calculation of \(A_1\) and \(A_3\) to yield:

\[
P_w = \beta atm + \frac{\mu_w}{2 \cdot K_a \cdot L} \frac{(z^2 - L^2)}{\partial \varepsilon} \frac{\partial L}{\partial t}
\]  

(25)
For simplicity, define an integral-average hydraulic pressure such that

\[ \bar{P}_w = \text{Patm} - \frac{\mu_w L}{3 \cdot K_a} \frac{\partial L}{\partial t} \]  

(26)

and use \( P = P_{\text{mech}} - \bar{P}_w \) in the compression equation, where \( P_{\text{mech}} \) is the absolute applied mechanical pressure. The applied mechanical pressure is the sum of \( P_{\text{mechg}} \) (the gage mechanical pressure) and ambient pressure and therefore

\[ P = P_{\text{mechg}} + \frac{\mu_w L}{3 \cdot K_a} \frac{\partial L}{\partial t} \]  

(27)

With \( C = M*t^N = BW/L \) and \( K_a = 1/(R*C) \) then

\[ \frac{\partial L}{\partial t} = \frac{3 \cdot ((C/M)^{1/N} - P_{\text{mechg}})}{\mu_w \cdot BW \cdot R} \]  

(28)

\( R \), the specific filtration resistance, is a function of \( P_{\text{mechg}} \); \( P_{\text{mechg}} \) is a prescribed function of time, so Eq. (28) is an initial value problem solvable by standard numerical techniques once \( L \) at \( t = 0 \) is specified.

Zone Thermal Energy Equation

Consider a one-dimensional energy equation where energy is transferred only by conduction or convection. Using the same kinds of manipulation as in the continuity equation gives:

\[ \frac{\partial}{\partial t} (Dc \ast T) = -\frac{\partial}{\partial z} (-K \ast \frac{\partial T}{\partial z}) \]

\[ + (Dc \ast \rho_v \ast C_{pv} \ast V_v + Dc \ast \rho_w \ast C_{pw} \ast V_w) \ast T \]  

(29)

where \( T \) is temperature, \( K \) is thermal conductivity, \( C_{pw} \) and \( C_{pv} \) are the constant pressure specific heats of water and vapor, and where
\[ Dc = \rho_F \cdot (1-\epsilon) \cdot Cpf + \rho_w \cdot \epsilon \cdot S \cdot Cpw + \rho_v \cdot \epsilon \cdot (1-S) \cdot Cpv \] (30)

Cpf is the constant pressure specific heat of cellulose and with Eq. (15)

\[ Dc = \rho_F \cdot (1-\epsilon) \cdot (Cpf + MR \cdot Cpw) \] (31)

Observe that \( Dc = b \cdot D \) where

\[ b = \frac{(Cpf + MR \cdot Cpw)}{(1 + MR)} \] (32)

Expand and rearrange Eq. (29) noting that \( b \) is independent of \( z \) within a given zone and use continuity Eq. (13) to simplify; divide by \( b \cdot D \) to obtain

\[ \frac{\partial T}{\partial t} + \frac{T}{b} \cdot \frac{\partial b}{\partial t} + \frac{T}{D} \cdot \frac{\partial}{\partial z} \left( \frac{Cpw}{b} - 1 \right) \cdot \rho_w \cdot Vw + \left( \frac{Cpv}{b} - 1 \right) \cdot \rho_v \cdot Vv = \]  

\[ \frac{K}{b \cdot D} \cdot \frac{\partial^2 T}{\partial z^2} - \frac{\rho_w \cdot Cpw \cdot Vw}{b \cdot D} + \frac{\rho_v \cdot Cpv \cdot Vv}{b \cdot D} \cdot \frac{\partial T}{\partial z} \] (33)

For a nonsaturated medium \( \partial b/\partial t = 0 \) (Cpf and Cpw held constant). Using the slug flow assumption and the approximation \( \rho_v \cdot Cpv/(b \cdot D) = 0 \) gives

\[ \frac{\partial T}{\partial t} = \frac{K}{b \cdot D} \cdot \frac{\partial^2 T}{\partial z^2} - Vf \cdot \frac{\partial T}{\partial z} \] (34)

for the nonsaturated heatup regime (with \( Vw = 0 \) as before) and

\[ \frac{\partial T}{\partial t} = \frac{K}{b \cdot D} \cdot \frac{\partial^2 T}{\partial z^2} - (Vf + \frac{\rho_w \cdot Cpw \cdot Vw}{b \cdot D}) \cdot \frac{\partial T}{\partial z} \] (35)

for the saturated heatup regime and the saturated or nonsaturated outer zone during the transition regime. Equations (34) and (35) must be solved to yield the temperature profiles.
For the inner zone during transition and all zones during the quasi-static regime no energy equation is required, since all temperature gradients are assumed linear.

**Convective-Diffusion Equations**

Two general methods available for the solution of Eq. (34) and (35) are transformation of variables and numerical solution. Transform Eq. (34) by defining $x = z/L$ and $t' = t$ so that $\partial x/\partial z = 1/L$, $\partial x/\partial t = -(z/L^2) * \partial L/\partial t$, $\partial t'/\partial z = 0$, and $\partial t'/\partial t = 1$. Thus, $\partial T/\partial z = (1/L) * \partial T/\partial x$, $\partial^2 T/\partial z^2 = (1/L^2) * \partial^2 T/\partial x^2$, and $\partial T/\partial t = \partial T/\partial t' - (z/L^2) * \partial L/\partial t * \partial T/\partial x$. Since $Vf = (z/L) * \partial L/\partial t$, substitution converts Eq. (34) to

$$\frac{\partial T}{\partial t'} = \psi * \frac{\partial^2 T}{\partial x^2}$$

(36)

where

$$\psi = \frac{K}{b * D * L}$$

(37)

The initial condition is $T = T_l$ at $t' = 0$ for all $x$. The boundary conditions are: $BI * (TH - T) = -\partial T/\partial x$ at $x = 0$ and $\partial T/\partial x = 0$ at $x = L$. The first BC is a statement of the imperfect thermal contact between the hot surface and sheet with $BI = Hc * L/K$. The second BC is the assumption of no conductive heat flux from the sheet to the felt.

Equation (35) requires different transformations depending on its application to the saturated heatup or saturated or nonsaturated transition regimes. For the saturated heatup regime continuity demands $Vw = -(z/L) * \partial L/\partial t$. The same transformation of variables as for Eq. (34) gives
\[
\frac{\partial T}{\partial t'} = \psi \frac{\partial^2 T}{\partial x^2} + \phi \frac{\partial T}{\partial x}
\]  

(38)

with \(\psi\) as in Eq. (37) and

\[
\phi = -\frac{\rho_w \cdot \text{C}_{pw} \cdot \text{V}_w}{b \cdot D \cdot L} \cdot \frac{\partial L}{\partial t'}
\]  

(39)

The initial and boundary conditions are the same as before.

The application of Eq. (35) to the outer zone during transition requires a different transformation. The outer zone is designated as zone 3 and is bounded by interfaces 1 and 3 or 2 and 3. Define \(x = (z - L_2 - L_1)/L_3\) and \(t' = t\) so that \(\partial x/\partial z = 1/L_3, \partial x/\partial t = -(\partial L_1/\partial t + \partial L_2/\partial t + x \cdot \partial L_3/\partial t)/L_3\), and again \(\partial t'/\partial z = 0\) and \(\partial t'/\partial t = 1\). L_1, L_2, and L_3 are the thicknesses of zones 1, 2, and 3. Substitution into Eq. (35) yields an equation of the form of Eq. (38) with

\[
\psi = \frac{K}{b \cdot D \cdot L_3}
\]  

(40)

and

\[
\phi = \frac{\rho_w \cdot \text{C}_{pw} \cdot \text{V}_w}{b \cdot D \cdot L_3}
\]  

(41)

The value of \(\text{V}_w\) is uniform in zone 3 by the slug flow assumption and is calculated using Darcy's law (with the pressure gradient given by the vapor pressure drop across zone 3). The initial condition for this case is the temperature distribution just after the heatup regime. The boundary conditions are that the heat conducted to interface 1 or 2 is just balanced by the sum of the heat conducted into zone 3 and a "source" or "sink" term composed of the latent heat and the net condensation or evaporation at interface 1 or 2. The other boundary condition is that there is no net conductive heat flux past interface 3.
A numerical scheme is needed to solve Eq. (38). A stable, high-order accuracy, finite difference method is available which uses weighted finite differences to overcome calculational instabilities. This method also removes some severe restrictions on the time step-grid spacing combination typical of other convective-diffusion numerical solutions. The second spatial derivative is treated as a central difference:

$$\frac{\partial^2 T}{\partial x^2} = \frac{T(i+1,j) - 2 * T(i,j) + T(i-1,j)}{\Delta x^2} \tag{42}$$

where $\Delta x$ is the grid spacing, $i$ is the grid number ($i = 1$ to $i = k$), and $j$ is the time increment number. The time derivative is treated as a forward difference:

$$\frac{\partial T}{\partial t} = \frac{T(i,j+1) - T(i,j)}{\Delta t} \tag{43}$$

where $\Delta t$ is the time increment. The temperature gradient is treated as an upstream weighted difference. Since $\phi > 0$ for the outer zone cases considered in this thesis,

$$\frac{\partial T}{\partial x} = \frac{2 * T(i+1,j) + 3 * T(i,j) - 6 * T(i-1,j) + T(i-2,j)}{6 * \Delta x} \tag{44}$$

Equations 42 through 44 are combined to give

$$T(i,j+1) = (A - B/3) * T(i+1,j) + (1 - 2 * A - B/2) * T(i,j)$$

$$+ (A + B) * T(i-1,j) - (B/6) * T(i-2,j) \tag{45}$$

where

$$A = \frac{\psi * \Delta t}{\Delta x^2} \tag{46}$$
and

\[ B = \frac{\phi \Delta t}{\Delta x} \]  

(47)

and HIDRYER1 maintains

\[ \Delta t < \frac{\Delta x}{2 \psi / \Delta x + \phi / 2} \]  

(48)

Equation 45 applies from \( i = 3 \) to \( i = k-1 \). At \( i = 2 \), a central difference operator is used for \( \partial T / \partial x \) to give

\[
T(2,j+1) = (A - B/2) \times T(3,j) + (1 - 2 \times A) \times T(2,j) + (A + B/2) \times T(1,j)
\]

(49)

At the boundaries \( i = 1 \) and \( i = k \) the operative equation is derived by integrating the energy equation over a half interval. At \( x = 0 \), integrate from 0 to \( \Delta x/2 \) to obtain:

\[
\frac{\Delta x}{2} \times \frac{\partial T}{\partial \tau'(\text{avg})} = \psi \times \frac{\partial T}{\partial x} \bigg|_{0}^{\Delta x/2} - \phi \times T \bigg|_{0}^{\Delta x/2}
\]

(50)

\( \phi \) and \( \partial T / \partial \tau'(\text{avg}) \) are averages over the half interval such that

\[ \bar{\phi} = \frac{\phi (\Delta x/2) + \phi(0)}{2} \]  

(51)

and

\[
\frac{\partial T}{\partial \tau'(\text{avg})} = \frac{1}{2} \times \left( \frac{\partial T}{\partial \tau'(\Delta x/2)} + \frac{\partial T}{\partial \tau'(0)} \right)
\]

(52)

Let

\[
\frac{\partial T}{\partial \tau' (\Delta x/2)} = \frac{1}{2} \times \left( \frac{\partial T}{\partial \tau' (\Delta x)} + \frac{\partial T}{\partial \tau'(0)} \right)
\]

(53)
so that
\[
\frac{\partial T}{\partial \tau'(\text{avg})} = \frac{1}{4} \left( \frac{\partial T}{\partial \tau'(\Delta x)} + 3 \frac{\partial T}{\partial \tau'(0)} \right)
\] (54)

and Eq. (33) can be used to find the time derivatives at \(x = \Delta x\) and \(x = 0\).

Let
\[
\frac{\partial T}{\partial x(\Delta x/2)} = \frac{1}{2} \left( \frac{\partial T}{\partial x(\Delta x)} + \frac{\partial T}{\partial x(0)} \right)
\] (55)

Apply the boundary condition \(B(\ast)(TH - T(1,j)) = -\partial T/\partial x(0)\) and
\[
\frac{\partial T}{\partial x(0)} = \frac{2}{\Delta x} \int_{0}^{\Delta x/2} T \, dx
\] (56)

to get \(T(\Delta x/2)\). Let
\[
\frac{\partial T}{\partial x(\Delta x)} = \frac{-2 \ast T(1,j) - 3 \ast T(2,j) + 6 \ast T(3,j) - T(4,j)}{6 \ast \Delta x}
\] (57)

to get
\[
T(1,j+1) = T(1,j) - (T(2,j+1) - T(2,j))/3
+ 4 \ast B \ast BI \ast \Delta x \ast (TH - T(1,j))/3 + (2 \ast A/9) \ast (6 \ast BI \ast \Delta x
\ast (TH - T(1,j)) - 2 \ast T(1,j) - 3 \ast T(2,j) + 6 \ast T(3,j) - T(4,j))
\] (58)

At the cold side, integrate from \(x = 1 - \Delta x/2\) to \(x = 1\). Apply the boundary
color condition \(\partial T/\partial x(1) = 0\) and use similar averaging techniques to get
\[
T(k,j+1) = T(k,j) - (T(k-1,j+1) - T(k-1,j))/3
- (2A/9) \ast (2 \ast T(k,j) + 3 \ast T(k-1,j) - 6 \ast T(k-2,j) + T(k-3,j))
\] (59)

Observe that when \(\phi = 0\) Eq. (45), (49), (58), and (59) are solutions of Eq. (36)
and so all cases are covered.
As 62 and 63 move into the sheet, a modification of the numerical method is employed. The first grid point in the transition zone is designated as i'. The last grid point of the transition zone is designated as i". δ' and δ" are the distances of these points from the origin. Because the distance between these special grid points and the interfaces closest to them may not correspond to the usual grid point spacing, temperatures at i', i", and the grid points adjacent to them must be calculated based on uncentered finite differences.

Taylor series expansions for the temperatures at the grid points around the one in question can be added, subtracted, and combined to give

\[
T(i', j + 1) = T(i', j) - \phi \Delta t (T(i' + 1, j) - T_x)/(\Delta x + DIFF') \\
+ 2 \psi \Delta t (T(i' + 1, j)/(\Delta x + DIFF')) \\
- T(i', j)/(\Delta x \times DIFF') + T_x/(DIFF' \times (\Delta x + DIFF'))
\]

where \(T_x\) is either \(T_1\) or \(T_2\) depending on which interface is involved. The model treats the transition zone as if it were part of one large zone undergoing heating and compression. Instead of applying boundary conditions and calculating new temperatures for all the grid points, the model simply calculates the bounding interface temperatures from the interface equations and applies these temperatures directly. In terms of the relative (dimensionless) distance \(\Delta x\)

\[
DIFF' = \frac{BW3 \times (1 + BW4/BW)}{BW} - \Delta x \times (1 - i' + i'')
\]  

At the other end

\[
T(i'', j + 1) = T(i'', j) - \phi \Delta t (T_x - T(i'' - 1, j))/(\Delta x + DIFF'') \\
+ 2 \psi \Delta t \times (T_x/(DIFF'' \times (\Delta x + DIFF'')) \\
- T(i'', j)/(\Delta x \times DIFF'') \\
+ T(i'' - 1, j)/(\Delta x \times (\Delta x + DIFF''))
\]
where

$$\text{DIFF}'' = \Delta x - \frac{BW3 \ast BW4}{BW} \quad (63)$$

and $T_x$ is either $T_2$ or $T_3$. The new temperature at $i' + 1$ is found from Eq. (49). If $\text{DIFF}'$ is equal to $\Delta x$ or if the interface advances across a grid point, then Eq. (49) is also used at $i'$ and Eq. (60) is bypassed. All other interior points are calculated with Eq. (45), but the temperature at $i''$ is found with Eq. (62) if $\text{DIFF}''$ is less than $\Delta x$ and the interface does not cross a grid point.

**Interface Equations**

During the high intensity drying process zones of different moisture content develop inside the sheet. These zones are bounded by interfaces at various temperatures. The temperatures determine the rates of heat transfer and rates of change of interface position; since the interfaces separate zones of different moisture content, their positions are directly related to the overall sheet moisture content. Refer to Fig. 10 for the zones that may be present and the terminology for the zones, interfaces, and temperatures.

The "dry" zones contain water vapor. Zone 2 contains liquid water only inside the fibers. Zone 3 contains liquid water inside and outside the fibers.

Consider a "general" interface. Heat, liquid, and gas (vapor only) flow toward the interface on the (−) side close to the hot surface and flow away from the interface on the (+) side toward the felt. The net mass flux results in a change in interface position and is calculated from

$$(\rho_w \ast Vw(+) - \rho_w \ast Vw(-)) + (\rho_v \ast Vv(+) - \rho_v \ast Vv(-)) = \varepsilon \ast S \ast \rho_w \ast d\delta/dt \quad (64)$$

for interfaces 1 and 2 and
\[ \rho_w \cdot V_w(-) - (\rho_v \cdot V_v(+) - \rho_v \cdot V_v(-)) = \varepsilon \cdot S \cdot \rho_w \cdot \frac{d\delta}{dt} \quad (65) \]

at interface 3. There is no liquid flow on the (+) side of interface 3 (unless \( \delta_3 = \delta_T \)) because any flow past \( \delta_3 \) would be absorbed by the dry fibers in zone 4.

An energy balance gives

\[ Q(-) = Q(+) + (\rho_v \cdot V_v(+) - \rho_v \cdot V_v(-)) \cdot (A_h + \Delta h^*) \quad (66) \]

at interfaces 1 and 2; at interface 3 the energy balance gives

\[ Q(-) = (\rho_v \cdot V_v(+) - \rho_v \cdot V_v(-)) \cdot (A_h + \Delta h^*) \quad (67) \]

where \( \Delta h^* \) is the average heat of desorption at the interface.

Heatup and Transition Regimes

During the heatup regime there is only one zone (2 or 3) present, since the sheet starts and stays at uniform saturation. Interface 1 is at \( z = 0 \). Interface 2 is at \( \delta_T \) if zone 2 is present and at \( z = 0 \) if zone 3 is present. Interface 3 is at \( \delta_T \). It is assumed that no evaporation takes place during heatup.

When TS is raised incrementally above the saturation temperature corresponding to the hydraulic pressure at \( z = 0 \), the liquid in the pores of the sheet sees the apparent pressure gradient corresponding to the vapor pressures at TS and TB. The liquid is assumed to flow in slug flow, and \( \delta_2 \) defines the limit of thermodynamic saturation (and linear temperature gradient) so that no vapor flows past \( \delta_2 \) in transition. For the first time increment the only nonzero term of Eq. (64) is \( \rho_w \cdot V_w(+) \). By assumption, the vapor and liquid pressures are identical and Darcy's law for the flowing liquid is

\[ V_w = -\frac{K_a3 \cdot Kw \cdot \frac{\partial Pa}{\partial z}}{\mu_w \cdot \frac{3}{2} \cdot PV} \quad (68) \]
where \( K_{a3} \) is the absolute permeability of zone 3. To link the mass and energy balance equations write \( \frac{\partial P_v}{\partial z} \) as \( (\frac{\partial P_v}{\partial T}) * (\frac{\partial T}{\partial z}) \). The correct expression for \( \frac{\partial T}{\partial z} \) is \( \frac{(T_B - T_S)}{\delta_T} \), the virtual gradient that the liquid experiences. Then, from Eq. (64) and (68)

\[
\rho_w * K_{aKw} * \frac{\partial P_v}{\partial T} * \frac{(TS - TB)}{(\nu_w * \delta_T)} = \epsilon' * S' * \rho_w * D2
\]  

(69)

where \( K_{aKw} = K_{a3} * K_w \), \( \epsilon' \) and \( S' \) are the interfiber porosity and saturation (since only interfiber water flows), and \( D2 \) is the rate of change of position of \( \delta_2 \) due only to vapor-induced liquid flow. This rate multiplied by \( BW * \Delta t/\delta_T \) gives an increment in the basis weight of zone 2 and a corresponding decrement in the basis weight of zone 3. The increment or decrement is added to the old value of zone basis weight to get a new value at \( \text{TIME(new)} = \text{TIME(old)} + \Delta t \). The liquid properties are evaluated at \( TS \).

If no interfiber water exists, the transition regime is simply a continuation of the heatup regime calculation until the temperature at \( \delta_T \) is raised incrementally above \( TB \). Then, a dry zone propagates into the sheet toward the hot surface. This case is treated later.

After the first time increment, two cases can occur: \( \delta_1 \) and \( \delta_2 \) are either equal or they are unequal. When \( \delta_1 = \delta_2 \) the only nonzero term in Eq. (64) is \( \rho_w * \nu_w(+) \). Since no vapor flows \( Q(-) = Q(+) \), where \( Q(-) = U * (T_H - T_2) \) and \( Q(+) = K3 * (T_2 - T')/(\delta' - \delta_2) \). \( U \) is defined so that \( 1/U = 1/Hc + \delta_2/K1 \). \( T' \) is the temperature at the first finite difference grid point in zone 3, \( \delta' \) is the distance of this grid point from the origin, and \( K1 \) and \( K3 \) are the thermal conductivities of zones 1 and 3. From the heat balance, a new value for \( T2 \) is isolated as
Of course, when $\delta_1 = \delta_2$, $T_1 = T_2$. The mass balance gives the rate of advance of interface 2 using Eq. (69) with the (virtual) temperature gradient $(T_2 - T_3)/(\delta_3 - \delta_2)$. If $\delta_3 = \delta_T$ then $T_B$ is used in place of $T_3$.

If $\delta_1$ and $\delta_2$ are not equal, then equations are needed at both interfaces. At $\delta_1$, $\rho_v^* \nu_v(\cdot) = 0$ is the only nonzero mass flow term. Thus,

$$\rho_v \frac{K_0}{\mu_v} \frac{\partial P_v}{\partial T} \frac{(T_1 - T_2)}{(\delta_2 - \delta_1)} = \varepsilon_2 * S_2 * \rho_w * D_4$$

$D_4$ is the rate of advance of $\delta_2$ due solely to evaporation. $\varepsilon_2$ and $S_2$ are the porosity and saturation of zone 2. Vapor properties are evaluated at $T_1$ and $T_2$ and then averaged. In the heat balance, $Q(-) = U * (TH - T_1)$ and $Q(+) = K_2 * (T_1 - T_2)/(\delta_2 - \delta_1)$. Isolating for $T_1$ gives

$$T_1 = \frac{TH + I * T_2}{1 + I}$$

where

$$I = \left( \frac{1}{H_c} + \frac{\delta_1}{K_1} \right) * \frac{1}{(\delta_2 - \delta_1)} * \left( \rho_v * \frac{K_0}{\mu_v} \frac{\partial P_v}{\partial T} + K_2 \right)$$

The vapor properties, except $\Delta h$, are averaged using $T_1$ and $T_2$. $\Delta h$ is evaluated at $T_1$ only and $\Delta h^*$ is the latent heat correction factor based on the moisture ratios of zones 1 and 2.
At $\delta_2$, $\rho_w \cdot Vw(+)\) and $\rho_v \cdot Vv(-)$ are the mass flow terms. $\rho_v \cdot Vv(-)$ at $\delta_2$ is just $\rho_v \cdot Vv(+)\) at $\delta_1$. $\rho_w \cdot Vw(+)\) is derived as for Eq. (68) and (69) so that

$$\frac{\rho_w \cdot KAKW \cdot (T2 - T3) \cdot \frac{\partial P_v}{\partial T} - \rho_v \cdot Ka2 \cdot (T1 - T2)}{\mu_w \cdot (\delta_3 - \delta_2)} \cdot \frac{\partial P_v}{\partial T} = \varepsilon' \cdot S' \cdot \rho_w \cdot D5$$

(75)

$D5$ is the net rate of motion of $\delta_2$. Vapor and liquid properties are averaged with $T2$ and $T3$ or $T1$ and $T2$ as appropriate. In the heat balance, $Q(-)$ is the same as $Q(+)$ at $\delta_1$. $Q(+) = K3 \cdot (T2 - T')/(\delta' - \delta_2)$, so that

$$T2 = \frac{II \cdot T1 + T'}{1 + II}$$

(76)

where

$$II = \left(\frac{K2}{K3} + \frac{\rho_v \cdot Ka2 \cdot (\Delta h + \Delta h^*)}{\mu_v \cdot K3} \cdot \frac{\partial P_v}{\partial T} \right) \cdot \left(\frac{\delta' - \delta_2}{\delta_2 - \delta_1}\right)$$

(77)

The vapor properties are evaluated in the usual way. Equations (73) and (76) then yield

$$T1 = \frac{(1 + II) \cdot TH + I \cdot T'}{1 + I + II}$$

(78)

$$T2 = \frac{II \cdot TH + (1 + I) \cdot T'}{1 + I + II}$$

(79)

HIDRYERI calculates $T'$ and then finds $T1$ and $T2$.

If $\delta_3 = \delta_T$ and $T3$ is equal to $TB$ then

$$\frac{K3}{\Delta h + \Delta h^*} \cdot \frac{T3 - T''}{\Delta x} = \varepsilon_3 \cdot S3 \cdot \rho_w \cdot D6$$

(80)
where $T''$ is the temperature of the first finite difference grid point just toward the origin relative to $\delta_3$. If $T_3$ is less than $T_B$ then $D_6 = 0$.

The liquid mass flow to $\delta_3$ is given by the first term of Eq. (75) so that

$$\epsilon' * S' * D_2 = \epsilon_3 * S_3 * D_7 \quad (81)$$

The net change in the position of $\delta_3$ is determined by the sum of $D_6$ and $D_7$. The new value of $T_3$ comes from the finite difference temperature calculations.

If $\delta_3$ is not equal to $\delta_T$ then

$$\frac{\rho_v * K_a4 * (T_3 - T_B)}{\mu_v * (\delta_T - \delta_3)} * \frac{\partial \rho_v}{\partial T} = -\epsilon_3 * S_3 * \rho_w * D_6 \quad (82)$$

and Eq. (81) still applies. The heat balance yields

$$T_3 = \frac{T'' + III \cdot T_B}{1 + III} \quad (83)$$

where

$$III = \frac{\rho_v * K_a4 * (\Delta h + \Delta h^*)}{\mu_v * K_3} * \frac{\partial \rho_v}{\partial T} \cdot \frac{(\delta_3 - \delta'')}{(\delta_T - \delta_3)} \quad (84)$$

$\delta''$ is the distance of the $T''$ grid point from the origin. HIDRYER1 calculates $T''$ and then $T_3$.

Once the interface temperatures have been calculated, the change in interface position (zone basis weight) is performed. The rate of change of basis weights is found from:

$$DBW1DT = RATE1 * BW1/L1 \quad (85)$$
$$DBW2DT = RATE2 * BW3/L3 - DBW1DT \quad (86)$$
$$DBW3DT = (RATE3 - RATE2) * BW3/L3 \quad (87)$$
$$DBW4DT = -RATE3 * BW3/L3 \quad (88)$$
where RATE1 is either 0 or D4, RATE2 is either D2 or D5, and RATE3 is the sum of D6 and D7. These are multiplied by \( \Delta t \) and added to the old basis weight values to get new values. The temperatures at the new positions are calculated and the cycle continues.

If no interfiber water exists at the end of heatup, the transition regime is a continuation of heatup until the temperature at \( \delta_T \) is raised incrementally above TB. \( \delta_2 \) moves into the sheet toward the hot surface. There is no liquid flow term and all evaporation occurs at \( \delta_2 \). Equation (82) is applicable with \( T_3 \) replaced by \( T_2 \), \( \delta_3 \) by \( \delta_2 \), and \( \varepsilon_3 \) and \( S_3 \) by \( \varepsilon_2 \) and \( S_2 \). \( T_2 \) is calculated by Eq. (83) with appropriate substitutions.

Linear Regime

The linear (quasi-static) regime begins when \( \delta_2 = \delta_3 \) (if interfiber water is present) or when all the temperature gradients in the outer zone become linear due to heat transfer. Vapor can flow through all zones in this regime. Several possible cases exist. If \( \delta_1 = \delta_2 \) and \( \delta_3 \) is not equal to \( \delta_T \) then the heat balance gives:

\[
T_2 = \frac{(1 + I) \cdot TH + II \cdot TB}{1 + I + II} \\
T_3 = \frac{I \cdot TH + (1 + II) \cdot TB}{1 + I + II}
\]

where

\[
I = \frac{K_3}{\Delta h + \Delta h^*} + \frac{\rho_v \cdot KAV}{\mu_v} \cdot \frac{P_v}{\delta_T} \cdot \frac{(\delta_T - \delta_3)}{\delta_3 - \delta_2}
\]
and \( KAKV = Ka3*Kv \). The vapor properties in \( II \) and the numerator of \( I \) are evaluated using \( T2 \) and \( T3 \). The latent heat term in \( I \) is evaluated at \( T3 \) and corrected using the moisture ratios of zones 3 and 4. The latent heat term in \( II \) is evaluated at \( T2 \) and corrected using the moisture ratios of zones 1 and 3. The vapor properties in the denominator of \( I \) are evaluated using \( T3 \) and \( TB \).

If \( \delta_1 \) is not equal to \( \delta_2 \) and \( \delta_3 \) is not equal to \( \delta_T \) then

\[
T1 = \frac{(1 + IV) \cdot TH + T \cdot TB}{1 + I + IV} \tag{93}
\]

\[
T2 = \frac{IV \cdot TH + (1 + I) \cdot TB}{1 + I + IV} \tag{94}
\]

\[
T3 = \frac{II \cdot III \cdot TH + (1 + I + II) \cdot TB}{1 + I + IV} \tag{95}
\]

where \( I \) is given by Eq. (74) and

\[
II = \frac{\Delta h + \Delta h^*}{\Delta h + \Delta h^*} + \frac{\rho_v \cdot Ka2}{\mu_v} \cdot \frac{\partial P_v}{\partial T} \cdot \frac{(\delta_3 - \delta_2)}{(\delta_2 - \delta_1)} \tag{96}
\]

\[
III = \frac{\Delta h + \Delta h^*}{\Delta h + \Delta h^*} + \frac{\rho_v \cdot KAKV}{\mu_v} \cdot \frac{\partial P_v}{\partial T} \cdot \frac{(\delta_T - \delta_3)}{(\delta_3 - \delta_2)} \tag{97}
\]
and \( IV = II \ast (1 + III) \). Vapor properties in the numerator of II are evaluated with \( T1 \) and \( T2 \). The latent heat in II is at \( T2 \) and the correction is made with the moisture ratios of zones 2 and 3. The vapor properties in the denominator of II and the numerator of III are evaluated with \( T2 \) and \( T3 \); the denominator of III is evaluated with \( T3 \) and \( TB \). The latent heat term is at \( T3 \) and corrected with the moisture ratios of zones 3 and 4.

If \( \delta_1 \) is not equal to \( \delta_2 \) and zone 3 does not exist, then

\[
T1 = \frac{(1 + I) \ast TH + II \ast TB}{1 + I + II} \tag{98}
\]

\[
T2 = \frac{I \ast TH + (1 + II) \ast TB}{1 + I + II} \tag{99}
\]

where

\[
I = \frac{\Delta h + \Delta h^*}{\mu_v} + \frac{\rho_v \ast Ka2}{\mu_v} \ast \frac{\partial \rho_v}{\partial T} \ast \frac{\partial \rho_v}{\partial \Delta T} \tag{100}
\]

and II is given by Eq. (74). Vapor properties in the numerator of I are evaluated with \( T1 \) and \( T2 \). The latent heat is at \( T2 \) and corrected with the moisture ratios of zones 2 and 4. The vapor properties in the denominator of I are evaluated with \( T2 \) and \( TB \).

The mass transfer terms for the linear regime are similar to those previously outlined for the transition regime with the additional consideration that when \( \delta_1 = \delta_2 \) there may be evaporation and flow of vapor. The mass transfer equations that apply when \( \delta_1 = \delta_2 \) are
\[ \rho_v \frac{KAKV}{\mu_v} \frac{\partial Pv}{\partial T} \frac{(T2 - T3)}{(\delta_3 - \delta_2)} = \varepsilon_3 * S_3 * \rho_w * D_1 \]  

\[ \rho_w \frac{KAKW}{\mu_w} \frac{\partial Pv}{\partial T} \frac{(T2 - T3)}{(\delta_3 - \delta_2)} = \varepsilon' * S' * \rho_w * D_2 \]  

\[ \rho_v \frac{KAKV}{\mu_v} \frac{\partial Pv}{\partial T} \frac{(T2 - T3)}{(\delta_3 - \delta_2)} = \varepsilon_2 * S_2 * \rho_w * D_3 \]  

where \( D_1 \) represents the evaporation of interfiber and intrafiber water, \( D_2 \) is the slug flow of interfiber water, and \( D_3 \) is the evaporation of intrafiber water accompanying \( D_2 \). \textsc{Hidryer1} selects the larger of \( D_1 \) or \( D_2 \) (or \( D_1 \) if they are equal) as the rate of advance. If \( D_1 \) is equal to or larger than \( D_2 \), \( \delta_1 \) and \( \delta_2 \) move according to \( D_1 \). If \( D_2 \) is larger, \( \delta_2 \) moves according to \( D_2 \) and \( \delta_1 \) moves according to \( D_3 \).

When \( \delta_1 \) is not equal to \( \delta_2 \), the mass balance gives

\[ \rho_v \frac{K_a2}{\mu_v} \frac{\partial Pv}{\partial T} \frac{(T1 - T2)}{(\delta_2 - \delta_1)} = \varepsilon_2 * S_2 * \rho_w * D_4 \]  

which is the evaporation of intrafiber water at \( \delta_1 \) and

\[ \rho_v \frac{KAKV}{\mu_v} \frac{\partial Pv}{\partial T} \frac{(T2 - T3)}{(\delta_3 - \delta_2)} = \varepsilon' * S' * \rho_w * D_5 \]  

which is the evaporation of interfiber liquid at \( \delta_2 \). The expression for \( D_2 \) also applies at \( \delta_2 \) and \textsc{Hidryer1} selects the larger of \( D_2 \) or \( D_5 \) as the rate of advance of \( \delta_2 \).
At $\delta_3$

$$\frac{-K_3}{(\Delta h + \Delta h^*)} \cdot \frac{(T_2 - T_3)}{(\delta_3 - \delta_2)} = \epsilon_3 \cdot S_3 \cdot \rho_w \cdot D_6$$  \hspace{1cm} (106)$$

and Eq. (81) also applies. Note that if $D_1$ or $D_5$ is greater than $D_2$ then $D_2$ is set to 0 and so $D_7 = 0$. $\delta_3$ is advanced according to the sum of $D_6$ and $D_7$.

In the special case where zone 3 is not present, the expression for $D_4$ is used to advance $\delta_1$ and

$$\frac{-K_2}{(\Delta h + \Delta h^*)} \cdot \frac{(T_1 - T_2)}{(\delta_2 - \delta_1)} = \epsilon_2 \cdot S_2 \cdot \rho_w \cdot D_8$$  \hspace{1cm} (107)$$

is used for $\delta_2$.

The size of the time increment used depends on the magnitudes of $D_1$, $D_2$, etc. $\delta_1$ can never pass $\delta_2$, and $\delta_2$ can never pass $\delta_3$. HIDRYER1 calculates the largest time increment which will not violate the interface position criterion or the finite difference stability criterion and compares it to DTO, the default time increment. The smaller of the two is chosen and used.

Because the interface temperature calculations involve vapor and liquid properties whose values depend on the temperatures, an iterative procedure is used such that a temperature is calculated and averaged with the previous temperature to obtain an updated value. The updated value is used for property calculations, and a new temperature is determined. The new temperature is averaged with the previously updated one and the cycle continues for a fixed number of iterations.
SUPPLEMENTARY RELATIONSHIPS

The following relationships are in the form of correlations which yield the required quantity, given an original input parameter or a value calculated in a previous step of the program.

**Applied Mechanical Pressure**

The nature of the applied mechanical pressure is specified in the form of input parameters. The peak pressure and time to achieve that pressure are required. HIDRYER1 offers the option of either a ramp-and-hold pressure pulse or a pulse that duplicates a press nip. The ramp-and-hold pulse rises linearly with time to the peak pressure value and maintains pressure at the peak value until drying is complete (at a final moisture content of 6%). An extremely short rise time mimics a step change in pressure.

The press-nip pulse uses a sinusoidal function to create a symmetrical pressure pulse that achieves its peak value at the input rise time. Thus, the "nip residence time" is twice the input rise time. HIDRYER1 terminates when the moisture content reaches its target value or when the nip residence time is exceeded.

The functional forms for the pressure options are:

\[ P = A_1 + A_2 \frac{\text{TIME}}{\text{RISTIM}} \]  \hspace{1cm} (108)

and

\[ P = A_1 + \frac{A_2}{2} \left( 1 + \sin \left( A_3 \frac{\text{TIME}}{\text{RISTIM}} + A_4 \right) \right) \]  \hspace{1cm} (109)

where \( A_1 \) is some small but finite pressure value (contact pressure at time zero) required for the compressibility equation; \( A_2 \) is the peak pressure, which is an
input parameter; A3 is the numerical constant \( \pi \) multiplied by 3600; and A4 is the numerical constant \( \pi \) multiplied by 1.5. The factor of 3600 is required since HIDRYER1 calculates TIME in hours and RISTIM, the time required to achieve the peak pressure, is specified in seconds.

Typical RISTIM values are on the order of 0.05 second. A1 is arbitrarily given the value of 0.7 kPa (0.1 psi), and A2 is specified in the input conditions.

Physical Properties

The vapor and liquid physical properties are derived by modeling steam table data with a multiple regression analysis program over the range from 0 to 232°C (32 to 450°F). The functional form for the properties is:

\[
PROP = B1 + T \times (B2 + T \times (B3 + T \times (B4 + T \times B5)))
\]  

where PROP is the property to be determined (latent heat, specific volume, etc.) and \( T \) is the temperature.

Latent Heat Correction Factor

The hygroscopic nature of cellulose requires that an additional quantity of energy above that of the latent heat (at a given temperature) be supplied during drying. This quantity is usually treated as a correction factor to the latent heat. Data on vapor pressure reduction in the presence of cellulose can be used to calculate the incremental heat of desorption at a given moisture ratio and temperature. Available data from\(^{68}\) have been used to derive a functional relationship for the incremental heat of desorption over the range of 65 to 80°C (149 to 176°F) from moisture ratios of 0.01 up to 0.24.\(^{69}\) Above moisture ratios of 0.24 the heat of desorption becomes infinitesimal relative to the latent heat.
The correlation has the form:

$$\Delta h' = C_1 \cdot \exp(C_2 \cdot MR)$$  \hspace{1cm} (111)$$

where $\Delta h'$ is the heat of desorption, $C_1$ has a value of 1157.5 kJ/kg (497.63 BTU/lbm), and $C_2$ has a value of -14.9522.

Because HIDRYER1 assumes a step change in moisture ratio from one zone to the next, an integral-average latent heat increment at each interface is used as the correction factor and is defined by integrating Eq. (111) from the moisture ratio of one zone to the moisture ratio of the adjacent zone so that:

$$\Delta h^* = D_1 \cdot \frac{\exp(D_2 \cdot MR_i) - \exp(D_2 \cdot MR_f)}{MR_f - MR_i}$$  \hspace{1cm} (112)$$

where $D_1$ has a value of 77.4 kJ/kg (33.28 BTU/lbm) and $D_2$ has a value of -14.9522.

**Thermal Conductivity**

The thermal conductivity is evaluated using the parallel conductor model and neglecting the contribution of vapor conductivity. The thermal conductivity is given by:

$$K = E_1 \cdot (1 - \varepsilon) + E_2 \cdot \varepsilon \cdot S$$  \hspace{1cm} (113)$$

where $E_1$ and $E_2$ are the thermal conductivities of cellulose and water, 0.24 W/m-K (0.14 BTU/ft-hr-°F) and 0.682 W/m-K (0.394 BTU/ft-hr-°F), and are assumed constant.

**Contact Coefficient**

The relationship for the contact coefficient between the sheet and the hot surface has the form:
\[ Hc = F1 \cdot (1 - \varepsilon) + F2 \cdot \varepsilon \cdot S \]  \hspace{1cm} (114)

where \( F1 \) is the contact coefficient for dry cellulose, obtained from data in,\(^71\) that depends on the mechanical pressure\(^72\) and \( F2 \) is a value typical of a boiling heat transfer coefficient between water and a flat plate that is on the order of 5678 W/m\(^2\)-K (1000 BTU/ft\(^2\)-hr-\(^\circ\)F).

Compressibility

Mathematical descriptions of saturated sheet compression originate in the modeling of wet pressing. The sheet is modeled in one of three ways: a power law model relating the concentration of fibers to the mechanical pressure; a Kelvin body model describing the sheet thickness in terms of the applied pressure and certain viscoelastic constants; and a combination model using a power law to describe fiber bending and a time dependent expression for fiber compression.

Strictly speaking, a power law model applies only to an equilibrium condition and not to a dynamic compression case. However, modification of the basic power law\(^73,74\) to account for time dependent effects is possible.\(^75\) A Kelvin body (spring and dashpot in parallel) exhibits a first order response to a step change in pressure and therefore only models flow-controlled pressing phenomena, which also exhibit a first order response.\(^76\) The combination model treats fiber bending with a power law expression and models fiber compression as a rate process, since it is time dependent.\(^77\) After short times (milliseconds), the rate of change of the fiber compression contribution is very small in comparison with the value of the bending contribution. Thus, it should be sufficient to describe the thickness in terms of just the bending term (power law) along with some slight correction which may amount to a nearly constant fraction of the bending term.

HIDRYERI uses the power law compression model because it is the simplest and most easily modified model and because the most data are available for relating
its constants to commonly measured sheet properties such as freeness and basis
weight. The form of the power law is:

\[ C = M \times p^N \]  \hspace{1cm} (115) 

The coefficients M and N vary with the degree of beating and the 
moisture ratio of the sheet. Data from, although limited to pressures on 
the order of 7 kPa (1 psi), demonstrated that the power law describes the 
compression behavior of unsaturated sheets as well as saturated sheets. Using 
this information, expressions for evaluating M and N at different moisture 
ratios are obtained by multiple linear regression. The form is:

\[ \text{COEFF} = G_1 + G_2 \times \text{MR} + \frac{G_3}{\text{MR} + 1.5} + \frac{G_4}{(\text{MR} + 1.5)^2} + \frac{G_5}{\text{MR} + 1} + \frac{G_6}{(\text{MR} + 1)^2} \] \hspace{1cm} (116) 

where COEFF is either M or N and the values of G1 through G6 change depending on 
whether M or N is to be calculated and on the freeness of the pulp in the sheet.

To account for the dependence on refining, the values for the regression 
constants in Eq. (116) are determined for the same pulp at two available 
freeness levels and fit to a parabola with an assumed minimum at a freeness of 
100 CSF. (Below 100 CSF, M and N are held fixed at the 100 CSF values.) Thus, 
each constant in Eq. (116) is found from an expression of the form:

\[ \text{CONST} = H_1 + H_2 \times \frac{(\text{CSF} - H_3)^2}{H_4} \] \hspace{1cm} (117) 

where CONST represents G1 through G6 and H1 through H4 change depending on which 
value of G is to be calculated.

The compressibility of a sheet is known to be highly temperature dependent. 
Data describing the overall gain in moisture removal by pressing at elevated
temperatures are available, but no data are available on the specific changes in sheet compressibility constants. To account for this effect, the value of \( M \) calculated from Eq. (116) is (arbitrarily) multiplied by a function of the mean temperature of the zone such that:

\[
M' = M \times \left( \frac{\text{TBAR}}{T_I} \right)^{II}
\]  

(118)

where \( M' \) is the modified \( M \) value, \( \text{TBAR} \) is the average zone temperature, \( T_I \) is the initial sheet temperature at which \( M \) and \( M' \) are identical, and \( II \) is an exponent less than unity (0.25 in HIDRYER1) so that the temperature effect moderates as \( \text{TBAR} \) increases.

A moist but unsaturated sheet can be brought to saturation if the mechanical pressure is high enough. To account for this observed behavior, the value of \( N \) is modified by making it a function of the effective mechanical pressure on the sheet. The effective mechanical pressure is the applied pressure minus the hydraulic pressure. \( N_{\text{sat}} \), the value of \( N \) which would give a saturated sheet at a reference pressure equal to or greater than the peak pressure, is calculated and \( N \) becomes a function of this saturation value and the original value (\( N_{\text{ref}} \)) calculated from Eq. (116) so that there is a smooth transition in the \( N \) value as effective pressure increases. \( N \) can never be greater than \( N_{\text{sat}} \) since the reference pressure is equal to or greater than the peak pressure. \( N \) can never be less than \( N_{\text{ref}} \) since the pressure is never less than the \( A_i \) constant in the pressure function. The form is:

\[
N = J_1 + J_2 \times \left( \frac{P-J_3}{J_4} \right)^{J_5}
\]

(119)

where \( J_1 \) and \( J_2 \) depend on \( N_{\text{ref}} \) and \( N_{\text{sat}} \), and \( J_3 \) and \( J_4 \) depend on the value of the large reference pressure chosen. \( J_5 \) is the reciprocal of an odd integer and
provides a smooth transition from $N_{\text{ref}}$ to $N_{\text{sat}}$ as effective mechanical pressure changes.\(^8\)

**Permeability**

The final supplementary relationship is that of permeability. Methods of characterizing permeability are based on theoretical or empirical relationships modeling permeability as a function of sheet porosity and/or fiber cross-sectional shape.\(^6\),\(^8\) The empirical relationships are, of course, limited to the ranges of porosities and fiber types investigated. The theoretical approaches in this class are of limited applicability because the fiber is assumed to be of smooth (but not necessarily circular) cross sectional shape. Consequently, the theoretical relationships tend to predict permeabilities larger (by one or two orders of magnitude) than experimentally determined ones, except at high porosities and/or freenesses.

Paper fibers have many fibrils extending into the interfiber space. While the volume of the fibrils is generally small in comparison to the volume occupied by the bulk of the fiber, the effect of the fibrils on the flow properties is quite dramatic. The amount of fibrils depends on the extent to which the fiber has been physically degraded. Since Canadian Standard Freeness is a commonly performed test and gives a reasonable (but indirect) indication of the trend of the flow properties, it seems likely that a relationship between permeability and CSF would be both convenient and consistent with a model based on macroscopic trends.

An empirical linear relationship exists between $\ln(\text{CSF})$ and the square root of specific filtration resistance\(^8\) over a range of 100 to 700 CSF. The relationship has the form:

$$\ln(\text{CSF}) = K_1 + K_2 \sqrt{R}$$  \hspace{1cm} (120)
The calculated value of R is for a given pressure drop across the mat. Data at a variety of pressure drops on the order of 7 kPa (1 psi) and a broad range of freeness values define a family of curves of R vs. pressure drop whose shape is roughly independent of freeness. Thus, by selecting some reference pressure (Pref) and the specific filtration resistance (Rref) at this pressure, a generalized relationship can be developed such as:

\[ R = L_1 + L_2 \cdot P + L_3 \cdot \sqrt{P} \]  \hspace{1cm} (121)

where \( L_1 \) depends on \( R_{\text{ref}} \), and \( L_2 \) and \( L_3 \) depend on \( R_{\text{ref}} \) and \( P_{\text{ref}} \). The pressure drop in a saturated flow experiment is equivalent to the effective mechanical pressure exerted on the mat, and the permeability is related to R by:

\[ K_a = \frac{1}{R \cdot C} \]  \hspace{1cm} (122)

Therefore, there is a direct link between mechanical pressure and permeability (for a given CSF).

The permeability determined in saturated flow experiments is the absolute permeability; this is the permeability in the presence of only one flowing species. To adjust for the presence of two or more flowing species, the absolute permeability is generally multiplied by a correction factor called the relative permeability. Relative permeabilities vary between zero and unity and typical relationships are:

\[ K_w = S' M_1 \]  \hspace{1cm} (123)

and

\[ K_v = (1 + N_1 \cdot S') \cdot (1-S')^{N_2} \]  \hspace{1cm} (124)

where \( M_1 \) is on the order of 4 and \( N_1 \) and \( N_2 \) are each on the order of 3. These relationships were developed for granular media. To be consistent with the
saturation concept for which they were developed, they are based here on the interfiber saturation of the paper, since it is the interfiber liquid (or intergranular liquid) that impedes the flow of vapor. This also makes them consistent with measurements of liquid relative permeability for paper at very low moisture ratios because below a critical but finite moisture ratio the liquid relative permeability becomes infinitesimally small.\textsuperscript{90}

HIDRYER1 is organized so that the values for constants used in the supplementary relationships are grouped in DATA statements and/or COMMON statements. Therefore, modification of the model by changing the numerical value of a constant is a simple procedure. Most supplementary relationships are implemented in either the form of a SUBROUTINE or a FUNCTION so that changing the functional form also becomes simple. Refer to Appendix 1 for a detailed program listing.

MODEL VALIDATION

HIDRYER1 is the culmination of a series of drying models that began with a numerical implementation of the Ahrens model. First, the analytical solution to the Ahrens model was programmed to provide a reference for future comparisons. Next, the equations of the Ahrens model were programmed and solved numerically to duplicate the analytical result.\textsuperscript{91} This numerical model was expanded by accounting for effects such as heat conduction into the outer zone, the influence of permeability on interface temperature, vapor-pressure-induced liquid flow, and an initial heatup period. At each stage of development, the model's predictions were compared to the previous version of the model to demonstrate that the advanced case reduced to the simpler case if conditions consistent with the less stringent assumptions were introduced into the advanced model.

The result was a model called HIDRYER that assumed zones of constant permeability and porosity. It was based primarily on low mechanical pressure cases
where the thickness did not change much as drying progressed, but gave good agreement with experimental data even in higher pressure cases, since any values for porosity, thickness, heat transfer coefficient, and permeability could be specified as inputs and held fixed through the drying simulation.

The final step was to convert HIDRYER to HIDRYER1 by specifying the required supplementary relationships that determine how porosity, etc., vary with pressure, temperature, moisture ratio, and freeness. Each relationship was tested separately before being incorporated into HIDRYER and then tested again after incorporation to verify that it had been implemented correctly. Thus, the model was validated at each stage of development so that the predictions of HIDRYER1 are a result of the model and its assumptions and not a result of problems in the FORTRAN coding of the equations.

SUMMARY

Fundamental heat and mass transfer relationships, with supplementary property equations, have been assembled into a model of high intensity paper drying. The model has been converted into a FORTRAN program called HIDRYER1.

The following sections describe simulations involving an exploratory or "parametric" study to determine the basic behavior of the model and direct comparisons to laboratory data to check on the values of constants used in the model.
PARAMETRIC STUDY

INPUT PARAMETERS

HIDRYER1 requires the user to provide values for hot surface temperature (TH), boiling point temperature (TB), basis weight (BW), Canadian Standard Freeness (CSF), initial moisture ratio (MRO), default time increment (DTO), peak mechanical pressure (PMAX), and pressure rise time (RISTIM). Additionally, the user must specify choices for the following options: ramp-and-hold or sinusoidal pressure pulse; English or SI units; and two options for a packaged subroutine used to calculate sheet thickness when the sheet becomes saturated during the heatup regime. These last two options select either a variable-order Adams predictor-corrector method or Gear’s method for solving a differential equation and specify how the Jacobian matrix is to be calculated (analytically, by finite differences, etc.).

OUTPUT VARIABLES

HIDRYER1 produces two types of output: printed output and output stored on magnetic disk. The printed output consists of the input parameters and the following calculated values: time (SEC), amount of moisture removed relative to the initial amount present (MREL), sheet surface temperature (TS), temperatures at the various interfaces in the sheet (T1, T2, T3), positions of the interfaces relative to total sheet thickness (RATIO1, RATIO2, RATIO3), total sheet thickness (DELTAT), instantaneous heat flux (Q), overall heat transfer coefficient (OHTC), and the gage vapor pressure corresponding to T1 (PGAUGE). The disk output does not include the input parameters, but contains all the calculated values of the printed output plus the temperature at a point midway through the basis weight of the sheet (TMID). Other variables calculated in the program can be obtained by modifying the WRITE statements in the output subroutine.
DESIGN OF PARAMETRIC STUDY

The effect of various input parameters on drying behavior is determined by running the program at different sets of conditions for each of the two pressure pulse options. Table 1 lists the parameters and the values investigated. The center column gives the values for the base case. Results from all other cases are compared against this base case and are generated by varying the value of an individual parameter from its base value while maintaining all other parameters at their base case values. The pressure option is designated as either RAMP or SINE.

Table 1. Input parameter values for parametric study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum</th>
<th>BASE</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>TH, °C(°F)</td>
<td>148.9(300)</td>
<td>204.4(400)</td>
<td>260.0(500)</td>
</tr>
<tr>
<td>MRO</td>
<td>1.00</td>
<td>1.25</td>
<td>1.50</td>
</tr>
<tr>
<td>BW, g/m$^2$(lbm/ft$^2$)</td>
<td>50.25(0.0105)</td>
<td>102.50(0.0210)</td>
<td>205.00(0.0420)</td>
</tr>
<tr>
<td>CSF</td>
<td>300</td>
<td>450</td>
<td>600</td>
</tr>
<tr>
<td>PMAX, kPa(lbf/in$^2$)</td>
<td>2068(300)</td>
<td>3447(500)</td>
<td>4826(700)</td>
</tr>
<tr>
<td>RISTIM, s</td>
<td>0.005</td>
<td>0.010</td>
<td>0.050</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

The HIDRYERl program was allowed to run to completion or for one hour of CPU time, whichever was shorter. In general, the SINE cases took about 20 seconds to run. The exception is the SINE case with 0.050 second RISTIM, which took about 18 minutes of CPU time. The RAMP cases averaged around 30 minutes of CPU time, and no case took longer than 38 minutes.
Figures 11 through 18 show the results of the base case with the RAMP pressure option. Figure 11 is the drying curve for this experiment. Two points on the curve are significant. The first point, at about 0.04 second, signals the onset of drying. Examination of the numerical output reveals that the transition regime actually started at about 0.02 second, but it takes several time increments of the transition regime before noticeable (on the graph) drying occurs. The second point, at about 0.13 second, signals the end of the transition regime and the onset of the linear regime. The steep slope of the drying curve in the transition regime indicates that the drying is dominated by liquid dewatering in this period. The abrupt change in slope at the start of the linear regime indicates a shift to an evaporation and bulk vapor flow dewatering mechanism.

Figure 12 traces the sheet thickness history. The rapid pressure rise during the heatup period causes a rapid sheet compression early in the process. As the pressure levels off and as the transition regime begins, the hydraulic pressure in the sheet builds and reduces the rate of compression. As more and more liquid is removed from the sheet, it becomes easier to compress and the rate of compression increases until all the interfiber liquid is removed (which coincides with the onset of the linear regime in this case). Once the interfiber liquid is removed, the permeability of the sheet increases and results in low hydraulic (vapor) pressure. The rate of compression slows as the moisture removal becomes dominated by an evaporation mechanism and the sheet approaches its final (zero moisture content) thickness.

Figure 13 tracks the relative position of the various interfaces in the sheet. Interfaces 1 and 2 move together from the start of the transition regime for a short time. In this period, the heat transfer rate is able to keep up
with the liquid flow rate. At about 0.05 second the liquid dewatering rate becomes greater than the heat transfer (evaporation) rate and interface 2 progresses into the sheet faster than interface 1. When interface 2 reaches the cool side of the sheet, the linear regime begins and heat transferred to the cool side causes evaporation. Interface 2 then recedes back toward the hot side. As interface 2 reaches the far side of the sheet the inflection and change in slope of the curve for RATIO1 signals the shift from liquid dewatering and internal sheet evaporation to an evaporation-only mechanism. Interface 3 is held at DELTAT because evaporation at the outer surface does not occur until all interfiber water is removed.

![Figure 11. Moisture removal as a function of time for the RAMP base case.](image)

\[ \Delta M, \text{ RELATIVE MOISTURE LOSS} \]

TIME, sec.
Figure 12. Sheet thickness as a function of time for the RAMP base case.

Figure 14 shows the temperature history of the interfaces. TS, T1, and T2 move together until the transition regime starts. T3 begins to rise then because of the quantity of heat transferred by convecting liquid. T1 and T2 remain together until interface 2 moves faster than interface 1. T2 and T3 become identical when interface 2 reaches DELTAT and the linear regime starts. T2 rises as interface 2 moves back into the sheet so that a vapor pressure gradient (determined by sheet permeability) can be maintained. T3 is fixed at TB since interface 3 is held at DELTAT.
Figure 13. Interface positions relative to total sheet thickness as functions of time for the RAMP base case.

Figure 15 depicts the gage vapor pressure corresponding to the value of $T_1$. The two abrupt drops and recoveries of vapor pressure occur at points where a slug of liquid is pushed through the sheet and the heat rate has to "catch up" to sustain continued flow. The first point occurs as interfaces 1 and 2 move into the sheet. The second point occurs as interface 2 moves ahead of interface 1. In both cases a zone of high vapor permeability (relative to zone 3) is suddenly created. This causes $T_1$ (and the vapor pressure corresponding to $T_1$) to
drop since the flow resistance is reduced. As the interfaces progress, T1 must increase to sustain continued vapor and liquid flow at points in the interior of the sheet.

Figure 14. Sheet surface temperature and interface temperatures as functions of time for the RAMP base case.

Figure 16 traces the temperature at a point half way through the basis weight of the sheet. Since this does not always correspond to the instantaneous location of an interface, TMID has to be interpolated based on the positions of the interfaces relative to the total sheet basis weight. Conduction in the
compressing sheet during heatup causes the internal temperature to rise above its initial value earlier than the cool side does. The temperature rises steadily until the linear regime when the rate of compression and the drying rate slow significantly. TMID achieves a nearly constant level until interface 2 moves far enough back into the sheet to affect the thermal behavior of the sheet's interior.

Figure 15. Gage vapor pressure corresponding to T1 as a function of time for the RAMP base case.
Figure 16. Temperature at one-half the sheet basis weight as a function of time for the RAMP base case.

Figure 17 graphs the heat flux from the hot surface to the sheet. Note that the hot surface temperature is assumed constant. The initial portion of the heat flux is controlled by the shape of the pressure pulse. The heat flux is initially zero and rises to its peak as the pressure peaks. When the pressure stabilizes, the heat penetrates the sheet, causing a temperature rise and a sharp drop in heat flux. Just as the transition regime begins, the drop in the heat flux moderates and when the linear regime begins the heat flux slowly
approaches an equilibrium value (zero) as the sheet approaches an equilibrium condition (dry).

Figure 17. Heat flux as a function of time for the RAMP base case.

Figure 18 presents the history of the overall heat transfer coefficient. This quantity is calculated by dividing the heat flux by the difference between TH and TMID. OHTC parallels the heat flux curve until transition begins. As Q moderates and TMID continues to rise, OHTC remains somewhat constant. As the
linear regime begins, OHTC again parallels Q since TMID stabilizes. As TMID starts to rise again, its increase is offset by the decrease in Q to yield a constant OHTC value.

Figure 18. Overall heat transfer coefficient as a function of time for the RAMP base case.

The behavior of the base case for the niplike pressure pulse is not shown. The variables essentially match the RAMP pressure base case up until the peak
pressure is reached. After that, the values plateau and decline slightly as the pressure rapidly declines. The SINE case with 0.05 second RISTIM is the only niplike case that predicts any moisture removal. This is shown in a later figure in comparison with the moisture removal predicted for the various RAMP pressure rise times. (For the conditions selected the sheet is still in the heatup regime for all but this one SINE case.)

Comparisons of Drying Behavior

Figures 19 through 24 show comparisons of the drying behavior for the values of the input parameters given in Table 1. Results from all cases are compared against the base case and are generated by varying the value of an individual parameter from its base value while maintaining all other parameters at their base values. The drying curve stops when the sheet reaches 6% moisture content or, in one case, when the niplike pressure pulse drops to its starting value. The heatup regime accounts for 5 to 10% of the total drying time; the transition regime accounts for 10 to 45% of the total time; and the linear regime accounts for 50 to 80% of the total time. The base case results for drying time to 6% moisture content fall in between the times predicted for the minimum and maximum parameter values.

Figure 19 displays the effect of hot surface temperature on the drying curve. As anticipated, higher hot surface temperature results in shorter drying time and there is nearly a one-to-one correspondence between drying time and the driving force (TH-TB). The greatest benefits of higher hot surface temperature are reduction of the heatup time and higher driving force (drying rate) in the linear regime.

Figure 20 shows the effect of initial moisture ratio on the drying curve. There is little effect on total drying time because the moisture removal is
dominated by the (rapid) liquid dewatering mechanism. The time required to evaporate the remaining water during the linear regime is comparable for each initial moisture ratio case.

Figure 19. Effect of hot surface temperature on moisture removal for RAMP cases.

Figure 21 presents the effect of basis weight on drying. The heatup time for each basis weight is comparable, but the slopes of the liquid dewatering portion are distinctly different. In the lowest basis weight case, the heat can
penetrate far into the sheet in a short time and liquid motion can be sustained at its initial pace. In the heavier basis weights (thicker sheets), the heat only penetrates into a fraction of the total sheet thickness and after liquid motion starts, it takes some amount of time for a sufficient quantity of heat to penetrate further and sustain the flow. In the linear regime, the heat and mass have a shorter distance to travel in the lower basis weight cases and the drying rate is faster than in the heavier basis weight examples.

Figure 20. Effect of initial moisture ratio on moisture removal for RAMP cases.
Figure 21. Effect of basis weight on moisture removal for RAMP cases.

Figure 22 shows how Canadian Standard Freeness affects drying. Lower CSF gives a more compressed sheet (at a given mechanical pressure), and in the case of 300 CSF liquid is removed from the sheet by mechanical dewatering in addition to the thermally induced liquid dewatering. The decrease in permeability accompanying lower CSF is not enough to offset the gains in drying resulting from a more compact sheet (which is better able to transfer heat) and the higher internal sheet temperatures going into the linear regime.
Figure 22. Effect of freeness on moisture removal for RAMP cases.

Figure 23 depicts the influence of peak pressure on drying. The curves are essentially parallel in slope but shifted in time. The results indicate that increasing pressure decreases drying time, but that the relative increase becomes smaller at higher pressures for the range of pressures examined here. This suggests that there may be some practical limit to the amount of pressure which is cost effective for a commercial implementation of high intensity drying technology.
Figure 23. Effect of peak pressure on moisture removal for RAMP cases.

Figure 24 shows the effect of the pressure rise time, the time it takes to achieve the peak pressure. There is virtually no effect on drying time for the RAMP cases, since the rise time is such a small percentage of the total drying time needed. Comparing the SINE case to a RAMP case with the same rise time shows that they behave similarly until the SINE case pressure begins to drop rapidly. The SINE case continues to show a decreasing rate of dewatering as the
heat transfer to the sheet declines, and drying stops when the pressure reaches a point at which the heat transfer can no longer sustain liquid flow.

Figure 24. Effect of pressure rise time on moisture removal for RAMP cases and one SINE case.

The relative magnitudes of the changes are summarized in Table 2.
Table 2. Effect of changes in input parameters on drying time for RAMP cases.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value Relative to Base Case Value</th>
<th>Change in Drying Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>TH</td>
<td>- 25% + 25%</td>
<td>+123% - 39%</td>
</tr>
<tr>
<td>MRO</td>
<td>- 20% + 20%</td>
<td>- 2% + 2%</td>
</tr>
<tr>
<td>BW</td>
<td>- 50% +100%</td>
<td>- 60% +180%</td>
</tr>
<tr>
<td>CSF</td>
<td>- 33% + 33%</td>
<td>- 7% + 18%</td>
</tr>
<tr>
<td>PMAX</td>
<td>- 40% + 40%</td>
<td>+ 16% - 9%</td>
</tr>
<tr>
<td>RISTIM</td>
<td>- 50% +400%</td>
<td>&lt;- 1% &lt;+ 1%</td>
</tr>
</tbody>
</table>

SENSITIVITY ANALYSIS

The calculation method in HIDRYER1 requires that values be specified (in the program) for the number of grid points used in the finite difference equations (KMIN) and for the number of iterations used in determining the interface temperatures (IMAX). The default time increment (DTO) is an input parameter, and it too can influence the predicted drying output. There are no clear-cut methods of choosing appropriate values for these variables and so a sensitivity analysis is necessary to determine what numerical inputs give the best compromise between prediction accuracy and CPU ("computer") time.

Table 3 shows the results of variations in KMIN, IMAX, and DTO using the same inputs as for the RAMP base case (with the exception of DTO when sensitivity to DTO was tested, of course). The central line for each variable gives the value used in conducting the parametric study.
Table 3. Effect of grid spacing, iteration counter, and default time increment on drying time and CPU time.

<table>
<thead>
<tr>
<th>Variable and Value</th>
<th>Predicted Drying Time, s</th>
<th>CPU Time, hr:min:s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>0.438</td>
<td>1:19:37</td>
</tr>
<tr>
<td>KMIN 101</td>
<td>0.432</td>
<td>0:28:20</td>
</tr>
<tr>
<td>251</td>
<td>0.431</td>
<td>4:46:58</td>
</tr>
<tr>
<td>5</td>
<td>0.432</td>
<td></td>
</tr>
<tr>
<td>IMAX 10</td>
<td>0.432</td>
<td>0:28:20</td>
</tr>
<tr>
<td>15</td>
<td>0.432</td>
<td>0:35:34</td>
</tr>
<tr>
<td>DTO (hr) 10⁻⁵</td>
<td>0.456</td>
<td></td>
</tr>
<tr>
<td>10⁻⁷</td>
<td>0.432</td>
<td></td>
</tr>
<tr>
<td>10⁻¹⁰</td>
<td>0.430</td>
<td>9:38:27</td>
</tr>
</tbody>
</table>

Changing the value of KMIN results in minor changes in predicted drying time and more drastic changes in CPU time. When KMIN is increased from 101 to 251, the increase in CPU time is a direct consequence of the increased amount of calculations required. When KMIN is decreased from 101 to 21, one might anticipate a reduction in calculation time. However, because HIDRYER1 uses a forward time difference procedure, interface 2 may be advanced to a location such that its temperature is less than TB. When this occurs, no drying takes place until heat transfer to the transition zone raises its temperature in the vicinity of interface 2 to the point at which T2 is calculated to be above TB. Thus, several time increments may elapse in which there is no drying. Using fewer grid points reduces the effective heat transfer by predicting a lower temperature at any given point inside the outer zone and therefore there are more time increments early in the process when the sheet is still heating up and not drying.

A change in the number of iterations for the interface temperature calculations is reflected directly in the amount of CPU time required. Since there is essentially no change in the predicted drying time or behavior, it appears that
5 iterations are sufficient and the system is "well behaved" with regard to interface temperature calculations.

Decreasing the default time increment has a tremendous effect on CPU time. Typically, the interface motion time increment restriction and the finite difference time increment stability criterion are more restrictive than the default time increment. These are dominant in the transition regime. In the linear regime the finite difference criterion is not operative and the interfaces are sufficiently separated that the default time increment becomes the more restrictive time step. It is in just this regime, however, that a larger time increment can be most useful, since the rate of drying slows relative to the liquid dewatering part of drying. Limiting the default time increment chiefly limits the number of calculations in the linear regime only. Clearly, maintaining DTO on the order of $10^{-7}$ hour produces a vast improvement in accuracy with little sacrifice in CPU time.

SUMMARY

The parametric study shows that hot surface temperature and basis weight have the greatest influence on drying time to 6% moisture content. Peak pressure and freeness have a more moderate effect, and initial moisture ratio and rise time have almost no effect.

Using about 101 finite difference grid points, 5 iterations for interface temperature calculations, and a default time increment on the order of $10^{-7}$ hour appears to be an adequate compromise for balancing prediction accuracy and CPU time.
EXPERIMENTAL COMPARISONS

PURPOSE

Comparisons between experimental results and the model's predictions can suggest changes and improvements, can validate the mechanisms assumed in the model, and can identify areas requiring further experimental study.

EXPERIMENTAL CONDITIONS

Two kinds of experiments were selected for comparisons to HIDRYER1 output based on the manner and magnitude of mechanical pressure application: ramp-and-hold high intensity drying and short duration (impulse) high intensity drying. Examination of the assumptions used in developing the model suggests that it should best predict cases of high hot surface temperature and moderate mechanical pressure (so that good thermal contact is promoted but capillary flow is discouraged by maintaining larger pores) and a ramp-and-hold pressure pulse (since a static compression equation is used).

HIDRYER1 appears to be impractical for modeling cases of mechanical pressure at or below 350 kPa (50 psi). HIDRYER, the earlier version of the program, gives reasonable results in much shorter times. At a mechanical pressure of 321 kPa (46.6 psi) and hot surface temperature of 274°C (525°F), HIDRYER requires about 2 minutes of CPU time but HIDRYER1 needs about 5 hours. HIDRYER gives a better estimate of the experimentally determined drying time of 1.7 seconds: 1.4 seconds for HIDRYER and 0.68 second for HIDRYER1; and a better estimate of the peak vapor pressure of 120 kPa (17.4 psi): 125 kPa (18.1 psi) for HIDRYER and 24 kPa (3.5 psi) for HIDRYER1.

HIDRYER1 requires so much CPU time because it calculates all the properties and sheet behaviors, even when they change by only very small amounts. Conversely, HIDRYER has many built-in assumptions that eliminate the necessity for the
calculation of quantities that do not change much. For example, since HIDRYER takes values of thickness, absolute permeability, and the relative permeabilities as inputs and holds them fixed, it does not have to perform repetitive determinations of these quantities.

The chief drawback to using HIDRYER is that there are no simple guidelines for selecting valid "average" values representative of the quantities throughout the course of drying. Values for input parameters can be easily manipulated to produce good agreement with laboratory data, but the extent to which they reflect real sheet properties can always be questioned. HIDRYER attempts to provide an accurate picture at every instant of drying and was developed to address the chief drawback by removing the subjective aspect of running a simulation.

Figures 25 and 26 show predicted moisture removal curves with representative experimental points for the two cases. The experimental points are determined gravimetrically. The agreement appears to be better in the higher temperature case. This is probably due to the decrease in capillary effects at the higher temperature from lowered surface tension and viscosity and from the higher vapor pressure generated near the hot surface.

Data are available for a peak pressure of 4826 kPa (700 psi) at two hot surface temperatures: 149°C (300°F) and 274°C (525°F). Basis weight is 205 g/m² (0.042 lbm/ft²); moisture ratio is 1.3256; and freeness is 625 CSF. The hydraulic system for application of the pressure pulse causes a small overshoot of PMAX before it settles to the designated value. RISTM is selected as the time at which the mechanical pressure first reaches the target (about 0.12 second). It takes about an equal amount of time for the system to then settle and hold the target pressure value.

RAMP-AND-HOLD PRESSURE PULSE

The chief drawback to using HIDRYER is that there are no simple guidelines for selecting valid "average" values representative of the quantities throughout the course of drying. Values for input parameters can be easily manipulated to produce good agreement with laboratory data, but the extent to which they reflect real sheet properties can always be questioned. HIDRYER attempts to provide an accurate picture at every instant of drying and was developed to address the chief drawback by removing the subjective aspect of running a simulation.
In both cases the model overpredicts the contribution of early liquid removal to overall moisture removal and underpredicts the rate of evaporative removal later in the process. Experimental results show liquid removal at about 30% of the total moisture removed, but the model predicts values in the range of 80%. Also, the predicted drying times are about half the experimental ones. This behavior is probably a function of the uniform fiber wall density assumption, which fixes the amount of liquid available for flow; the assumption of no vapor...
flow through the outer zone during transition, which limits the rate of rise of internal sheet temperature; and the calculated permeability for the outer zone, which controls the flow resistance.

![Graph showing moisture removal](image)

Figure 26. Predicted and measured moisture removal for 274°C (525°F) ramp-and-hold pressure pulse.

Figures 27 and 28 show heat flux comparisons for the two cases. The experimental heat flux is calculated from the measured hot surface temperature using Duhamel's Theorem. In both cases the model severely underpredicts the peak heat flux and less severely underpredicts the heat flux later in drying. The model curve also peaks before the experimental curve. This behavior is due to at
least two factors. First, the model assumes a constant hot surface temperature and determines heat flux by multiplying HC and the driving force (TH - TS). Experimentally, TH drops by about 4% of its initial value, therefore the value that the model predicts for HC must be low relative to the true value. Second, the experimental pressure actually exceeds the nominal target and this makes a contribution to the true value for HC but not for the calculated value for HC. Thus, the thermal and mechanical pressure lags of the physical system are not completely described by the model.

Figure 27. Predicted and measured heat flux for 149°C (300°F) ramp-and-hold pressure pulse.
Figure 28. Predicted and measured heat flux for 274°C (525°F) ramp-and-hold pressure pulse.

Figures 29 and 30 show predicted and measured sheet thicknesses. The model curves qualitatively describe the compression pattern: a rapid compression ending in an abrupt change in compression rate followed by a moderate compression regime ending in an accelerating rate of compression followed by a quasi-equilibrium regime. The first regime results from the rapidly rising mechanical pressure. As the pressure attains the target value, heat transfer to the sheet begins to raise the hydraulic (vapor) pressure and the mechanical pressure plateaus, both of which slow the compression. Later, the heat flux drops, the interfaces move
into the sheet, moisture removal is dominated by liquid dewatering, and the vapor pressure decrease in the sheet increases the rate of compression. As the sheet enters the regime of drying by evaporation only the rate of moisture loss slows and the quasi-static compression regime starts. Quantitatively, the model underpredicts the initial sheet thickness and overpredicts the equilibrium thickness. This suggests a decrease in the M compression value and an increase in the N compression value would be appropriate so that the lower M value would dominate at lower pressures and the higher N value would dominate at higher pressures.

Figure 29. Predicted and measured sheet thickness for 149°C (300°F) ramp-and-hold pressure pulse.
Figures 30, 31, and 32 again show that the model qualitatively describes these drying conditions. The temperature at a point midway through the basis weight of the sheet is plotted for both cases. The experimental curves indicate that the rate of heat transfer to the interior of the sheet is much higher than that predicted by the model. This is probably due to the model's assumption of no vapor flow through the outer zone during the transition regime. The large latent heat carried into the zone and released by vapor condensation raises the temperature there much faster than simple conduction would. Including this
effect would complicate the transition regime calculations by introducing a source term in the transient heat transfer equation and by requiring a more complicated mass balance (since the moisture ratio would be changing) but would be a reasonable next step in improving the model.

![Graph showing temperature over time for an experimental and model comparison](Image)

Figure 31. Predicted and measured midpoint temperature for 149°C (300°F) ramp-and-hold pressure pulse.

To demonstrate the effect of the proposed changes to the model, constants in the model were simultaneously modified by 10% of their original values. The reference values for contact coefficient and the N compression constant were increased. The apparent cell wall density, the absolute permeability, and the M
compression constant were decreased. To simulate the transport and condensation of vapor in the outer zone, the thermal conductivity was modified by the addition of a diffusion term for the heatup period\textsuperscript{94} and a bulk vapor flow term for the transition period.\textsuperscript{95} This combined "effective" conductivity can be orders of magnitude larger than the simple conductivity and should greatly increase heat transfer to the interior of the sheet. Note that no attempt was made to account for any changes in saturation from the condensing vapor. This approximation is reasonable because the large latent heat implies that only a small amount of condensation is necessary to produce a large change in temperature.

\[ \text{Figure 32. Predicted and measured midpoint temperature for } 274^\circ \text{C (525}^\circ \text{F) ramp-and-hold pressure pulse.} \]
The results of this "optimization" are shown in Fig. 33 through 40 for the ramp-and-hold pressure cases. Figures 33 and 34 display the changes in drying behavior caused by the modifications. In both cases there is little effect on heatup time, since the diffusion term augmenting thermal conductivity is relatively small. The transition time is greatly reduced because the bulk flow term augmenting conductivity is very large. Trapping more water in the fibers causes a decrease in the amount of moisture removed in liquid form (from 80% down to 70%), and increases the drying time, since more moisture has to be removed by an evaporation mechanism.

Figure 33. Predicted, measured, and modified model moisture removal for 149°C (300°F) ramp-and-hold pressure pulse.
Figure 34. Predicted, measured, and modified model moisture removal for 274°C (525°F) ramp-and-hold pressure pulse.

Figures 35 and 36 show the influence on heat flux. In the 149°C (300°F) case the heat flux is decreased, which is the opposite of the anticipated trend. The change in compression constants causes a general increase in porosity and therefore an overall decrease in the contact coefficient even though the reference values for Hc were increased by 10%. In the 274°C (525°F) case, there is little effect because the higher driving force (TH - TS) tends to mask the influence of changes in the Hc reference values and compression constants.

Figures 37 and 38 depict the changes in predictions of sheet thickness. Changing the constants causes a slight increase in the initial thickness...
prediction and significant changes in the slope and duration of the intermediate compression regime. The increase in N is not enough to offset the decrease in M and the modified model predicts an even higher thickness in the third compression regime. The slope is also changed in the third regime and shows a more rapid compression in the later stages of drying.

Figure 35. Predicted, measured, and modified model heat flux for 149°C (300°F) ramp-and-hold pressure pulse.

Figures 39 and 40 graph the effects of the modifications on the prediction of midpoint temperature. The first-peak midpoint temperature is significantly increased and the time required to achieve the peak is decreased. The duration of the predicted plateau period is increased. In a qualitative sense, the
changes benefit the lower temperature case more than the higher temperature case. This tends to indicate that the initial values for most constants were reasonable and that it is a change in mechanism going from lower temperature to higher temperature (such as the relative importance of capillary liquid flow) that causes the difference between measured and predicted behavior. Since the assumptions of HIDRYER1 are more appropriate to the higher temperature case, changing the constants should be expected to shift it away from its initially reasonable qualitative fit.

Figure 36. Predicted, measured, and modified model heat flux for 274°C (525°F) ramp-and-hold pressure pulse.
The previous figures clearly show that the model can be easily modified to alter its predictions by changing the constants in the model. An optimization of these constants in conjunction with further experimental information should be able to produce a highly accurate predictive tool.
Figure 38. Predicted, measured, and modified model sheet thickness for 274°C (525°F) ramp-and-hold pressure pulse.
Figure 39. Predicted, measured, and modified model midpoint temperature for 149°C (300°F) ramp-and-hold pressure pulse.
Figure 40. Predicted, measured, and modified model midpoint temperature for 274°C (525°F) ramp-and-hold pressure pulse.

SHORT DURATION (IMPULSE) PRESSURE PULSE

The time scale for the application of the mechanical pressure pulse in impulse drying is an order of magnitude shorter than the ramp-and-hold method. Rise times of a few milliseconds are possible. The heat and mass transfer phenomena that take place in both circumstances are fundamentally the same, but because of the dynamic nature of the impulse process the compression properties of the sheet assume great importance. The moisture loss by mechanical compression is
greater in the impulse case and the resulting sheet properties tend to be different. The impulse process is conceptually more identifiable with a (very high temperature) "heated wet pressing" operation than with a "drying" operation.

Figures 41 and 42 show comparisons of experimental and predicted sheet thicknesses for impulses delivered by a drop press simulator at two hot surface temperatures. Figure 42 corresponds to a wet pressing case since the temperature is only 18°C (65°F). The difference in magnitudes for the predicted and experimental results comes from the values used for M and N in the model and because the model calculates the thickness at every point in time (i.e., there is no initial thickness input to the model). If the model curve is simply shifted vertically so that the initial predicted thickness matches the initial measured thickness, a better comparison can be made. This is also shown in Fig. 41 and 42. Note that this method could be built into the model by supplying the initial thickness and correcting the model's predictions by a constant value equal to the difference between initial measured and predicted thicknesses. (An alternative would be to supply the initial measured thickness and modify M and N so that the initial predicted thickness would match.) Apart from the difference in magnitudes, the model exhibits an elastic type of behavior consistent with its compression equation. The experimental result shows how the paper fails to recover after the peak pressure has been achieved. This is due in part to the viscous nature of the fiber matrix and in part from irreversible alterations in the matrix structure. The depression in the center of the predicted curve results from the combination of rapid rate of change in pressure and N (which is a function of pressure) as the peak pressure is reached.
In the 316°C (600°F) case, Fig. 42, the model more closely mimics the experimental result in a qualitative sense. Thermal softening at the elevated temperature moderates the rapid change in thickness as the peak pressure is attained. The model predicts a faster rate of compression in this case and a slower rate of thickness recovery relative to the lower temperature case. The experimental measurements show about the same rates in both cases. The model predicts a somewhat lower minimum thickness in the higher temperature case, which is the opposite of the experimental result. The model results are directly related to
the use of a compression equation in a drying model instead of using a heat transfer equation in a dynamic wet pressing model. A compression equation does not fully describe the internal sheet behavior to the extent necessary for direct application to impulse conditions.

![Diagram](image)

**Figure 42.** Predicted and measured sheet thickness for 316°C (600°F) impulse case.

Figure 43 shows the results from experiments in a heated, rotating roll press nip. Equivalent dewatering can be achieved at many combinations of hot surface temperature and nip residence time.
Figure 43. Impulse drying moisture removal for various combinations of hot surface temperature and nip residence time.

Table 4 summarizes the model's dewatering predictions for a variety of operating conditions selected from Fig. 43. The basis weight is 100 g/m² (0.0205 lbm/ft²); moisture ratio is 1.381; freeness is 570 CSF; and PMAX is 12144 kPa (1760 psi). There are certain combinations of time and temperature which cause the model to predict an apparent zone 3 density which is greater than the (assumed constant) effective fiber wall density of 1 g/cc. The higher temperature cases can complete the calculations at shorter nip residence times than the lower temperature cases. This is a consequence of the rate of dewatering (rates of heat transfer and vapor pressure generation) relative to the rate of compression.
Table 4. Comparison of predicted and measured moisture removal for impulse drying conditions.

<table>
<thead>
<tr>
<th>TH, °C (°F)</th>
<th>Nip Residence Time, s</th>
<th>Experimental Moisture Removal, %</th>
<th>Model Moisture Removal, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>149 (300)</td>
<td>0.020</td>
<td>20</td>
<td>55&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>0.060</td>
<td>37</td>
<td>33&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>204 (400)</td>
<td>0.011</td>
<td>20</td>
<td>30&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>0.042</td>
<td>37</td>
<td>58&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>0.130</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>260 (500)</td>
<td>0.030</td>
<td>37</td>
<td>64&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>0.083</td>
<td>75</td>
<td>82</td>
</tr>
<tr>
<td>316 (600)</td>
<td>0.022</td>
<td>37</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>0.063</td>
<td>75</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>0.114</td>
<td>90</td>
<td>89</td>
</tr>
<tr>
<td>371 (700)</td>
<td>0.016</td>
<td>37</td>
<td>0&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>0.044</td>
<td>75</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>0.082</td>
<td>90</td>
<td>88</td>
</tr>
</tbody>
</table>

<sup>a</sup> Computation terminated when zone 3 porosity becomes lower than the minimum allowable porosity.

Higher temperatures produce faster drying and higher hydraulic (vapor) pressures before the critical density is achieved by compression so that these cases can run to completion. At a basis weight of 50 g/m<sup>2</sup> (0.01025 lbm/ft<sup>2</sup>) the model runs to completion but predicts no dewatering, even at 316°C (600°F) and 4137 kPa (600 psi), when the nip residence time is 5.4 milliseconds. Experimental moisture removals of up to 80% have been demonstrated for these conditions.<sup>98</sup>

In Table 4 all model cases overpredict the amount of moisture removed but the trend of increasing removal with increasing time is intact. The overprediction is a function of the assumed fiber wall density which determines the amount of (trapped) moisture unavailable for liquid flow. Decreasing the density would lower the amount available for flow but would raise the minimum porosity (lower
the effective critical density). The model therefore needs to be modified to treat both a compressible matrix, so that sheet thickness is a function of mechanical pressure; and compressible fibers, so that the liquid available for flow becomes a function of mechanical pressure and the limiting density is the density of cellulose (at a porosity of zero).

SUMMARY

HIDRYER1 gives good qualitative agreement with experimental results. The quantitative agreement could be improved by varying some of the constants used in the model and modifying the model to account for the phenomena of vapor flow and condensation during the transition regime and liquid expression from the fiber walls.
SUMMARY

This mathematical model is a significant first effort in the development of a convenient predictive tool for investigating high intensity drying options. The zone concept and simple solution method provide a methodology and framework for easy modification, expansion, and improvement.

The model requires few input parameters (hot surface temperature, boiling point temperature, basis weight, Canadian Standard Freeness, initial moisture ratio, mechanical pressure pulse) and qualitatively accounts for the observed macroscopic phenomena: internal sheet temperature, heat flux, sheet thickness, and moisture removal in liquid and vapor form. The degree of quantitative agreement varies with drying conditions. The agreement with all experimentally measured quantities could be improved by the specific suggestions in the thesis using a mathematical optimization procedure (with the empirical results as constraints on the output).

Capillary liquid flow appears to be significant at lower hot surface temperatures. Vapor flow with condensation appears to be significant during the transition regime under all conditions. A better model of dynamic sheet compression at high temperatures needs to be developed and tested.
RECOMMENDATIONS

The first extension of this work should be the modification of HIDRYER1 to run faster. This could be accomplished in several ways. The number of finite difference grid points could be reduced; the number of iterations for the calculation of the interface temperatures could be reduced; an alternative to the finite difference method could be used; or a reorganization of the computational algorithm could be performed. Any reduction in the CPU time would encourage more use of the model and allow a more comprehensive parametric investigation.

Second, a mathematical optimization of the model's constants would yield improvements in its quantitative predictions. There is already enough empirical evidence to make a reasonable effort in this area.

The third area for future research involves permeability. Transport models for paper have been limited in that a thorough investigation of the factors (freeness, moisture ratio, etc.) affecting permeability has not been performed. Isolated efforts are apparent, but are limited in scope and depth.

The fourth area is related to the compression properties of paper. The quantitative effects of moisture ratio, temperature, mechanical pressure, and freeness for a wide range of conditions are unknown. Each should be investigated individually and in combination to cover the complete range of process possibilities from wet pressing to high intensity drying.
ACKNOWLEDGMENTS

I would like to thank The Institute of Paper Chemistry for providing the facilities and financial support for this thesis.

The members of my advisory committee, Nai Chang, Peter Parker, and Douglas Wahren, offered many helpful insights and suggestions. My friend and principal adviser, Fred Ahrens, always found a way to keep me on the right track, whether by example, encouragement, or experience.

Finally, I would like to express my love and gratitude to my wife Deborah and my son Daniel for their endless supply of patience, support, love, and understanding.
### NOMENCLATURE

The abbreviations for SI units in this section are: m (meter), s (second), kg (kilogram), K (kelvin), J (joule), N (newton), W (watt), and Pa (pascal).

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>fraction of liquid water external to fibers</td>
</tr>
<tr>
<td>A1-4</td>
<td>equation constants</td>
</tr>
<tr>
<td>b</td>
<td>equation constant</td>
</tr>
<tr>
<td>B1-5</td>
<td>equation constants</td>
</tr>
<tr>
<td>BI</td>
<td>heat transfer Biot number</td>
</tr>
<tr>
<td>BW</td>
<td>mass of dry fibers per unit sheet area, kg/m²</td>
</tr>
<tr>
<td>BW1-4</td>
<td>BW of individual zones, kg/m²</td>
</tr>
<tr>
<td>C</td>
<td>mass of dry fibers per unit sheet volume, kg/m³</td>
</tr>
<tr>
<td>C1,C2</td>
<td>equation constants</td>
</tr>
<tr>
<td>COEFF</td>
<td>arbitrary equation coefficient</td>
</tr>
<tr>
<td>CONST</td>
<td>arbitrary equation constant</td>
</tr>
<tr>
<td>Cpf</td>
<td>specific heat of cellulose, J/(kg K)</td>
</tr>
<tr>
<td>Cpv</td>
<td>specific heat of gas or vapor, J/(kg K)</td>
</tr>
<tr>
<td>Cpw</td>
<td>specific heat of liquid water, J/(kg K)</td>
</tr>
<tr>
<td>CSF</td>
<td>Canadian Standard Freeness</td>
</tr>
<tr>
<td>D</td>
<td>equation constant</td>
</tr>
<tr>
<td>D1-7</td>
<td>equation constants and rates of change</td>
</tr>
<tr>
<td>DBWxDT</td>
<td>rate of change of zone x basis weight, kg/m² s</td>
</tr>
<tr>
<td>Dc</td>
<td>equation constant</td>
</tr>
<tr>
<td>DIFF'</td>
<td>relative position increment</td>
</tr>
<tr>
<td>DIFF''</td>
<td>relative position increment</td>
</tr>
<tr>
<td>DTO</td>
<td>default time increment, s</td>
</tr>
</tbody>
</table>
E1, E2  
equation constants
F1, F2  
equation constants
G1-6  
equation constants
H1-4  
equation constants
Hc  
th hot surface to paper contact coefficient, W/(m² K)
Δh  
latent heat of vaporization, J/kg
Δh'  
incremental latent heat of desorption, J/kg
Δh*  
average latent heat of desorption, J/kg
I1  
equation constant
i'  
grid point designation
i"  
grid point designation
IMAX  
iteration counter
J1-5  
equation constants
K  
thermal conductivity, W/(m K)
K1-3  
equation constants or zone thermal conductivities
KAKV  
product of Ka3 and Kv, m²
KAKW  
product of Ka3 and Kw, m²
Ka  
absolute permeability, m²
Ka2-4  
zone absolute permeabilities, m²
Kd  
dry zone thermal conductivity, W/(m K)
KMIN  
minimum number of grid points
Kv  
relative gas or vapor permeability
Kw  
relative liquid permeability
L  
distance in zone, m
L  
zone thickness, m
L1-3  
equation constants or zone thicknesses
M  
compression equation constant, (kg/m³)/PaN
M' modified M value, \((\text{kg/m}^3)/\text{Pa}^N\)
Ml equation constant
Mo initial mass of water per unit area, \(\text{kg/m}^2\)
MR mass of water per unit mass of dry fiber
MRI starting MR
MRf ending MR
MREL mass of water removed divided by initial mass
MRO initial MR
N compression equation constant
N1, N2 equation constants
OHTC overall heat transfer coefficient, \(\text{W/(m}^2\text{K)}\)
P pressure, Pa
Patm ambient pressure, Pa
Pcap capillary pressure, Pa
PMAX maximum gage mechanical pressure, Pa
Pmech absolute mechanical pressure, Pa
Pmechg gage mechanical pressure, Pa
PROP arbitrary vapor or liquid property
Pv vapor pressure, Pa
Pw liquid pressure, Pa
\(\overline{Pw}\) average hydraulic pressure, Pa
Q conduction heat flux, \(\text{W/m}^2\)
r pore radius, m
R specific filtration resistance, m/kg
RATE1-3 rates of advance, m/s
RATIO1-3 interface position divided by DELTAT
RISTIM time required to attain PMAX, s
- 116 -

$S$ saturation
$S'$ interfiber saturation
$S_{2,3}$ zone saturations
$SEC$ time, s
$t$ time, s
$\Delta t$ time increment, s
$t'$ time, s
$T$ temperature, K
$T'$ grid point temperature, K
$T''$ grid point temperature, K
$T_{1-3}$ interface temperatures, K
$TB$ boiling point temperature, K
$TBAR$ average zone temperature, K
$TH$ hot surface temperature, K
$TI$ initial sheet temperature, K
$TIME$ time, s
$TS$ sheet surface temperature, K
$U$ same as OHTC, $W/(m^2 K)$
$V_f$ velocity of fibers, m/s
$V_f'$ interface velocity, m/s
$V_{gas}$ gas velocity, m/s
$V_v$ superficial vapor velocity relative to $V_f$, m/s
$V_w$ superficial liquid water velocity relative to $V_f$, m/s
$V_{water}$ velocity of liquid water, m/s
$x$ relative position
$\Delta x$ relative position increment
$z$ position coordinate, m
\( \gamma \)  
\text{surface tension, N/m}

\( \delta \)  
\text{thickness, m}

\( \delta' \)  
\text{grid point coordinate, m}

\( \delta'' \)  
\text{grid point coordinate, m}

\( \delta_{1-3} \)  
\text{interface positions, m}

\( \delta_T \)  
\text{total thickness, m}

\( \varepsilon \)  
\text{porosity}

\( \varepsilon' \)  
\text{interfiber porosity}

\( \varepsilon_{2,3} \)  
\text{zone porosities}

\( \theta \)  
\text{contact angle, radians}

\( \mu_v \)  
\text{vapor viscosity, N s/m}^2

\( \mu_w \)  
\text{liquid viscosity, N s/m}^2

\( \rho_F \)  
\text{fiber density, kg/m}^3

\( \rho_v \)  
\text{vapor density, kg/m}^3

\( \rho_w \)  
\text{liquid density, kg/m}^3

\( \tau \)  
\text{time parameter}

\( \phi \)  
\text{equation coefficient}

\( \bar{\phi} \)  
\text{averaged equation coefficient}

\( \psi \)  
\text{equation coefficient}


82. Davies, C. The separation of airborne dust and particles. Institute of Mechanical Engineers 1B:185-98(1952).


To run HIDRYER1 the user needs to have or must be able to access three files on the Burroughs B6900 main frame:

- HIDRYER1/JOB, the WFL job deck to run the object code;
- OBJECT/HIDRYER1, the compiled and saved FORTRAN object code; and
- HIDRYER1/PARAMS, the data file containing input parameters.

HIDRYER1/JOB is the following WFL job deck:

```
BEGIN JOB HIDRYER1(INTEGER Q, STRING NAME1, STRING NAME2);
  QUEUE=Q;
  RUN OBJECT/HIDRYER1;
  FILE FILE1=#NAME1;
  FILE FILE2=#NAME2;
  STATION=MYSELF(SOURCESTATION);
END JOB
```

To run the program the user enters

```
START HIDRYER1/JOB(Q,"NAME1","NAME2")
```

where Q is the queue number, NAME1 is HIDRYER1/PARAMS (or other data file conforming to the correct input syntax), and NAME2 is the name of the disk data file to which the output information is written and saved.

OBJECT/HIDRYER1 is obtained by compiling HIDRYER1 and saving the result. HIDRYER1 and its documentation are listed later in this appendix. About 20 seconds of processor time and 60 seconds of elapsed time are required for compilation of HIDRYER1.
HIDRYER1/PARAMS is a data file containing the following numerical information separated by commas:

\[
\text{TH, TB, BW, CSF, MRO, DTO, PMAX, RISTIM, IOPTP, IOPTU, METH, MITER}
\]

For example:

\[
525.0, 212.0, 0.0420, 650, 1.500, 1.37E-07, 750.0, 0.025, 1, 1, 2, 2
\]

The input parameters are defined in the thesis and in the HIDRYER1/DOC section of this appendix. HIDRYER1 performs all calculations in English units, but the input and output may be given in either English or SI units.

HIDRYER1/DOC

HIDRYER1 is a FORTRAN implementation of the equations in this thesis. It mathematically performs a drying "experiment" based on the inputs from HIDRYER1/PARAMS and outputs the results to the printer and to a disk file named by the user.

The main part of the program is divided into four sections. The first section contains the file declarations, statements for inclusion of packaged subroutines, real variable declarations, values for constants, common statements, and preliminary input and output statements. The next three sections contain the equations for the heatup, transition, and linear drying regimes.

The main program is followed by a SUBROUTINE section containing 13 subroutines and a FUNCTION section containing 12 functions. The subroutine names and their purposes are:
CALLER: calls property subroutines
CNSTMN: determines constants for calculation of M and N
CNVRT1: converts from English to SI units
CNVRT2: converts from SI to English units
DLDTFN: calculates the compression of a saturated sheet
DUMFUN: calculates the Jacobian matrix for DLDTFN
PRESSR: calculates applied pressure and time derivative
PROP12: calculates and averages physical properties at T1 and T2
PROP23: calculates and averages physical properties at T2 and T3
PROP3B: calculates and averages physical properties at T3 and TB
PROPTB: calculates the physical properties at TB
WARNIN: corrects error conditions or prints warning messages
WRITER: writes output to printer and disk

Subroutine DLDTFN calls a set of subroutines from the International Mathematical and Statistical Library package for the solution of an initial value problem. More information on these subroutines may be found in the appropriate IMSL documentation.

The function names and their purposes are:

DELHD : calculates latent heat of vaporization increment
DPVDT : calculates derivative of vapor pressure with temperature
EVALM : calculates the M compression constant
EVALN : calculates the N compression constant
HFG : calculates the latent heat of vaporization
HYDRAL: calculates the hydraulic pressure
SPRES : calculates the specific filtration resistance
VF : calculates the liquid water specific volume
VG : calculates the water vapor specific volume
VISF : calculates the liquid water viscosity
VISG : calculates the water vapor viscosity
PV : calculates the vapor pressure

The main program variable names and definitions are:

A thermal diffusivity term
Ax interface rate-of-advance terms
ALF DELTA2 - DELTA1
ALFA DELTA3 - DELTA1
BET DELTA3 - DELTA2
BETA DELTAT - DELTA3
BIDX product of Biot number and DX
BW sheet basis weight
BWx basis weight of zone x
BWCORR basis weight correction factor
BWSUM sum of corrected zone basis weights
Cx dry fiber concentration of zone x
COEFF coefficient in mechanical pressure calculations
CONST C3/DFIBER
CPF specific heat of cellulose
CPW specific heat of water
CSF Canadian Standard Freeness
Dx rates of interface advance
DBWxDT rate of change of basis weight of zone x
DC product of density, specific heat and moisture ratio
DELTAx position of interface x
DELTAF position of grid point closest to outer interface
DELTAI position of grid point closest to inner interface
DELTAT sheet thickness
DELTSI DELTAT in SI units
DENOM denominator term used in various calculations
DF reciprocal of DFIBER
DFIBER density of cellulose
DHx constants in DELHD
DIFF relative distance term
DIFFX relative distance term
DIFFI relative distance term
DIFFIX relative distance term
DK product of MR, DFIBER, and KWATER
DLDT rate of change of saturated sheet thickness
DPDT rate of change of mechanical pressure
DPDTxy vapor pressure with temperature derivative over x and y
DPVDTB vapor pressure at TB
DSTAR interface rate of advance
DT time increment
DTx  calculated time increments
DTD2xy  temperature gradient over x and y
DTMAX  maximum time increment
DTO  default time increment (in hours)
DW  density of liquid water
DX  relative position increment
DXX  relative position increment
Ex  porosity of zone x
EMIN  minimum allowable porosity
ESTAR  interfiber porosity
ESx  constants for calculation of ESTAR
Fx  factors for temperature calculations
F3x  product of F3 and DX
FACTOR  factor for conversion of English units
FLAG  signal for absence of zone 3
GAMM  DELTAT - DELTA3
H  time increment
HC  contact coefficient
HCx  constants for calculation of HC
HCDRY  contact coefficient of dry cellulose
HCREF  HCDRY at PREF2
HCWET  contact coefficient of water
HPGx  latent heat of vaporization at interface x
HFGTB  latent heat of vaporization at TB
I  loop iteration counter
IDUMMY  subroutine work vector
IER  subroutine error indicator
IFINI  number of grid point closest to outer interface
IMAX  maximum iteration counter
INDEX  subroutine call parameter
INIT  number of grid point closest to inner interface
ILOPTx  interface motion indicators
ILOPTP  pressure pulse option (1=ramp, 2=sine)
ILOPTU  units option (1=English, 2=SI)
IWK  subroutine work vector
J  print control variable
K  loop iteration counter
Kx  thermal conductivity of zone x
KABSx  absolute permeability of zone x
KAKV  product of KABS3 and KV
KAKW  product of KABS3 and KW
KFIBER  thermal conductivity of dry cellulose
KK  grid point counter
KMIN  initial number of grid points
KV  vapor relative permeability
KW  liquid relative permeability
KWATER  thermal conductivity of water
L  print control variable
LIQDEW  mass of liquid water removed
LMAX  print control variable
M  number of points for internal temperature calculations
Mx  compression constant for zone x
MC  moisture content
METH  subroutine parameter (1=Adams method, 2=Gear's method)
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFINAL</td>
<td>target final moisture content</td>
</tr>
<tr>
<td>MITER</td>
<td>subroutine parameter (0=iteration, 1=analytic, etc.)</td>
</tr>
<tr>
<td>MO</td>
<td>initial mass of water present</td>
</tr>
<tr>
<td>MR</td>
<td>moisture ratio</td>
</tr>
<tr>
<td>MREL</td>
<td>relative amount of moisture removed</td>
</tr>
<tr>
<td>MREM</td>
<td>amount of moisture remaining</td>
</tr>
<tr>
<td>MRO</td>
<td>initial moisture ratio</td>
</tr>
<tr>
<td>MRSTAR</td>
<td>intrafiber MR</td>
</tr>
<tr>
<td>N</td>
<td>print control variable</td>
</tr>
<tr>
<td>Nk</td>
<td>compression constant for zone x</td>
</tr>
<tr>
<td>NEXP</td>
<td>exponent in calculation of Nx</td>
</tr>
<tr>
<td>OHTC</td>
<td>overall heat transfer coefficient</td>
</tr>
<tr>
<td>OHTCSI</td>
<td>OHTC in SI units</td>
</tr>
<tr>
<td>P</td>
<td>structural pressure</td>
</tr>
<tr>
<td>Px</td>
<td>structural pressure in zone x</td>
</tr>
<tr>
<td>PDENOM</td>
<td>denominator in pressure calculation</td>
</tr>
<tr>
<td>PGAGSI</td>
<td>PGAUGE in SI units</td>
</tr>
<tr>
<td>PGAUGE</td>
<td>gage vapor pressure at T1</td>
</tr>
<tr>
<td>PHx</td>
<td>hydraulic pressure in zone x</td>
</tr>
<tr>
<td>PHI</td>
<td>thermal diffusivity term</td>
</tr>
<tr>
<td>PMAX</td>
<td>maximum mechanical pressure</td>
</tr>
<tr>
<td>PMID</td>
<td>pressure midway between PMAX and PREF1</td>
</tr>
<tr>
<td>PREFx</td>
<td>reference mechanical pressures</td>
</tr>
<tr>
<td>PR3LOG</td>
<td>natural log of PREF3</td>
</tr>
<tr>
<td>PSI</td>
<td>velocity term</td>
</tr>
<tr>
<td>PS3</td>
<td>structural pressure of saturated sheet</td>
</tr>
<tr>
<td>PS3</td>
<td>structural pressure of saturated sheet</td>
</tr>
<tr>
<td>PW3</td>
<td>vapor pressure at TB</td>
</tr>
<tr>
<td>PW</td>
<td>liquid pressure</td>
</tr>
<tr>
<td>Q</td>
<td>instantaneous heat flux</td>
</tr>
<tr>
<td>QINIT</td>
<td>heat supplied during heatup regime</td>
</tr>
<tr>
<td>QSI</td>
<td>Q in SI units</td>
</tr>
<tr>
<td>QTHEOR</td>
<td>theoretical heat requirement</td>
</tr>
<tr>
<td>QTHERX</td>
<td>term in calculation of QTHEOR</td>
</tr>
<tr>
<td>QTOT</td>
<td>total heat input during drying</td>
</tr>
<tr>
<td>QTOTAL</td>
<td>heat supplied during transition and linear regimes</td>
</tr>
<tr>
<td>R</td>
<td>resistance factor</td>
</tr>
<tr>
<td>RATEx</td>
<td>rates of interface advance</td>
</tr>
<tr>
<td>RATIOx</td>
<td>DELTAX/DELTAT</td>
</tr>
<tr>
<td>REM</td>
<td>remainder in distance calculations</td>
</tr>
<tr>
<td>RISTIM</td>
<td>time required to attain PMAX (in seconds)</td>
</tr>
<tr>
<td>S3STAR</td>
<td>interfiber saturation</td>
</tr>
<tr>
<td>SDUMMY</td>
<td>subroutine work variable</td>
</tr>
<tr>
<td>SEC</td>
<td>time in seconds</td>
</tr>
<tr>
<td>SIGN</td>
<td>variable in LIQDEW calculation</td>
</tr>
<tr>
<td>STAR</td>
<td>variable in MRSTAR calculation</td>
</tr>
<tr>
<td>SUM12</td>
<td>sum of BW1 and BW2</td>
</tr>
<tr>
<td>SUM123</td>
<td>sum of SUM12 and BW3</td>
</tr>
<tr>
<td>TX</td>
<td>temperature of interface x</td>
</tr>
<tr>
<td>TmSI</td>
<td>Tx in SI units</td>
</tr>
<tr>
<td>TB</td>
<td>boiling point temperature</td>
</tr>
<tr>
<td>TBARx</td>
<td>average temperature of zone x</td>
</tr>
<tr>
<td>TC</td>
<td>temperature at a fixed point in the sheet</td>
</tr>
<tr>
<td>TERMx</td>
<td>terms used in various calculations</td>
</tr>
</tbody>
</table>
TH hot surface temperature
THICKx thickness of zone x
TI initial sheet temperature
TIME time
TIMEND time endpoint for initial value problem
TIMER factor used in temperature calculations
TMID temperature midway through the sheet basis weight
TMIDSI TMID in SI units
TNEW new temperature at a given grid point
TOL subroutine convergence tolerance
TOLD old temperature at a given grid point
TOx old temperature at interface x
TS sheet surface temperature
TSSI TS in SI units
U fractional basis weight
V velocity term
VFxy specific volume of liquid water over x and y
VFTB specific volume of liquid water at TB
VGxy specific volume of water vapor over x and y
VGTB specific volume of water vapor at TB
VISFxy viscosity of liquid water over x and y
VISFTB viscosity of liquid water at TB
VISGxy viscosity of water vapor over x and y
VISGTB viscosity of water vapor at TB
W product of MRSTAR and C2
WK subroutine work variable
X product of MR and C3
XX grid point variable
Y product of (MR-MRSTAR) and C3
YL thickness of saturated sheet
Z Y/X
ZTC location of fixed points within the sheet

In the subroutines, the variables not linked to the main program by COMMON statements are:

CALLER

all variables in common with main program

CNSTMN

Ax constants for calculation of CMx
Bx constants for calculation of CMx
Cx constants for calculation of CNx
CMx constants for calculation of M compression constant
CNx  constants for calculation of N compression constant
Dx   constants for calculation of CNx
Ex   constants for calculation of TERM
TERM constant for calculation of CMx and CNx

CNVRT1
Ax   constants in unit conversions

CNVRT2
Ax   constants in unit conversions

DLDTFN

YPRIME rate of change of saturated sheet thickness

DUMFUN

PD   partial derivative of YPRIME with respect to YL

PRESSR
Ax   constants in sine pressure pulse calculation
PI   numerical value 3.14159...

PROP12
all variables in common with main program

PROP23
all variables in common with main program

PROP3B
all variables in common with main program
In the functions, the variables not linked to the main program by COMMON statements are:

DELHD

all variables in common with main program

DPVDT

Ax constants used in property calculation

EVALM

A constant used in calculation of M compression constant
Ax constants used in calculation of A and B
B constant used in calculation of M compression constant
CMx constants in common with CNSTMN
CORRCT correction in calculation of M compression constant

EVALN

A constant used in calculation of N compression constant
Ax constants used in calculation of A and B
B constant used in calculation of N compression constant
C uncorrected value for N compression constant
CNx constants in common with CNSTMN
NDENOM  denominator in correction of N compression constant
NMID value of N at PMID
NSAT value of N at PREF3
PTERM pressure term in correction of N compression constant
SIGN variable in correction of N compression constant
HFG
Ax  constants used in property calculation
HYDRAL
   all variables in common with main program
SPRES
Ax  constants used in property calculation
RREF reference specific filtration resistance
X variable used in property calculation
VF
Ax  constants used in property calculation
VG
Ax  constants used in property calculation
VISF
Ax  constants used in property calculation
VISG
Ax  constants used in property calculation
PV
Ax  constants used in property calculation
The following discussion of HIDRYER1 is divided into sections by program line numbers and headings. Refer to the program listing for the actual FORTRAN statements.

OPENING SECTION OF MAIN PROGRAM

1 : Format line.
   Sets standard FORTRAN format.

5 - 23 : Headers
   Program references and identification.

28 - 32 : File declarations.
   File 1 is the parameter input file; file 2 is the disk output file;
   file 5 is the terminal; and file 6 is the line printer.

34 - 44 : Include statements.
   Include the required subroutines from the IMSL package.

46 - 48 : Real variable declarations.
   Sets variables ordinarily assumed to be integers to be real variables
   and dimensions some arrays.

50 : Dimension statement.
   Sets dimension of an integer array.

52 : External statement.
   Declares two subroutines external to the IMSL package.

55 - 64 : Fixed input assignment.
   Assigns values to certain constants in the program.

67 - 85 : Subroutine common blocks.
   Names common blocks for subroutines.

88 - 91 : Input statement.
   Reads input parameters in free format from file 1.
94 - 101 : Write statements.
Write headings and repeat input parameters on line printer.

104 - 107 : Set print controls.
Set counters for frequency of printing output results.

110 - 114 : Set fixed internal points.
Set fixed fractions of basis weight at which temperatures are to be calculated. This is for direct comparison to experimental results.

117 - 120 : Compute properties at TB.
Convert to English units if necessary and compute vapor and liquid properties at TB for use later in the program.

HEATUP REGIME

129 - 168 : Initialize variables.
Set initial variable values for heatup regime and for use later in the main program.

171 - 223 : Calculate mechanical pressure and sheet properties.
Calculate mechanical pressure for nonsaturated or saturated sheets and determine sheet properties like thickness, porosity, etc.

226 - 232 : Calculate heat transfer parameters.
Determine contact coefficient, thermal conductivity and BIDX.

235 - 260 : Calculate interior temperatures.
Use finite difference methods to find internal temperatures for a non-saturated or saturated sheet undergoing compression.

263 - 275 : Calculate boundary temperatures.
Use finite difference methods to calculate boundary temperatures for nonsaturated or saturated sheets.
278 - 282: Reset old temperature values.
   Reset TOLD for next set of finite difference calculations.
285 - 291: Compute temperatures at fixed locations.
   Use linear interpolation to find temperatures at fixed basis weight
   fractions in the sheet.
294 - 314: Increment quantities and write results.
   Calculate quantities which must be calculated at every time increment
   and determine if the output should be printed on this iteration. If
   the output needs to be printed, then calculate additional output quan-
   tities that do not have to be determined at every time step.
317 - 320: Increment print control variables.
   Increase the values of the counters for print control.
323 - 327: Determine exit criteria.
   Check time and physical criteria for exit to transition regime or
   program termination.
330 - 345: Write heatup regime final output.
   Calculate final values for quantities and write output if it is not
   a duplication of the last printed output.

TRANSITION REGIME

354 - 356: Write transition regime heading.
   Write heading on printer to signal onset of transition regime.
359 - 404: Initialize variables.
   Set initial values for transition regime variables.
407 - 417: Compute required derivatives.
   Calculate the rates of advance for the different interfaces which may
   be present in the sheet.
420 - 460: Set maximum allowable time increment.
Examine rates of interface advance and determine the maximum allowable
time increment which will not violate the interface position criteria.
Determine if new interface position permits the use of usual finite
difference formulations or requires use of unequally spaced points.
Increment the time and include the factor TIMER to account for round-
off or truncation errors in the determination of DT.

463 - 501: Calculate new temperature distribution.
Use finite difference methods to determine internal and "boundary"
(INIT and IFINI) temperatures in the transition zone and in zone 4, if
it exists.

504 - 519: Calculate rates of basis weight change.
Select the dominant rate at each interface and determine any liquid
dewatering that takes place.

522 - 535: Calculate mechanical and hydraulic pressure.
Calculate applied mechanical pressure based on time and IOPTP and
calculate the hydraulic (vapor) pressure for each zone. Obtain the
effective structural pressure for each zone by subtraction.

538 - 585: Calculate basis weight, concentration, and thickness.
Calculate rates of basis weight change and new basis weights. Correct
basis weights for slight calculation errors. Evaluate the compression
constants, dry fiber concentration, and thickness of each zone.

588 - 623: Calculate porosity and saturation.
Calculate porosity based on dry fiber concentration, and saturation
based on dry fiber concentration and moisture ratio. Correct zone 3
saturation if greater than unity.
626 - 645: Increment interface positions.
   Calculate new interface positions, locations of INIT and IFINI, and
   position increments for finite difference calculations.
648 - 658: Compute thermal conductivity and contact coefficient.
   Find thermal conductivity of each zone and contact coefficient.
661 - 669: Calculate permeability factors.
   Calculate specific filtration resistance, absolute permeability for
   the zones and KAKW.
672 - 680: Set relative interface positions.
   Compute the RATIOx values and calculate the remaining moisture and
   relative moisture loss.
683 - 735: Compute new interface temperatures.
   Calculate new interface temperatures based on equations appropriate for
   types and locations of interfaces present.
738 - 761: Recompute variables for derivative calculations.
   Calculate temperature gradient terms for zones and multipliers for rate
   expressions.
764 - 879: Handle special case of intrafiber water only.
   If FLAG = 1, then this section handles all calculations for the tran-
   sition regime. The calculations are based on those of the previous
   sections and modified for this special case. If FLAG = 0, then this
   section is bypassed.
882 - 889: Reset temperature distribution and time options.
   Reset TOLD values for next finite difference calculations and reset
   IOPT1 and IOPT2 for the next time increment.
892 - 912: Compute temperatures at fixed locations.
   Same strategy as for lines 285 - 291.
915 - 934: Increment quantities and write results.
   Same strategy as for lines 294 - 314.
937 - 940: Increment print control variables.
   Same strategy as for lines 317 - 320.
943 - 949: Determine exit criteria.
   Same strategy as for lines 323 - 327.
952 - 968: Write transition regime final output.
   Same strategy as for lines 330 - 345.

LINEAR REGIME

977 - 979: Write linear regime heading.
   Same strategy as for lines 354 - 356.
982 - 989: Set FLAG and go to first temperature calculation.
   Set the value for FLAG and go directly to interface temperature calculation right from the transition regime.
992 - 1005: Compute required derivatives.
   Same strategy as for lines 407 - 417, with additional calculations for other types of interfaces that may be present.
1008 - 1032: Set maximum allowable time increment.
   Same strategy as for lines 420 - 460, but no restriction on interface position relative to grid points.
1035 - 1053: Calculate rates of basis weight change.
   Same strategy as for lines 504 - 519.
1056 - 1070: Calculate mechanical and hydraulic pressure.
   Same strategy as for lines 522 - 535.
1073 - 1121: Calculate basis weight, concentration, thickness.
   Same strategy as for lines 538 - 585.
1124 - 1159 : Calculate porosity and saturation.
    Same strategy as for lines 588 - 623.

1162 - 1169 : Increment interface positions.
    Same strategy as for lines 626 - 645, but no finite difference grid
    spacings need to be calculated.

1172 - 1182 : Compute thermal conductivity, contact coefficient.
    Same strategy as for lines 648 - 658.

1185 - 1194 : Calculate permeability factors.
    Same strategy as for lines 661 - 669, with KAKV also determined.

1197 - 1204 : Set relative interface positions.
    Same strategy as for lines 672 - 680.

1207 - 1286 : Compute new interface temperatures.
    Same strategy as for lines 683 - 735, but with equations appropriate
    for linear regime (including vapor flow in zone 3).

1289 - 1317 : Recompute variables for derivative calculations.
    Same strategy as for lines 738 - 761.

1320 - 1338 : Compute temperatures at fixed locations.
    Same strategy as for lines 892 - 912.

1341 - 1357 : Increment quantities and write results.
    Same strategy as for lines 915 - 934.

1360 - 1363 : Increment print control variables.
    Same strategy as for lines 937 - 940.

1366 - 1369 : Determine exit criteria.
    Same strategy as for lines 943 - 949, but time and moisture content are
    the only criteria for the linear regime.

1372 - 1385 : Write final output.
    Calculate and write total values for cumulative variables.
1388 - 1410: Format statements.

Statements for printer headings and output variable format.

1413 - 1416: End main program.

STOP and END statements for main program.

The remainder of HIDRYER1 is composed of the SUBROUTINE and FUNCTION sections, which have been previously described.
** HIGH INTENSITY DRYING PROGRAM **

** HIDRYEI **

** INSTITUTE OF PAPER CHEMISTRY **

** JOSEPH R POUNDER **

** MARCH 25, 1985 **

***********************************************************************

*** PROGRAM DOCUMENTATION IS IN THE HIDRYEI/DOC FILE ***

*** INSTRUCTIONS FOR RUNNING THE PROGRAM ARE IN THE HIDRYEI/USE FILE ***

***********************************************************************

ILE 1(KIND=DISK,NEWFILE=FALSE,FILETYPE=7,MYUSE=IN)
ILE 2(KIND=DISK,NEWFILE=TRUE,WA,RECSIZE=21,PROTECTION=SAVE,
  * MYUSE=CUT)
ILE 3(KIND=REMOTE,MYUSE=IC)
ILE 4(KIND=PRINTER)

INCLU "*INSL/CONS"
INCLU "*INSL/GEAR"
INCLU "*INSL/DERIA"
INCLU "*INSL/DERPS"
INCLU "*INSL/GRSI"'
INCLU "*INSL/LLCATF"
INCLU "*INSL/LUELWF"
INCLU "*INSL/LEG18"
INCLU "*INSL/LEATST"
INCLU "*INSL/UEC10"
INCLU "*INSL/UEC10"

REAL KAES2, KABS3, KABS4, KAKV, KAKW, KFIBER, KV, KM, KATER, K1, K2, K3,
  K4, KDGE, MC, MFIAL, MO, MR, MREL, MREM, MR0, MRSTAR, M1, M2, M3, M4, MEXP,
  N1, N2, N3, N4, IC(10), TAEH(5C1), TOLC(5C1), WKC(250), YLC(2), ZTC(10) ...

DIMENSION IMK(1)
EXTERNAL DLG1FA=DUMFLN

*DATA
*CH1=DX1=1.23=3.31X=1.4522/=14.9522/=15.055/=0.55/= IMAX/100/=0
*KMIN/101/= M/3/= OFIBER=KFIBER=CPF/96.76/0.14/0.346/=0
*KWATER=CFW/=0.394/=1.00/= FACTOR/1.6679002E+07/= LMAX/25/=0
*STAR=C=505684/= KFINAL/0.06/= TIMER/0.55/= TI/75.0/= TJ/25/=0
*HREF=HET/100/=1000/= PREF1=PREF2=PREF3/0.10/=1.000/=0
*HCl=HC2=HC3/I.45159/0.3333333/0.479354/= TOL/1.0E-05/=0
*INDEX/1/= NEXP/3.0/=0

*COMMON BLOCKS ARE:

COMMON /GEM/ CUMMY(48)=SCUMMY(4)=1OLMMY(38)
COMMON /LICL/ TBPVCT=DFVCTB=VF2B=V2T0=HGTGB=VISGTB=VISFTB
COMMON /LICL/ T=TI1=TI2=TI3=TI4=0
COMMON /LICL/ DPOT12=VF12=V212=VISG12
COMMON /LICL/ DPOT23=VF23=VISG23
COMMON /LICL/ DPOT38=V38=VISG38
COMMON /LICL/ DX=DIFF=CFDIFF=EC DIFF=EMIN
COMMON /LICL/ PREF1=PMAX=RISTIM=PLOPT=PDPDT
COMMON /LICL/ M=K3=N4=N1=N2=N3
COMMON /LICL/ DLGT=FACTGR=BA=DFIBER=COEFF=PS3
COMMON /LICL/ CSF
COMMON /LICL/ SEC=MREL=TS=RAT01=RAT102=RAT103=DELTAT=QHTC=

* PGALGE
COMMON /LICL/ TSSI=TSI=TSI2=TSI3=QSI=QHTCSI=PSGI=
* TMICSI
COMMON /LICL/ DH1=DH2=HR=MR=STAR
COMMON /LICL/ NEXP=PR3LCG=PREF3=PID=POEM=OF

****READ INPUT FROM DATA FILE

READ(1//) TB,BW,CSF,MRO=ITO=PMAX=RISTIM=LOPT=LOPTU=

** HET=MITER

****WRITE HEADING AND STARTING PARAMETERS

WRITE(6,900)
WRITE(6,905)
WRITE(6,910) TB,BW,CSF,MRO=PMAX=RISTIM
WRITE(6,915)
WRITE(6,920) DIO=LOPT=LOPTU=METH=MITER
WRITE(6,925)

****SET VARIABLES FOR PRINTING OF RESULTS

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000091
000092
000093
000094
000095
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000099
000100
000101
000102
000103
000104
A = J
L = 1

***** SET POSITIONS FOR FIXED-POINT TEMPERATURE CALCULATIONS

CG 10 I=1*N
2IC(I)=I/(N+1)
1C CONTINUE

***** COMPUTE PROPERTIES AT SATURATION TEMPERATURE

IF(ICPT6.EQ.2) CALL CNVRT1
CALL PRCPRT

***************
***** THE HEATUP REGIME *****

***************

***** INITIALIZE VARIABLES

Cht=1./VF(TI)
VF23=1./Gw
CF=1./OFIBER

F3LCG=ALCG(PREF3)
FCENOM=(PREF3-FREF1)/2.
FMI0=(PREF3+FREF1)/2.

RSTAR=STAR*Db
IF(MRSTAR.GT.MRO) MRSTAR=MRO
IF(MRSTAR.EQ.MRO) FLAG=1
PO=MRO*Eb
EMIN=ES2/ES1
CALL CNSTMN(CSF)

K=KMIN
XX=(K-1)/(K+1)
CX=1./X/(K-1)

CC 2C I=1*N
1CLO(I)=71
2C CONTINUE

IF(FLAG.EQ.1) RAT1C2=1.
RAT1C3=1.
MR=MRO

P1=EVALP(CO.,TB)
P2=EVALP(MRSTAR,TB)
\*4=M1
\*1=EVALN(1*C*>0.0)
\*2=EVALN(1*MRSTAR+0.0)
\*4=N1

\*C
C = CFIBER*(CPF+MR+CPW)
CM=MR*DFIBER*K&ATER
A=(KFIBER+OM/0)/DC

C
C*****CALCULATE MECHANICAL PRESSURE AND SHEET PROPERTIES
C
IC 1F(S3*EQ.1) GO TO 40
CALL PRESSC(TIME)
TBAR1=(TOLQO(1)+TOLQO(K))/2.
\*3=EVALN(MR+TBAR1)
\*4=EVALN(2*PR+F)
DELTAT=CM/(\*3*P**M3)
\*5=A/DELTAT**2
\*T=TIMER*DX**2/(2*PSI)
\*b=PVIB
TIME=TIME+DT
\*C TO 50

C
\*C YL(1)=DELTAT
K=R=CH*(YL(1)/B+1./DFIBER)
TBAR1=(TOLQO(1)+TOLQO(K))/2.
\*3=EVALN(MR+TBAR1)
\*4=EVALN(2*PR+F)
C=DFIBER*(CPF+MR+CPW)
CM=MR*CFIBER*K&ATER
A=(KFIBER+OM/0)/DC

C
\*FHI=-Gw*CPB*DLQT*DFIBER/(CC*BW)
\*PSI=A/(YL(1)**2)

C
\*CT=TIMER*DX/(2*PSI/DX+ABS(PHI)/2.)
\*2=PSI*CT/(DX**2)
\*3=PHI*DT/0X
\*4=PHI*DT/3.
\*8=2.*F2/9.

C
\*=DT/100.
\*TIMEEN=TIM+CT
CALL DGEAR1(1,0,DLDFHR,DMFUN,TIME*,YL,TIMEND,TOL*METH*MITER)@*
INDEX=1HR+MR+IER)
\*IF (IER.GT.128) WRITE(6/)/1CL,YL(1),TIMEND,H,TIMEMETHMITER
* INDEX
\*P=(CH/(YL(1)*M3)+(1./M3)
\*b=PVIB+1.5*DLQT/CCEFF
\*TIME=TIMEND

SC \*C=3*M3**P**M3
\*Y=(MR-MRSTAR)*C3
000160
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*****CALCULATE HEAT TRANSFER PARAMETERS

HCORY=HCORF*(HC1*(P/PREF2)*HC2-MC3)
HC=(HCORY+MFDFIBER+HCET/DK)*CONST
M1=KFIBER*CONST
M3=K1*DK*CONST/DK
EIDX=HC*DELTA*D/DO

*****CALCULATE INTERIOR TEMPERATURES

IF(S3<EC1) GO TO 70
CC GC I=2-K-1
1NEW(I)=TIMER*(TOLD(I+1)+TOLD(I-1))/2.+(1-TIMER)*TOLD(I)
6C CONTINUE
GO TO 110

7C IF(PHI<LI0) GO TO 90
CC GC I=3-K-1
F3X=F3*(I-1)*DO
1NEW(I)=(F2-F3)+(G3/3)*TOLD(I+1)+(1-G2+F2+F3/2)*TOLD(I)+
(2+F3)*TOLD(I-1)+(3+F3/6)*TOLD(I-2)
8C CONTINUE
1NEW(2)=(F2-F3)*DX/2.)*TOLD(3)+(1-G2)*TOLD(2)+(F2+F3)*DO/2.)*
TOLD(1)
6C TO 120

9C CC GC I=2-K-2
F3X=F3*(I-1)*DO
1NEW(I)=(F2-F3)+TOLD(I+1)*(1-G2+F2+F3/2)+TOLD(I)+
(2+F3)*TOLD(I-1)+(3+F3/6)*TOLD(I-2)
10C CONTINUE
1NEW(K-1)=(F2-F3)*(K-2)*DX/2.)*TOLD(K)+(1-G2)*TOLD(K-1)+
(2+F3)*(K-2)*DX/2.)*TOLD(K-2)
6C TO 120

*****CALCULATE BOUNDARY TEMPERATURES

11C 1NEW(1)=TOLD(1)-CTNEW(2)-TOLD(2)+TOLD(1)+
(TIMER/9.)*((6+BIIDX+CENT-2.)*TOLD(1)-3.*TOLD(2)+TOLD(3)-TOLD(4)
1NEW(K)=TOLD(K)-CTNEW(K-1)-TOLD(K-1)-TOLD(K)+
(2.*TOLD(K)+
3.*TOLD(K-1)-6.*TOLD(K-2)+TOLD(K-3)
6C TO 13C
12c  INEW(1)=TOLD(1)-(TNEW(2)-TCLD(2))/3.*TERM1*81D0*TH-TOLD(1)) +
   * TERM2*6.*81D0*TH-TOLD(1)-2.*TOLD(1)-3.*TOLD(2)+6.*TOLD(3)-
   * TOLD(4))
  INEW(K)=TOLD(K)-(TNEW(K-1)-TOLD(K-1))/3.*TERM2*(2.*TOLD(K)+
   * 3.*TOLD(K-1)-6.*TOLD(K-2)+TOLD(K-3))
C
C*****RESET OLD TEMPERATURE VALUES
C  13c  GO 140  I=1*K
  TOLD(I)=TNEW(I)
  14c  CONTINUE
C
C*****COMPUTE TEMPERATURES AT FIXED-POINT LOCATIONS
C  15c  I=1*K
  KK=I+XX
  REM=I+XX-KK
  TCI(I)=TNEW(1+KK)-REM*(TNEW(1+KK)-TNEW(2+KK))
  15c  CONTINUE
C
C*****INCREMENT QUANTITIES AND WRITE RESULTS
C  16c  TNEW(1)
  CINIT=QINIT*(Q+HC*(TH-TS))=DT/2.
  C=HC*(TH-TS)
  IF(K.LT.J.AND.L.GT.LMAX.AND.TNEW(1).LT.TB) G0 TO 160
C  17c  TS=TNEW(1)
  C11=QINIT*(Q+HC*(TH-TS))=DT/2.
  C=HC*(TH-TS)
  IF(K.LT.J.AND.L.GT.LMAX.AND.TNEW(1).LT.TB) G0 TO 160
C  18c  FGAUCE=FM-PVTB
  IF(FAUCE.LT.0.) PFAUGE=0.
  SEC=TIME-A3600.
  TM=TC(1+N/2)
  CHDC=Q/(TH-TIC)
  REM=M1/RK
  REL=1.-REM/MK
C  19c  T3=TNEW(K)
  CALL WRITER(IOPUT)
  A=1
  GO TO 170
C
C*****INCREMENT PRINT CONTROL VARIABLES
C  20c  A=N+1
  L=L+1
C
C*****DETERMINE EXIT CRITERIA
IF(1800*TIME.GE.RISTIM.ANC.IOPTP.EQ.2) GO TO 9999
IF((FLAG.EQ.1.AND.INEW(K).LT.TB).OR.
* PN(INEW(I)).LT.PH.OR.PV(INEW(I)).LT.PVTB) GO TO 30

*****WRITE HEATUF REGIME FINAL OUTPUT

11=TS
12=TI
PGAUGE=Pw-PVTB
IF(PGAUGE.LT.0.) PGAUGE=0.
SEC=TIME/3600.
1MIC=TC(1+M/2)
CHIC=G/(TH-TPIC)
PREM=MR*BW
*REL=1.*MRE/NG

13=INEW(K)
IF(K.NE.1) CALL WRITR(IOPTU)
WRITE(6,930)
WRITE(6,935) (1,INEW(I),I=1,K)

*******************************************************************************

*******************************************************************************

***** THE TRANSITION REGIME *****

*******************************************************************************

*****WRITE TRANSITION REGIME HEADING

WRITE(6,940)

*****INITIALIZE VARIABLES

L=1
IF(FLAG.EQ.1) DELTA2=DELTA1
DELTA3=DELTA1
THICK2=DELTA2
THICK3=DELTA3
IF(FLAG.EQ.1) THICK3=0.

RATIC2=DELTA2/DELTA1
RATIC3=DELTA3/DELTA1
LIQCHw=NG-E3*S3*OW*DELTA1
F=SPRES(F)/FACTOR
NAB=SSSTAR**4/(R*C3)
Eh3=Bw
IF(FLAG.EQ.1) Eh3=0.
IF(FLAG.EQ.1) Eh2=Bw
C1=M1*P**N1
C2=M2*P**N2
C4=M4*P**N4
w=NRSTAR*C2
x=MR*C3

C
T1=TB
2=1.-NRSTAR/MR
CXX=DX
CIFFIX=CXX
CIFFI=DX
CIFFFX=DXX
CIFFF=DX

DELTA1=DIFFIX*THICK3

DELTAF=DELTA1-CIFFFX*THICK3

C
INIT=2
IFINI=K-1

C
IF(FLAG.EQ.-1) GO TO 35C

C
CTDZ23=(T2-T3)/DELTA1

C
CALL PROP23(1)
A2=KAKW*CDTD23/(VIS23*VF23*Y)

C
FHI=V/DELTA1

C

C*****COMPUTE REQUIRED DERIVATIVES

C
10C C2=A2*CDTD23
C4=A4*CDTD212
C5=D2-A5*CDTD212
C6=-A6*CTCZ23

C
IF(RATIC3.EQ.1. AND TNEW(K).GE.TB) D6=M3*(TNEW(K)-TNEW(K-1))/

C
* (CHFG(C3)*DELHD(3))*CXX*THICK3*X)

C
C7=D2*Z

C
CENOM=D6+C7

C

C*****SET MAXIMUM ALLOWABLE TIME INCREMENT

C
CTMAX=TIMER=CX/(C2*PSI/DO+PHI/2.)

C
C1=C1MAX
C2=C2MAX
C3=C3MAX
C4=C4MAX
C5=C5MAX

C
IF(DELTA1.NE.DELTA2) GO TO 19C
IF(D2.NE.CE4MOM) CT1=(DELTA3-DELTA2)/(D2-CENOM)
EC 1C 200

19C IF(D0.4. NE.0.5) DT1=(DELTA2-DELTA1)/(D0.4.-D5)
IF(CT1.LT.0.) DT1=DTMAX
IF(D0.4. NE.0.5) DT2=(DELTA3-DELTA2)/(D5-DEONM)
IF(CT2.LT.0.) DT2=DTMAX
CT=AMIN1(DT1+DT2+DTMAX)
IF((C5=CT).GE.(DIFFX*THICK3) IOPT1=1

20C IF((DENOM*C1).GE.(DIFFX*THICK3) IOPT2=1
IF(IOPT1.EQ.1.AND.IOPT2.EQ.1) GO TO 210

IF(IOPT1.EQ.0) DT3=DIFF*X/(2.*PSI)
IF(DEONM.LE.0.0) DT4=DIFF*X/(2.*PSI)
IF(DEONM.GT.0.0.AND.RATIO3.GE.1.) CT5=(OX-DIFFX)*THICK3/DEONM
IF(DT5.EQ.0) DT5=OX*THICK3/DEONM
CT=AMIN1(DT1+DT2+DT3+DT4+CT5+DTMAX)

IF(DELTA1.EQ.DE.LTA2.AND.D2=DT1.GE.(DIFFX*THICK3) IOPT1=1
IF(DELTA1.EQ.DE.LTA2.AND.D2=DT1.LT.DIFFX*THICK3) IOPT1=0
IF(DELTA1.EQ.DE.LTA2.AND.D2=DT1.GE.(DIFFX*THICK3) IOPT1=1
IF(DELTA1.EQ.DE.LTA2.AND.D2=DT1.LT.DIFFX*THICK3) IOPT1=0
IF((DEONM.C1).GE.(DIFFX*THICK3) IOPT2=1
IF((DEONM.C01).LT.(DIFFX*THICK3) IOPT2=0

CT=TIME+DT
21C TIME=TIME+DT

*****CALCULATE NEW TEMPERATURE DISTRIBUTION

CC=DFIBER*(CPP*MR*CPw)
CK=MR*DFIBER*KAT1ER
A=(MKIBER+OK*VF23)/DC
V=D2*Y*CPw/(1.-E3)*DC
FSI=A*(C3/Bw)**2
PHI=F/C3/Bw
F2=PSI+DI*DX**2
F3=PHI+DI*DX
TERM2=2.*F2**5.

CC 22C I=INIT+INIT+1
IMEK(I)=(F2-F3/2)*TOLDC(I+1)+(1-2*F2)*TOLDC(I)+(F2+F3/2)*TOLDC(I-1)

CC 23C I=INIT+2-IFINI
IMEK(I)=(F2-F3/3)*TOLDC(I+1)+(1-2*F2-F3/3)*TOLDC(I)+(F2+F3)*
* TOLDC(I-1)=(F3/6)*TOLDC(I-2)

CC 23C CONTINUE

IF(IOPT1.EQ.0) IMEK(INIT)=TOLDC(INIT)-PHI*DT*(TOLDC(INIT+1)-T2)/
* (C3+DIFFX)**2.*PSI*CT*(TOLDC(INIT+1)/OX*(DIFFX/OFX)-TOLDC(INIT)

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* * (DIFFI+Dx)+12*(DIFFI+DIFFI+DIFFI+DIFFI))

C IF((IGPT2.EQ.0.AND.RATIO3.NE.1.) INEW(IFINI)=TOLC(IFINI)-PHI*DT*
* ((T3-TOLC(IFINI-1))/(DX+DIFFI)) +2.*PSI*DT*(T3/COX4)
* ((X+DIFFI)-TOLC(IFINI)/(COX+DIFFI)*TOLC(IFINI-1)/DX*(DX+* DIFFI)))

C INEW(K)=TOLC(K)-(TNEW(K-1)-TOLD(K-1))/3.-TERM2*(2.*TOLD(K)+
* 3.*TOLD(K-1)-6.*TOLD(K-2)*TOLD(K-3))

IF((TNEW(K)<<.EQ.1.) TNEW(K-1)) TNEW(K)=TNEW(K-1)
IF((TNEW(K).GE.18) TNEW(K)=18

IF((RATIO3.EQ.1.+)) GO TO 240

C C 240 I=IFINI+1-K

C INEW(I)=18

C 240 CONTINUE

C C*****CALCULATE RATES OF BASIS WEIGHT CHANGE

C RATE1=0.

IF((DELTA1.EQ.-DELTA2) RATE1=0.

C RATE2=02

IF((DELTA1.EQ.-DELTA2) RATE2=0.

C RATE3=0DEN

C IF(FLAG.EQ.1.) RATE3=0.

C SIGN=0.

IF((DE.EQ.0.) SIGN=1.-

IF((RATIO3.EQ.1.) LIQDEN=SIGN*MAEL*NO*(1.-SIGN)*

*(LIQDEN*RATE3+1.)*DT)

C C*****CALCULATE MECHANICAL AND HYDRAULIC PRESSURE

C CALL PRESSR(TIME)

C F1=HYDRA(F1=PH1.

IF((P1.EQ.0.) P1=PREF1

F2=F-PH2

F3=F-PH3

F4=F-PH4

C C*****CALCULATE BASIS WEIGHT, CONCENTRATION AND THICKNESS

C
CEB1CT = C2 * RATE1
CEB2CT = C3 * RATE2 - DB11DT
CEB3DT = C3 * RATE3 - RATE2
IF (RATIO3.EQ.1.0. AND RATE3.EQ.1.0.) DB3DT = -C3 * RATE2
CEB4CT = -C3 * RATE3

EW1 = BW1 + DBW1DT * DT
EW2 = BW2 + DBW2DT * DT
EB3 = BW3 + DBW3CT * DT
IF (FLAG.EQ.1) EW3 = O.
EW4 = BW4 + DBW4CT * DT

IF (EW1.LE.0.) EW1 = 0.
IF (EW2.LE.0.) EW2 = 0.
IF (EW3.LE.0. OR FLAG.EQ.1) EW3 = 0.
IF (EW4.LE.0.) EW4 = 0.

250 EWSUM = BW1 +BW2 + BW3 + BW4
EWCORR = EW / EWSUM

EB1 = EW1 * EWCORR
EB2 = EW2 * EWCORR
EB3 = EW3 * EWCORR
EB4 = EW4 * EWCORR

TBAR1 = (TS + T1) / 2.
TBAR2 = (T1 + T2) / 2.
TBAR3 = (T2 + TNEW(IFINI)) / 2.
TBAR4 = (TNEW(IFINI) + TNEW(K)) / 2.

P1 = EVALN(0, TBAR1)
P2 = EVALN(MRSTAR, TBAR2)
P3 = EVALN(MR, TBAR3)
P4 = EVALN(0, TBAR4)

A3 = EVALN(2, P4, P3)

C1 = M1 * P1 * N1
C2 = M2 * P2 * N2
C3 = M3 * P3 * N3
C4 = M4 * P4 * N4

THICK1 = EB1 / C1
THICK2 = EB2 / C2
THICK3 = EB3 / C3
THICK4 = EB4 / C4

*****CALCULATE PERGOSITY AND SATURATION

E1 = 1 - C1 / DFIBER
E2 = 1 - C2 / DFIBER
E3 = 1 - C3 / DFIBER
ESTAR = E51 * E3 - E52
E4=1.-C4/DFIBER
IF(C1.GT.DFIBER) CALL WARNING(1,1,C1)
IF(E2.LT.EMIN) CALL WARNING(2,2,E2)
IF(E3.LT.EMIN) CALL WARNING(2,3,E3)
IF(C4.GT.DFIBER) CALL WARNING(1,4,C4)
IF(C1.GT.DFIBER.OR.E2.LT.EMIN.OR.E3.LT.EMIN.OR.C4.GT.DFIBER) GO TO 5999

CALL CALLER(4)
B=MRSSTAR+C2
X=MRS+C3
Y=(MRR-MRSSTAR)*C3
Z=Y/X

S2=W*VF12/E2
S3=X*VF23/E3
S3STAR=Y*VF23/ESTAR
IF(S3.LE.1.) GO TO 270
IF(BW4.NE.0.) GO TO 260
S3=1.
S3STAR=1.
MR=E3/(VF23*C3)
X=E3/VF23
Y=(MRS-MRSSTAR)*C3
Z=Y/X
GO TO 270

26C BW4=BW4-(S3-1.)*BW3
IF(BW4.LT.0.) BW4=0.
EW3=BW-BH1-BH2-BH4
GO TO 250

C
C
C******INCREMENT INTERFACE POSITIONS
C

27C CELTA1=THICK1
CELTA2=CELTA1+THICK2
CELTA3=CELTA2+THICK3
CELTA4=CELTA3+THICK4
IF(THICK3.EQ.0.) DELTA3=DELTAT

C
IF(DS.GT.0.) INIT=(BH1+BH2)/BW*(K-1)*2
IF(INI=(K-1)-(K-1)*BH4/BW
IF(INI.LE.INIT) GO TO 450
DXX=DXX*BW/BH3
DIFFX=DXX-EW4/BW
DIFFX=DIFFX-(CFINI-INIT)*DXX
IF(CDIFFX.GT.DXX) CALL WARNING(3,1,C5)
IF(DIFFX.GT.DXX) CALL WARNING(4,1,C5)
CELTA1=CELTA2+DIFFX*THICK3
CELTA3=CELTA3+DIFFX*THICK3
CIFFF=DIFFX*BH3/BH
CIFFF=DIFFX*BH3/BH

C
C
C******CALCULATE THERMAL CONDUCTIVITY AND CONTACT COEFFICIENT
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K1=KFIBER*(1.-E1)
K2=KFIBER*(1.-E2)*KNATER=E2*S2
K3=KFIBER*(1.-E3)*KNATER=E3*S3
K4=KFIBER*(1.-E4)
HCORY=HCREF*(HC1*(PI/PREF2)**HC2-HC3)
HC=HCORY*(1.-E1)
IF(DELTA1.EQ.0.) HC=HCORY*(1.-E2)*E2*S2*HCWET
IF(DELTA2.EQ.0.) HC=HCORY*(1.-E3)*E3*S3*HCWET

*****CALCULATE PERMEABILITY FACTORS

&=SPREC(F)/FACTOR
MABS2=1./(R*C2)
MABS3=1./(R*C3)
MABS4=1./(R*C4)
MAB=KABS3*S3STAR**4

*****SET RELATIVE INTERFACE POSITIONS AND REMAINING MOISTURE

FATIC1=DELTA1/DELTAT
FATIC2=DELTA2/DELTAT
FATIC3=DELTA3/DELTAT
PREM=MR*Bb3*MRSTAR*Bb2
MREL=1.-PREM/MC
IF(RATIC2.EQ.1.) GO TO 390

*****COMPLETE NEW VALUES FOR T1, T2 AND T3

IF(DELTA1.NE.DELTA2) GO TO 280
ALPA=DELTA3-DELTA1
TERM1=(1./MC*DELTA1/K1)*K3/(DELTA1-DELTA1)
T1=(TH+TERM1*TAEK(INIT))/T1+TERM1
T2=T1
GO TO 290

280 GO 250 I=1,IMAX

101=11
102=12

CALL PRCP12
TGF1=HG6(T1)+DELHD(1)
TGF2=HG6(T2)+DELHD(2)
ALF=DELTA2-DELTA1
C TT=DELTA3-DELTA2
  C TERMIN=(1./HC*DELTA1/K1)*(1./ALF)*(HFG1*KABS2*DPDT12/
* (VG12*VISG12)*K2)
  C TERMIN2=(KABS2*DPDT12*HFG2/(K3*VG12*VISG12)*K2/K3)*
* (DELTA1-DELTA2)/ALF
  C DENOM=1.*TERM1*TERM2
  C 11=(1.*TERM2)*TH*(TERM1*TH)(INIT))/DENOM
  C 12=(TC1+11)/2.
  C 12=(TERM2*TH*(1.*TERM1*TH)(INIT))/DENOM
  C 12=(TC1+12)/2.
C 9C CONTINUE
C IF(RATIC3.EQ.1.) GO TO 310
C CALL PROF3E
  HFG3=HFG(T3)+DELHD(3)
C GO 360 I=1*IMAX
C T3=13
C TERMIN=(KABS4*HFG3*DPDT3B/(K3*VISG3B*VG3B)*(DELTA3-DELTAF)
* (DELTA1-DELTA3)
C 13=(TERM1*TH)+TERM1*TH)/G(1.*TERM1)
  C 13=(TC3+13)/2.
C 30C CONTINUE
  C GO 320
C 31C T3=18
C 32C IF((TERM1*TH)-T3)/DIFF. EQ. ((T2-T3)) GO TO 45C
C C C#####RECOMPUTE VARIABLES FOR DERIVATIVE CALCULATIONS
C IF(Delta1 NE DELTA2) GO TO 330
  C TDZ12=0.
  C TDZ23=(T2-T3)/ALFA
  C IF(T2-LE-TB) TDZ23=0.
  C GO TO 340
C 33C TDZ12=(T1-T2)/ALF
  C IF(T2-LE-TB) TDZ12=(T1-TB)/ALF
  C IF(T1-LE-TB) TDZ12=0.
  C TDZ23=(T2-T3)/BET
  C IF(T2-LE-TB) TDZ23=0.
C 34C TDZ23=0.
  C IF(RATIC3.EQ.1.) TDZ33=(T3-TB)/(DELTA1-DELTA3)
C CALL CALLER(1)
HANDLE SPECIAL CASE OF INTRA-FIBER WATER

35C C=(TNA)=TIMER*C0*2/(2.*PSI)
CIFFlx=CTX
11=TNEW(1)
12=TNEW(K)
+GF2=HFC(T2)+DELHD(1)
C7=0.
X=MR*C2

36C C6=M3*(12-TNEW(IFIN1))/HFC2*DX*THICK2*2)

CT1=CTMAX
CT2=CTMAX
CT=KDELTA2-DELTAK1)/(-G6)
CT2=AMINI(DT1-DTMAX)
IFCC=-C6+CT)*GF=12FFX*THICK2 ICPT2=1
IF(CPT1+EQ.1) GO TO 37C

CT2=DX*CIFFX/(2.*PSI)
CT1=AM21(DT1-DT2-DTMAX)
CT=TIMER=DT

37C TIME=TIME+DT

A=(K*FIBER*DX*VF12)/DC
FSI=A*(C2/B1)**2
F2=PSI*DT/DX**2

CC 380 I=INITIAL IFIN1
1NEW(I)=F2*(TOLD(I+1)+TOLD(I-1))/2.*(1.-2.*F2)*TOLD(I)

380 CONTINUE

1NEW(I)=TLC(I)-TNEW(I)-TLD2(I))/3.*(2.*F2/9.)*(G6*BIDX*(TH-
* TDEC(I))/2.*TLD(I)-3.*TLC(I)+6.*TOLD(I)+TOLD(I)-TOLD(I))
11=TNEW(1)
TLC2(1)=TNEW(1)

IF(CPT2+EQ.0) TNEW(IFIN1)=TLC2(IFIN1)+2.*PSI*DT*T2/CIFFX
* (CIFFX*DX)-TLD2(IFIN1)/C0*DIFFX+TOLD(IFIN1-1)/C0*DX+* CIFFX)

FORE=06
CALL PRESSR(TIME)

F4=F-PH4
F4=F-PH4
CEw2DT=C2*RATE2
CEb4DT=-DBw2DT

Eh2=Eb2+DBw2DT*DT
Eb4=EBw4+DBb4DT*DT

Ebh2=DBb2+Bb2
EBCCRD=EBw/EBSUM
EB2=EB2*EBCCRD
EB4=EB4*EBCCRD
TBAR2=(T1+T2)/2
TER4=(T2+TE)/2
P2=EVALCMHRSTAR*TBAR2
P4=EVALCMHRSTAR*TER4
C2=M2*P2=M2
C4=M4*P4=M4

THICK2=EB2/C2
THICK4=EB4/C4

E2=1.0-C2/DFIEEER
E4=1.0-C4/DFIEEER

IF(E2 LT EMIN) CALL WARNINC2*E2
IF(E4 GT DFIEEER) CALL WARNINC1*E4
IF(E2 LT EMIN OR E4 GT DFIEEER) GO TO 9999

CALL PACP12
X=M*RC2
Z=C-
S2=X*VF12/E2

CELT2=THICK2
CELTA1=CELTA2*THICK4
IFINI=(K-1)-(K-1)*Bw4/Bw
CXX=CEb/EB2
CIFFFX=DXX-Bb4/Bb
IF(CIFFFX GT 0.0) CALL WARNINC4*0.0
CELTF=CELTA2-CIFFFX*THICK2
K2=KFIBER*(1.-E2)*RATER=E2*S2
M4=KFIBER*(1.-E4)
HOCR=HCREF=(HC1*CP2/PREF2)*HC2-HC3
HC=HCRRY=(1.-E2)*E2*S2*HC*ET
EIDX=HC*Bw*CXX/K2*C2

F=SPRES(P)/FACTOR
NABS2=1./M*RC2
NABS4=1./M*RC4

FAIG1=C-
FAIG2=DELTA2/CELTA
FAIG3=1-

PREW=MRSTAR*Ew2
PREL=1.-PREW/4C
CALL PROF23(2)

HFG2=HFG1(T2)*DELHD(1)

IF(RATIC2.EQ.1.) GO TO 390

CG 39C I=1.IMAX

T2=12

TERM1=KAES4*HFG2*CPCT23/(T3*VISG23*VG23)*(DELTA2-DELTA1)/

* (DELTA1-DELTA2)

T2=12*(1+DELTA1/DELTA2)

T2=12*(T2+T2)/2.

39C CONTINUE

IF(RATIC2.EQ.1.) T2=T6

IF((DELTA1/DELTA2)-DIFFX.EQ.(T1-T2)) GO TO 450

*****RESE TEMPERATURE DISTRIBUTION AND TIME OPTIONS

40C DO 410 I=INIT.K

41D(I)=TNEW(I)

41C CONTINUE

ICPT1=0

ICPT2=0

*****COMPUTE TEMPERATURES AT FIXED-POINT LOCATIONS

SUM12=SUM12+B1+B2

SUM123=SUM12+B1+B3

CG 420 I=1.IK

L=2T(I)*B4

KK=0.XX

REM=I+XX-MM

IF(U.LT.BW1.AND.BW1.NE.0.) T(I)=TS-(TS-T1)*(U/BW1)

IF((U.GT.BW1.AND.U.LT.SUM12.AND.BW2.NE.0.) T(I)=T1-(T1-T2)*

* (L-BW1)/BW2

IF(U.GT.BW1.AND.U.LT.SUM123.AND.BW3.NE.0.) T(I)=TNEW(I+KK)-

* REM*(TNEW(K1+KK)-TNEW(2+KK))

IF((U.GT.SUM123.AND.U.LT.B4.AND.BW4.NE.0.) T(I)=T3-(T3-TB)*

* (SUM123)/BW4

IF(U.EQ.BW1) T(I)=T1

IF(U.EQ.SUM12) T(I)=T2

IF(U.EQ.SUM123) T(I)=T3

IF(U.EQ.BW4) T(I)=T4

42C CONTINUE

*****INCREMENT QUANTITIES AND WRITE RESULTS

PC=PREM/(HREM+EW)

TS=(TH*HC*DELTA1/K1+T1)/(1.0*HC*DELTA1/K1)
C TOTAL=TOTAL+(G+MC*(TH-TS))*DT/2.
C=MC*(TH-TS)
IF(NLJ[2] AND LLEGTMAX AND MCGTMAXFINAL) GO TO 430
C
FGAUGE=PVC(TJ)-FVTB
IF(FGAUGE.LT.0.) PGAUGE=0.
SEC=TIME*3600.
TMID=TC(1+M/2)
CHIC=G/(TH-TMID)
C
IF(RATIC3.EQ.1.) T3=THENR(K)
IF(FLAG.EQ.1) T3=TE
CALL WRITER(IOPTU)
T3=TE
A=1
GO TO 440
C
C
C*****INCREMENT PRINT CONTROL VARIABLES
C
43C A=A+1
44C L=L+1
C
C
C*****DETERMINE EXIT CRITERIA
C
IF(1800*TIME.GE.RISTIM.AND.IOPTP.EQ.2) GO TO 9999
IF(MC.LT.MFINAL) GO TO 9999
IF(RATIC2.EQ.1.) GO TO 450
IF(FLAG.EQ.1.AND.MCGTMAXFINAL) GO TO 180
IF(FLAG.EQ.1.AND.MCGTMAXFINAL) GO TO 360
C
C
C*****WRITE TRANSITION REGIME FINAL OUTPUT
C
45C MC=MC+1/2(MC+6)
TS=(TH-MCDELTA1/K1+T1)/(1.+MCDELTA1/K1)
TOTAL=TOTAL+(G+MC*(TH-TS))*DT/2.
C=MC*(TH-TS)
FGAUGE=PVC(TJ)-FVTB
IF(FGAUGE.LT.0.) PGAUGE=0.
SEC=TIME*3600.
TMID=TC(1+M/2)
CHIC=G/(TH-TMID)
C
IF(RATIC3.EQ.1.) T3=THENR(K)
IF(FLAG.EQ.1) T3=TE
IF(NLJ[2] CALL WRITER(IOPTU)
WRITE(6,930)
C
IF(INI.0.LE.K) WRITE(6,935) (I,THENR(I),I=INIT,FINI)
C
C*****************************************************************************
C
C
C
C
C
C***** THE LINEAR REGIME *****
***********

******WRITE LINEAR REGIME HEADING

WRITE(6,945)

******SET FLAG AND GO TO FIRST TEMPERATURE CALCULATION

L=1
T3=TE

VAR=KAES3*(1.-S3STAR)**3*(1.+3.*S3STAR)

IF(RAT/C2.EQ.1.) FLAG=1

CTMAX=DT0

GO TO 550

******COMPUTE REQUIRED DERIVATIVES

460 C1=A1*D10223
C2=A2*D10223
C3=A3*D10223
C4=A4*D10212
C5=A5*D10223
C6=-K3*D10223/(HF63*X)
C7=D2*Z
C8=A8*D10212

IF(Delta1.GE.Delta2.AND.D1.GE.D2) D7=0.
IF(Celta1.NE.Delta2.AND.D5.GE.D2) D7=0.

CEN0M=D6+C7

******SET MAXIMUM ALLOWABLE TIME INCREMENT

CT1=CTMAX
CT2=CTMAX

IF(Delta1.NE.Delta2) GO TO 470

IF(C1.GE.C2.AND.C1.LE.C6) CT1=(Delta3-Delta1)/(C1-D6)

IF(C1.LT.C2.AND.C2.LE.CENCM) CT1=(Delta3-Delta2)/(C2-DENCM)

GO TO 490

470 IF(FLAG.EQ.1) GO TO 480

CSTAR=AMAX1(D3-D5)

IF(CSTAR.NE.DENCM) DT1=(Delta3-Delta2)/(CSTAR-DENCM)

IF(C4.C1.CSTAR) DT2=(Delta2-Delta1)/(C4-CSTAR)

GO TO 490

480 CSTAR=0.

IF(C4.GE.C8) DT1=(Delta2-Delta1)/(C4-D8)

490 IF(DT1.LE.0.) CT1=CTMAX

IF(C12.LE.0.) CT2=CTMAX

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001019
001020
001021
001022
001023
001024
001025
001026
001027
001028
C
CT=APMIN(OT1+OT2+OTMAX)

C
CT=TIMER+DT
TIME=TIME+DT

C
*****CALCULATE RATES OF BASIS WEIGHT CHANGE

C
IF(DELTA1.NE.DELTA2) GO TO 500
IF(D1.GE.D2) RATE1=D1
RATE2=RATE1
IF(D1.LT.D2) RATE2=D2
IF(D1.LT.0.ANC.D3.GE.D2) RATE1=RATE2
IF(D1.LT.0.ANC.C3.LT.D2) RATE1=D3
GO TO 510

C
50C RATE1=D4
RATE2=DSTAR
IF(FLAG.EQ.1) RATE2=D8

C
51C RATE3=DENOM
IF(FLAG.EQ.1) EW3=0.
IF(FLAG.EQ.1) RATE3=0.

C
IF(BM4.EQ.0.) LIGDEW=LIGDEW+RATE3*X+DT

C
*****CALCULATE MECHANICAL AND HYDRAULIC PRESSURE

C
CALL PRESSR(TIME)

C
FH1=HYDRA1(T1+11)
FH2=HYDRA1(T1+12)
FH3=HYDRA1(T2+13)
FH4=HYDRA1(T3+18)
IF(FLAG.EQ.1) PH4=PH3

C
IF(P1.LE.0.) P1=PREF1
F2=P-PH2
F3=P-PH3
F4=P-PH4

C
*****CALCULATE BASIS WEIGHT, CONCENTRATION AND THICKNESS

C
CB41DT=C2*RATE1
CB42DT=C3*RATE2-DB41DT
IF(FLAG.EQ.1) DB42DT=C2*(RATE2-RATE1)
CB43DT=C3*(RATE3-RATE2)
IF(RATIC3.EQ.1.AND.RATE3.GT.0.) DB43DT=-C3*RATE2
CB44DT=-C3*RATE3
IF(FLAG.EQ.1) CB44DT=-C2*RATE2
Ek2 = Bw1*DBw1DT*DT
Ek2 = Bw2*DBw2CT*DT
Ek3 = Bw3*DBw3DT*DT
Ek4 = Bw4*DBw4DT*DT

IF(Ek1.LT.0.) Ek1 = 0.
IF(Ek2.LT.0.) Ek2 = 0.
IF(Ek3.LT.0.NOR.FLAG.EQ.1) Ek3 = 0.
IF(Ek4.LT.0.) Ek4 = 0.

52C EWSUP = Ek1*Bw2*Bw3*Bw4
EBCCCRR = Bw1/EWSUP

Ek1 = Ek1/BWCCCR
Ek2 = Ek2/BWCCCR
Ek3 = Ek3/BWCCCR
Ek4 = Ek4/BWCCCR

TBAR1 = (TS*T1)/2.
TBAR2 = (T1*T2)/2.
TBAR3 = (T2*T3)/2.
TBAR4 = (T3*T4)/2.

P1 = Eval9(C0, TBAR1)
P2 = Eval9(MRSTAR, TBAR2)
P3 = Eval9(MR, TBAR3)
P4 = Eval9(C0, TBAR4)
IF(FLAG.EQ.1) P4 = Eval9(C0, TBAR3)

C1 = N1**P1**N1
C2 = N2**P2**N2
C3 = N3**P3**N3
C4 = N4**P4**N4

THICK1 = Ek1/C1
THICK2 = Ek2/C2
THICK3 = Ek3/C3
THICK4 = Ek4/C4

*****CALCULATE POROSITY AND SATURATION

E1 = 1. - C1/DFIEER
E2 = 1. - C2/DFIEER
E3 = 1. - C3/DFIEER
ESTAR = ES1*E3 - E92
E4 = 1. - C4/DFIEER

IF(C1.GT.0.) CALL WARNIN(1, 1, C1)
IF(C2.GT.0.) CALL WARNIN(2, 2, C2)
IF(C3.GT.0.) CALL WARNIN(2, 3, C3)
IF(C4.GT.0.) CALL WARNIN(1, 4, C4)
IF(C1.GT.0 OR.E2.GT.0 OR.E3.GT.0 OR.E4.GT.0)
* GO TO 9999

001083 001084 001085 001086 001087 001088 001089 001090 001091 001092 001093 001094 001095 001096 001097 001098 001099 001100 001101 001102 001103 001104 001105 001106 001107 001108 001109 001110 001111 001112 001113 001114 001115 001116 001117 001118 001119 001120 001121 001122 001123 001124 001125 001126 001127 001128 001129 001130 001131 001132 001133 001134 001135 001136 001137
CALL CALLER(4)

\[ b = K \cdot R \cdot S \cdot T \cdot A \cdot R \cdot S \cdot T \cdot C \]

\[ y = K \cdot R \cdot C \]

\[ x = (K \cdot R \cdot M) \cdot C \]

\[ z = Y / X \]

\[ s_2 = w \cdot V \cdot F \cdot 12 / E \]

\[ s_3 = x \cdot V \cdot F \cdot 23 / E \]

\[ s_3 \cdot S \cdot A \cdot R = y \cdot V \cdot F \cdot 23 / E \]

IF(\(S_3 \leq 1.0 \) OR \(S_2 \leq 0.0 \)) GO TO 540

IF(\(B \cdot M \cdot A \)-NE.0) GO TO 530

\[ s_3 = 1.0 \]

\[ s_3 \cdot S \cdot A \cdot R = 1.0 \]

\[ y = E \cdot 3 / V \cdot F \cdot 23 \]

\[ x = E \cdot 3 / V \cdot F \cdot 23 \]

IF(GO TO 540)

\[ s_3 \cdot B \cdot M \cdot A = E \cdot 4 - (s_3 \cdot -1.0) \cdot B \cdot M \cdot A \]

IF(GO TO 540)

\[ E \cdot 4 = E \cdot 4 - (s_3 \cdot -1.0) \cdot B \cdot M \cdot A \]

IF(GO TO 540)

\[ E \cdot 3 = E \cdot 3 - B \cdot M \cdot A \]

GO TO 520

C

**** INCREMENT INTERFACE POSITIONS ****

C

540 CELTA1 = THICK1

CELTA2 = DELTA1 + THICK2

CELTA3 = DELTA2 + THICK3

DELTA1 = DELTA3 + THICK4

IF(THICK3.EQ.0) FLAG = 1

IF(THICK3.EQ.0) DELTA3 = DELTA1

C

***** CALCULATE THERMAL CONDUCTIVITY AND CONTACT COEFFICIENT *****

C

\[ K_1 = K \cdot F \cdot I \cdot B \cdot R \cdot E \cdot (1.0 - E) \]

\[ K_2 = K \cdot F \cdot I \cdot B \cdot R \cdot E \cdot (1.0 - E) \cdot M \cdot W \cdot A \cdot T \cdot E \cdot 2 + S \]

\[ K_3 = K \cdot F \cdot I \cdot B \cdot R \cdot E \cdot (1.0 - E) \cdot M \cdot W \cdot A \cdot T \cdot E \cdot 3 + S \]

\[ K_4 = K \cdot F \cdot I \cdot B \cdot R \cdot E \cdot (1.0 - E) \]

C

\[ H \cdot C \cdot D \cdot R \cdot Y \cdot = H \cdot C \cdot R \cdot E \cdot F \cdot * (C \cdot H \cdot C \cdot 1 \cdot (P \cdot 1 \cdot P \cdot R \cdot E \cdot F \cdot 2) \cdot * (H \cdot C \cdot 2 - H \cdot C \cdot 3) \]

\[ H \cdot C = H \cdot C \cdot D \cdot R \cdot Y \cdot (1.0 - E) \]

IF(DELTA1.EQ.0) HC = H \cdot C \cdot D \cdot R \cdot Y \cdot * (1.0 - E) + E \cdot 2 + S \cdot 2 * H \cdot C \cdot W \cdot E \cdot T

IF(DELTA2.EQ.0) HC = H \cdot C \cdot D \cdot R \cdot Y \cdot * (1.0 - E) + E \cdot 3 + S \cdot 3 * H \cdot C \cdot W \cdot E \cdot T

C

***** CALCULATE PERMEABILITY FACTORS *****

C

\[ R = S \cdot P \cdot R \cdot E \cdot (P) \cdot F \cdot A \cdot T \cdot R \cdot C \]

\[ X \cdot A \cdot B \cdot S \cdot 2 = 1.0 / (R \cdot C \cdot 2) \]

\[ X \cdot A \cdot B \cdot S \cdot 3 = 1.0 / (R \cdot C \cdot 3) \]

\[ X \cdot A \cdot B \cdot S \cdot 4 = 1.0 / (R \cdot C \cdot 4) \]
**SET RELATIVE INTERFACE POSITIONS AND REMAINING MOISTURE**

FATIC1=DELTA1/DELTAT
FATIC2=DELTA2/DELTAT
FATIC3=DELTA3/DELTAT

PREW=MR*GW3*MRSTAR*Bw2
PREL=1.-PREW/ME

**COMPLETE NEW VALUES FOR T1, T2 AND T3**

550 IF(Delta1,NE.Delta2) GO TO 570

CO 560 I=1,IMA,

102=T2
103=T3

CALL CALLER(2)

HFG2=HFG(T2)*DELHD(3)
HFG3=HFG(T3)*DELHD(3)

ALFA=DELTA3-DELTA2
BETA=DELTA1-DELTA3

TERM1=(1./HC+DELTA1/K1)*(1./ALFA)*(HFG2*KAKV*DPDT23/
* (VG23*VISG23)*K3)
TERM2=(BETA)*(KAKV*DPDT23/(VG23*VISG23)*K3/HFG3))/
* (ALFA*KABS4*DFDT3E/(VG38*VISG38))

DENOM=1.*TERM1*TERM3

12=(TERM3*TERM3*TERM1)/DENOM
12=(102+T2)/2.
13=(TERM3*TG*(1.*TERM1))/DENOM
13=(T2+T3)/2.

560 CONTINUE

11=T2
60 TO 590

570 GO 550 I=1,IMA,

101=T1
102=T2
103=T3

CALL CALLER(3)
PFG1=HFG(T1)+DELHD(1)
HFG2=HFG(T2)+DELHD(2)
IF(FLAG.EQ.1) HFG2=HFG(T2)+DELHD(1)
HFG3=HFG(T3)+DELHD(3)
C
ALF=DELTA2-DELTA1
BET=DELTA3-DELTA2
GAM=DELTA1-DELTA3
IF(BET.EQ.0) FLAG=1
IF(FLAG.EQ.1) GO TO 58C
C
TERM1=(1./HC*DELTA1/K1)*(1./ALF)*(HFG1*KABS2*DPDT12/
* (VG12*VIGS12)+K2)
TERM2=(BET*(KABS2*DPDT12/(VG12*VIGS12)+K2/HFG2))/
* (ALF*(KAVV*DPDT23/(VG23*VIGS23)+K3/HFG2))
TERM3=(GAM*(KAVV*DPDT23/(VG23*VIGS23)+K3/HFG3))/
* (BET*KABS4*DPDT38/(VG38*VIGS38))
TERM4=TERM2*(1./TERM3)
DENOM=1.+TERM1+TERM4
C
T1=(TH*(1.+TERM4)+TB*TERM1)/DENOM
11=(T1+11)/2.
12=(TH*TERM4+TB*(1.+TERM1))/DENOM
12=(TQ2+T2)/2.
13=(TH*TERM2+TE*(1.+TERM1))/DENOM
13=(103+13)/2.
EO TO 590
C
58C TERM1=(1./HC*DELTA1/K1)*(1./ALF)*(HFG1*KABS2*DPDT12/
* (VG12*VIGS12)+K2)
TERM2=(BET*(KABS2*DPDT12/(VG12*VIGS12)+K2/HFG2))/
* (ALF*(KAVV*DPDT23/(VG23*VIGS23))
DENOM=1.+TERM1+TERM2
C
T1=(TH*(1.+TERM2)+TB*TERM1)/DENOM
11=(T1+11)/2.
12=(TH*TERM2+TE*(1.+TERM1))/DENOM
12=(TQ2+T2)/2.
13=TB
59C CONTINUE
C
C FOR COMPUTE VARIABLES FOR DERIVATIVE CALCULATIONS
C
IF(Delta1.NE.Delta2) GO TO 600
C
C
600 CTD212=(T1-T2)/ALFA
C TTD23=(T2-T3)/ALFA
C GO TO 610
C
**CALL CALLER(4)**

```fortran
HFG2=HFG(T2)*DELHDC(1)
IF(FLAG.EQ.1) GO TO 620
A1=KAV*DPDT23/(VISG23*VG23*X)
A2=KAV*DPDT23/(VISF23*VF23*Y)
A3=KAV*DPDT23/(VISG23*VG23*W)
A4=KAVS2*DPCT12/(VISG12*VE12*W)
A5=KAV*DPDT23/(VISG23*VG23*Y)
GO TO 630
```

**A1=0.**

**A2=0.**

**A3=0.**

**A4=KAVS2*DPCT12/(VISG12*VE12*W)**

**A5=0.**

**A8=-M2/(HFG2*W)**

*****COMPUTE TEMPERATURES AT FIXED-POINT LOCATIONS

```fortran
63C SLM12=BW1+BW2
SUM123=SUM12+BW3
CG 64C I=1*M
L=2*CG(I)*BW
IF(U<LT-BW1.AND.BW1.NE.0.) TC(I)=TS-(TS-T1)*(U/BW1)
IF(U<GT-BW1.AND.LT-SUM12.AND.BW2.NE.0.) TC(I)=T1-(T1-T2)*
* (U-BW1)/BW2
IF(U<GT-SUM12.AND.LT-SUM123.AND.BW3.NE.0.) TC(I)=T2-(T2-T3)*
* (U-SUM12)/BW3
IF(U<GT-SUM123.AND.LT-BW4.AND.BW4.NE.0.) TC(I)=T3-(T3-T4)*
* (U-SUM123)/BW4
```

**IF(U.EQ.BW1) TC(I)=T1**

**IF(U.EQ.SUM12) TC(I)=T2**

**IF(U.EQ.SUM123) TC(I)=T3**

**IF(U.EQ.BW4) TC(I)=T4**

**CONTINUE**

*****INCREMENT QUANTITIES AND WRITE RESULTS

```fortran
PC=RMEM/(RMEM+EW)
TS=(TH+HC*DELTA1/M1+T1)/(1+HC*DELTA1/M1)
CTOTAL=CTOTAL+(Q+HC*(TH-TS))*DT/2.
C=HC*(TH-TS)
IF(CL<LT-AH2.AND.LT-LMAX.AND.HC<GT-MFINAL) GO TO 650
```

**FGAUGE=FV(T1)-FVTB**

**SEC=TIME*3600.**

**TMID=TC(T1+M2)**

**HTC=G/(TH-TMID)**

**01300**

**01301**

**01302**

**01303**

**01304**

**01305**

**01306**

**01307**

**01308**

**01309**

**01310**

**01311**

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**01350**

**01351**

**01352**

**01353**
IF(L.NE.) CALL WRITER(IOP14)
WRITE(6,/) NREL.LICODEM.S3.PR. RATE1.RATE2.RATE3.XD7.DT
H=1
GO TO 660
C
C
C*****INCREMENT PRINT CONTROL VARIABLES
C
660 H=N+1
660 L=L+1
C
C*****DETERMINE EXIT CRITERIA
C
IF(1860.0.GT.RESTRA.NS.AN.IOPTP.EQ.2) GO TO 5999
IF(MC.GT.MFINAL) GO TO 460
C
C
C*****WRITE FINAL OUTPUT
C
IF(N.NE.1) CALL WRITER(IOP14)
WRITE(6,950) QINIT
WRITE(6,950) QITOTAL
QIT=QINIT+QITOTAL
WRITE(6,960) QITOT
QTHR1=(EW.CFF+MC.CPW)*(TB-TI)
QTHR2=MG.HFTE
QTHEOR=QTHR1+QTHR2
IF(TB.LT.TI) QTHEOR=QTHR2
WRITE(6,965) QTHEOR
LICODEM=LICODEM+100./MO
WRITE(6,970) LICODEM
C
C*****FORMAT STATEMENTS
C
500 FORMAT(* *** WICRYER1 PROGRAM OUTPUT *****)
505 FORMAT(1H0,TH TE BW CSF MRG"
** PMAX RISTIM")
515 FORMAT(1H0,DTU IOPTPF IOPTU"
** MITH MTER")
520 FORMAT(E13.5,218,2111)
525 FORMAT(1H0,SEC NREL TS T1 T2"
** T3 RATI01 RATI02 RATI03 DELTAT Q"
** QMTH PGALGE SEC")
530 FORMAT(1H0)
535 FORMAT(10E5,3))
540 FORMAT(1H0," START OF TRANSITION REGIME")
545 FORMAT(1H0," START OF LINEAR REGIME")
550 FORMAT(1H0," BTU/F12 REQUIRED TO HEAT THE SHEET")
555 FORMAT(1H0," BTU/F12 REQUIRED TO DEMATERIZING THE SHEET")
560 FORMAT(1H0," BTU/F12 TOTAL THERMAL ENERGY INPUT")
565 FORMAT(1H0," BTU/F12 THEORETICALY REQUIRED FOR HEATUP")
"AND EVAPORATION OF ALL LIQUID AT SATURATION TEMPERATURE")
97C FORMAT(4H0.1x,F6.2=" PERCENT OF THE MOISTURE IS REMOVED IN"
** LIQUID FORM")

******END MAIN PROGRAM
9595 STOP
END

*********************************************************************

************** THE SUBROUTINES ************

*********************************************************************

******SUBROUTINE TO CONVERT FROM ENGLISH TO SI UNITS

SUBROUTINE CAVATI

DATA A1,A2,A3,A4,A5/9.5,32.4,8224,6.8948/

COMMON /LABEL1/ TH,PT,VT,OT,FT,GT,VTG,GTG,VTIS,GTIS,VTFT,GTFT

COMMON /LABEL2/ TH,T1,T2,T3,T4,TMID

COMMON /LABEL9/ DLCT,FACTOR,BW,CD,DFIBER,COEFF,PS3

TH=A1*TH/A2+A3
TB=A1*TB/A2+A3
EH=B1/A4
FMAX=FMAX/A5

RETURN

END

*********************************************************************

******SUBROUTINE TO DETERMINE THE CONSTANTS FOR CALCULATION OF M AND N

SUBROUTINE CASMNX(x)

DATA
A1,A2,A3,A4,A5,A6/2.9613453E+00,-2.6919415E-01,5.7420518E+01,
* -3.3756161E+01,4.113187E+00,1.2974508E+00/

E1=2.3853945E-02,-2.7498142E-03,-1.305774E-03/
E2=1.405545E-02,-5.497606E-04,-6.4943036E-02,

RETURN

END

*********************************************************************
CCMGN /LABL15/ CM1*CM2*CP3*CM4*CM5*CM6 001463
CCMGN /LABL16/ CN1*CN2*CN3*CN4*CN5*CN6 001464
C
TERM=(X-E1)/E2)**2 001465
IF(X-LT-0.) TERM=0. 001466
CM1=A1+B1*TERM 001467
CM2=A2+E2*TERM 001468
CM3=A3+B3*TERM 001469
CM4=A4+E4*TERM 001470
CM5=A5+E5*TERM 001471
CM6=A6+B6*TERM 001472
C
CN1=C1+D1*TERM 001473
CN2=C2+D2*TERM 001474
CN3=C3+D3*TERM 001475
CN4=C4+D4*TERM 001476
CN5=C5+D5*TERM 001477
CN6=C6+D6*TERM 001478
C
RETURN
END 001479
C
SUBROUTINE TO CALCULATE PROPERTIES AT TB 001480
C
SUBROUTINE PROPTB 001481
C
COMMON /LABEL1/ TB,PVTB,DFVDTB,VFTB,VGETB,HGETB,VISGTB,VISFTB 001482
C
PVTB=P(V(TB)) 001483
DFVDTB=DF(V(TB)) 001484
VFTB=VF(TB) 001485
VGETB=VG(TB) 001486
HGETB=HG(TB) 001487
VISGTB=VISG(TB) 001488
VISFTB=VISF(TB) 001489
C
RETURN
END 001490
C
SUBROUTINE TO CALL PROPERTY SUBROUTINES 001491
C
SUBROUTINE CALLER(I) 001492
C
COMMON /LABEL2/ TH,T1,T2,T3,TI,TMID 001493
C
IF(I.EQ..4) GC 10 10 001494
C
CALL PROPTB 001495
IF(I.EQ..2) GC 10 20 001496
C
1C CALL PROPT12 001497
**SUBROUTINE TO CALCULATE T1-T2 AVERAGE PROPERTIES**

```fortran
SUBROUTINE PROP12
    COMMON /LABEL2/ TH,T1,T2,T3,TI,THID
    COMMON /LABEL3/ DPOT12,VF12,VG12,VISG12
    CPOT12=(DPVD1(T1)*DPVD1(T2))/2.
    VF12=(VF(T1)+VF(T2))/2.
    VG12=(VG(T1)+VG(T2))/2.
    VISG12=(VISG(T1)+VISG(T2))/2.
    RETURN
END
```

**SUBROUTINE TO CALCULATE T2-T3 AVERAGE PROPERTIES**

```fortran
SUBROUTINE PROP23(I)
    COMMON /LABEL2/ TH,T1,T2,T3,TI,THID
    COMMON /LABEL4/ DPOT23,VF23,VISF23,VG23,VISG23
    GC TO (10=20) 1
    IF(I.EQ.3) GC TO 20
    CALL PROP23(I)
    GC TO 30
20 CALL PROP23(I)
30 RETURN
END
```

**SUBROUTINE TO CALCULATE T3-T8 AVERAGE PROPERTIES**

```fortran
VF23=(VF(T2)+VF(T3))/2.
VISF23=(VISF(T2)+VISF(T3))/2.
GC TO 30
20 VF23=(VF(T2)+VF(T3))/2.
VISF23=(VISF(T2)+VISF(T3))/2.
30 RETURN
END
```
SUBROUTINE PROP3B

COMMON /LABEL1/ TB,PVTB,DFVCTB,VFTB,VGTB,HFGTB,VISGTB,VISFTB
COMMON /LABEL2/ TH,T1,T2,T3,T1,T2,T3,T4,TMD
COMMON /LABEL5/ DPT3B,VG3B,VISG3B

C
CPOT3B=CDPV(DT3)+CPDV(TB)/2.
VG3E=(VGT3)+VGTB)/2.
VISG3E=(VISG(T3)+VISGTB)/2.

RETURN
END

******************************************************************************

SUBROUTINE TO CALCULATE APPLIED PRESSURE AND ITS DERIVATIVE

SUBROUTINE PRESSRCA

DATA PI,A2/3.14159274,712389/

COMMON /LABEL7/ PREF1,PMAX,RISTIM,P,IOFTP,DPOF

C TO (10-20) IOFTP

C
IPDT=PMAX*3600./RISTIM
F=PREF1*+A*DPDT
IF(F.GT.PMAX) F=PMAX
IF(F.GE.PMAX) DPDT=0.
EO TO 3C

C
A1=PI*3600./RISTIM
IF(1800.-A.GE.RISTIM) P=PREF1
IF(1800.-A.GE.RISTIM) CLOPT=C.

C
RETURN
END

******************************************************************************

SUBROUTINE TO CALCULATE THE THICKNESS OF A SATURATED MEDIUM

SUBROUTINE CDIFN(N,TIME,YL,YPRIME)

REAL YLN(N),YFRIME(N),TIME

COMMON /LABEL1/ TB,PVTB,DFVCTB,VFTB,VGTB,HFGTB,VISGTB,VISFTB
COMMON /LABEL7/ PREF1,PMAX,RISTIM,P,IOFTP,DPOF
COMMON /LABEL8/ M1,M2,M3,M4,N1,N2,N3,N4
COMMON /LABEL9/ CLDT,FACTGR,BW,DFIBER,CQEFF,PS3

CALL PRESSR(TIME)
FS3=(BW/CYL(1)*N3)**(1./N3)

******************************************************************************
VPRIPE(1) = (FS3-P) * COEFF
RETURN

END

SUBROUTINE TO CALCULATE THE JACOBIAN FOR A SATURATED MEDIUM

REAL TIME, YL(N), FD(1,1)

COMMON /LABEL8/ N1, N2, M3, M4, N1, N2, N3, N4
COMMON /LABEL9/ OLDT, FACTOR, BW, DB, DFIBER, COEFF, PS3
FD(1,1) = -COEFF * PS3 / (N3 * YL(1))
RETURN
END

SUBROUTINE TO WRITE OUTPUT

SUBROUTINE WRITER(I)

COMMON /LABEL2/ TH, T1, T2, T3, T4, TMID
COMMON /LABL11/ SEC, MREL, TS, RATIO1, RATIO2, RATIO3, DELTAT, Q, QHTC,
* PGAGE
COMMON /LABL12/ TSSI, T1SI, T2SI, T3SI, DELTSI, QSI, CHICS, PGAGSI,
* TDMSI

IF (I = EQ 2) GO TO 10
WRITE(6, 20) SEC, MREL, TS, T1, T2, T3, RATIO1, RATIO2, RATIO3, DELTAT, Q,
* CHIC, PGAGE, SEC
WRITE(2, 20) SEC, MREL, TS, T1, T2, T3, RATIO1, RATIO2, RATIO3, DELTAT, Q,
* CHIC, PGAGE, TPID
GO TO 30

10 CALL CNWR12
WRITE(6, 20) SEC, MREL, TSSI, T1SI, T2SI, T3SI, RATIO1, RATIO2, RATIO3,
* DELTSI, QSI, CHICS, PGAGSI, SEC
WRITE(2, 20) SEC, MREL, TSSI, T1SI, T2SI, T3SI, RATIO1, RATIO2, RATIO3,
* DELTSI, QSI, CHICS, PGAGSI, TMIDSI

30 RETURN
C******************************************************************************
C SUBROUTINE TO CONVERT FROM ENGLISH TO SI UNITS
C******************************************************************************
C SUBROUTINE CKWRT2
C
C CATA A1*A2*A3*A4*A5*A6*A7/5*32*9*0,3048,3,1546,5,6783,6,8948/
C
C COMMON /LABEL2/ TH,T1,T2,T3,TH,TID
C COMMON /LABL11/ SEC,HREL,T5,RATIO1,RATIO2,RATIO3,DELTAT,G,HTC,
C * PGAUGE
C COMMON /LABL12/ TSSI,T1SI,T2SI,T3SI,DELTSI,QSI,QH,TCSI,PGAESI,
C * TMIDSI
C
C TSSI=A1*(TS-A2)/A3
C 11SI=A1*(T1-A2)/A3
C 12SI=A1*(T2-A2)/A3
C 13SI=A1*(T3-A2)/A3
C TMIDSI=A1*(TH-A2)/A3
C DELTSI=DELTAT*A4
C QSI=G*A5
C QH,TCSI=GHTC*A6
C PGAESI=PGAUGE*A7
C
C RETURN
C END
C******************************************************************************
C SUBROUTINE TO CORRECT ERROR CONDITION OR PRINT WARNING MESSAGE
C*******************************************************************************************************
C SUBROUTINE BARKIN(I,J,X)
C
C COMMON /LABEL6/ DXX,DIFFX,DIFFFX,EKIN
C COMMON /LABEL9/ CLDT,FACTCR,WM,CFIBER,COEFF,PS3
C
C GO TO (10,20,30,40) I
C
C 10 WRITE(6,50) J,DFIBER
C GO TO 70
C
C 20 WRITE(6,60) J,EKIN
C GO TO 70
C
C 30 DIFFX=DXX
C GO TO 70
C
C 40 DIFFFX=DXX
C
C 5C FORMAT(*** ZONE *12* DENSITY *E16.10* IS GREATER THAN THE*
C * MAXIMUM ALLOCABLE DENSITY *E16.10* *** COMPUTATION***
C
C 001681 001682 001683 001684 001685
C 001686 001687 001688 001689
C 001690 001691 001692 001693
C 001694 001695 001696 001697
C 001698 001699 001700 001701
C 001702 001703 001704 001705
C 001706 001707 001708 001709
C 001710 001711 001712 001713
C 001714 001715 001716 001717
C 001718 001719 001720 001721
C 001722 001723 001724 001725
C 001726 001727 001728 001729
C 001730 001731 001732 001733
** TERMINATE**

**COMPUTATION**

**VAPOR PRESSURE FUNCTION**

FUNCTION PV(T)

DATA
FV=A1*T*(A2*T*(A3+T*(A4+T*A5)))
RETURN
END

**VAPOR PRESSURE DERIVATIVE FUNCTION**

FUNCTION DPVDT(T)

DATA
CPVDT=A1*T*(2*A2+T*(3*A3+T*A4))
RETURN
END

**LIQUID SPECIFIC VOLUME FUNCTION**

FUNCTION VF(T)

DATA
VF=A1*T*(A2+T*(A3+T*(A4+T*A5)))
C RETURN
END
C*****************************************************************************
C VAPOR SPECIFIC VOLUME FUNCTION
C
FUNCTION VG(T)
C DATA
* 9.35084E-11/
C VG=EXP(A1+T*(A2+T*(A3+T*(A4+T*A5))))
C RETURN
END
C*****************************************************************************
C LATENT HEAT FUNCTION
C
FUNCTION HFG(T)
C DATA
* -6.91038E-10/
C HFG=A1+T*(A2+T*(A3+T*(A4+T*A5)))
C RETURN
END
C*****************************************************************************
C LIQUID VISCOSITY FUNCTION
C
FUNCTION VISF(T)
C DATA
C VISF=A1+T*A2+A3/T+A4/T**2
C RETURN
END
C*****************************************************************************
C VAPOR VISCOSITY FUNCTION
C
FUNCTION VISG(T)
C
CASE
*/A1=2/5.499E-06,1.3908E-06/*
VISG=A1*Y*A2
RETURN
END

******************************************************************************

***** EVALUATION FUNCTION

FUNCTION EVALM(X*T)
CASE A1=A2=A3=1.51=0.25/
COMMON /LABEL2/ TH=1*T2*T3*T4*TMIC
COMMON /LABL15/ CM1=CM2=CM3=CM4=CM5=CM6
F=X*A1
E=X*A2
R=SQRT((1/T1)**A3)
EVALM=CM1*CM2*X*CM3/A+CM4/A**2+CM5/B+CM6/B**2)*R
RETURN
END

******************************************************************************

***** EVALUATION FUNCTION

FUNCTION EVALN(I*X*Y)
REAL NDOCMN*MID*NSAT
CASE A1=A2=1.51=1/
COMMON /LABEL4/ DPDT23*VF23*VISF23*VG23*VISG23
COMMON /LABEL7/ PREF1*PMAY*RSTIM*P*IOPT*DPDT
COMMON /LABL16/ CN1*CN2*CN3*CN4*CN5*CN6
COMMON /LABEL8/ M1*M2*M3*M4*M5*M6
COMMON /LABL13/ CH1=DH2*MR*KRSTAR
COMMON /LABL14/ REXP*PR3LOG*PREF3*PMID*PDENOM*DF
F=X*A1
E=X*A2
C=CN1*CN2*X*CN3/A+CN4/A**2+CN5/B+CN6/B**2
EVALN=C
IF(I=EQ.1) GO TO 10
IF(X.LE.KRSTAR) GO TO 10
ASAT=ALCG((1/(M3*X*VF23)*CF))/PR3LOG
NMID=CN5*CN1*2.
NDOCMN=NSAT-NMID
FTRUE=ABS(Y-PMID)/PDENOM

C
SIGN=1.
IF(Y.LY=PMID) SIGN=-1.
IF(Y.EQ=PMID) SIGN=0.
EVALN=NMD+SIGN*NDENCM*PTERM**((1./NEXP))
IF(Y.EQ=PREF1) EVALN=C
IF(Y.GT=PREF3) EVALN=NSAT
WRITE(5,*) I,X,Y,C,NSAT,PMID,NDENCM,PTERM,PMID,PODENM,EVALN

C IC RETURN
C END
C
C******************************************************************************
C
C*****SPECIFIC FILTRATION RESISTANCE FUNCTION
C
FUNCTION SPRES(P)
C DATA A1,A2,A3,A4,A5,A6/S7,C27,S2,013E-05,S0,142*S0,464*S0,187*S0,344/
C COMMON /LABL10/ CSF
C RREF=((A1-ALOG(CSF))/A2)**2
C X=A/A3
C SPRES=RREF*(A4*A5*X*A6*SQRT(X))
C RETURN
END

C******************************************************************************
C
C*****HYDRAULIC PRESSURE FUNCTION
C
FUNCTION HYDRA(A,B)
C COMMON /LABEL1/ TB,PVTB,DFVCTB,VFTB,VGTB,HFGTB,VISGTB,VISFTB
C HYDRA=(FVA(A)*PV(B))/2.-PV1B
C RETURN
END

C******************************************************************************
C
C*****LATENT HEAT INCREMENT FUNCTION
C
FUNCTION DELHC(I)
C COMMON /LABL13/ DH1,DH2,MR,MSTAR
C GC TO (10-20,30) I
C GC TO 40
C IC DELHC=DH1*(1.-EXP(DH2*MSTAR))/MSTAR
C IC TO 40
-179-

2C CELHC=DH1*(EXP(DH2*MRSTAR)-EXP(DH2*MR))/(MR-MRSTAR)
CC TC 4C

3C CELHC=DH1*(1.-EXP(CH2*MR))/MR

4C RETURN
END

*****************************************************************************

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The programs for the various stages of model development and the cata files used to generate the graphs for this thesis are stored on magnetic tape in the Institute computer center.

The model equations, supplementary relationships, and cata file information and names are in Institute research notebooks 3578 and 3711.