Moisture effects on webs and rolls

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ABSTRACT: Cellulose is highly hygroscopic and will take on or give up moisture until it reaches equilibrium with its environment. The profound effects of these changing web/roll/box moistures on material properties and converting operations are described. The simple diffusion model derived here allows prediction of changing moisture contents at any time and location within webs, rolls, and boxes for a variety of converting situations. Strong parallels are developed between moisture diffusion and heat conduction.

KEYWORDS: Bibliographies, boxes, conversion, humidity, machine components, models, moisture content, paper board containers, paper boards, rolls, storage, temperature, webs.

Why moisture is important

Moisture content

The term "moisture content" is defined simply enough and seemingly well understood. As we will see, however, there are a few complications.

Moisture content for webs is defined as

$$\text{moisture (web), \%} = [(\text{wet weight} - \text{dry weight})/\text{wet weight}] \times 100\% \quad (1)$$

Curiously, moisture content for pulp is defined with a dry denominator as:

$$\text{moisture (pulp), \%} = [(\text{wet weight} - \text{dry weight})/\text{dry weight}] \times 100\% \quad (2)$$

In both cases, the wet weight must be defined as either "as received" (in the rail car, wound roll or product) or "as is" (TAPPI conditions of 50% ± 2% RH and 23°C ± 1°C) (*1*). This ambiguity could result in potential confusion if the condition is not explicitly named, along with its value.

The situation for dry weight is even trickier. There is a common misconception that oven-dry samples contain no water, implying a 0% moisture content. However, this is not usually the case with conventional drying practices, since wood fibers are extremely hydrophilic and do not give up water easily. Even with indefinitely long oven-drying times at 100°C, a fraction of a percent of water is still intimately bound up with the cellulose.

What is even more startling is that in the process of trying to drive out moisture by oven-drying the fibers, one is doing a slow "cook," or oxidation (low-temperature burn), on the material. Oven-drying at 135°C for 24 h will cause a 1% mass loss from oxidation and form several chemical breakdown products (*2*). In other words, in conventional oven-drying, one cannot easily separate the mass loss due to moisture evaporation from the chemical breakdown due to heat.

Thus, defining "dry" is not a simple task. This is why the applicable TAPPI test method defines a drying period such that another hour of drying time will not statistically affect the resulting oven-dry weights by more than 0.1% (*3*).

Figure 1 shows the weight loss during drying as a function of log time for a 10-g sample of a cellulose product. Weight loss is shown as a percent moisture content, with the longest drying time as the reference (0% moisture). As seen here, the total curve is composed of three regions. The first is the warmup transient region for a cool specimen put into a hot oven. The intermediate region is the normal drying rate (at elevated temperature), where most of the weight loss is due to the loss of moisture. The cooking region is where most of the weight loss is the result of oxidation and other chemical reactions, with some weight lost to departing moisture. The extreme flatness of the curve in this region means that a drying time anywhere from 1 h to 1 day will achieve essentially the same result (for this sample). As we will see later, moisture loss in converting or storage has similar curves but lacks the transient and cooking stages.

Moisture content can also be measured indirectly with handheld or scanning instruments based on one of two principles: (a) the attenuation of an infrared or radio wave whose wavelength is tuned to the absorption of water molecules (*4–6*), or (b) the resistance to a small electrical current applied between two electrode probes. The latter is often used to measure the moisture content of lumber. Unfortunately, both principles may be paper-

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grade dependent and must be calibrated for a particular application. Furthermore, the handheld units can be operator dependent.

Weight

The most obvious result of moisture content on cellulose products is the effect on weight, either total product weight or as nondimensionalized web basis weight. The water fraction of a product's weight can vary from just over 1% to more than 20%, depending on the grade as well as manufacturing and environmental conditions.

The water fraction affects the economics of a product in at least two ways. The first is on advertised weight. If, for example, a product is tested in manufacturing at a high moisture content and is received by a customer at a lower content, the recipient may feel shorted. Thus, it is customary to advertise weight based on standard lab testing conditions of 50% RH. The second effect is for the mass-balance accounting of fibers of a manufacturing system. The difference between raw fiber weight and finished product weight is a measure of material loss and waste. Again, mass balance must account for moisture content in all of its constitutive measurements and calculations.

Geometry

Another major effect of moisture content is hygroexpansivity, the swelling of cellulose fibers and fiber products. However, this expansion is not the same along the three axes of the fiber or product. A cellulose fiber tends to swell five to seven times as much across its girth as it does along its length (*7*), and a fiber web will swell about 10–100% more in the cross-machine direction (CD) than in the machine direction (MD) (*8–9*), as seen in **Fig. 2**. This hygrothermal change in length can be calculated from Eq. 3:

$$\varepsilon_l = \Delta l / l = \alpha_l \Delta T + \beta_l \Delta C \qquad (3)$$

where

ε_l = strain in MD

l = length (width or thickness)

α_l = coefficient of MD thermal expansion

T = temperature

β_l = coefficient of MD hygroexpansivity

C = moisture content

Similar equations can be written for the CD and ZD (thickness). Note how both thermal and hygroscopic expansion are entirely analogous. Indeed, most aspects of the rich field of heat transfer and temperature dependence are directly applicable to moisture diffusion and effects of moisture content on cellulose webs.

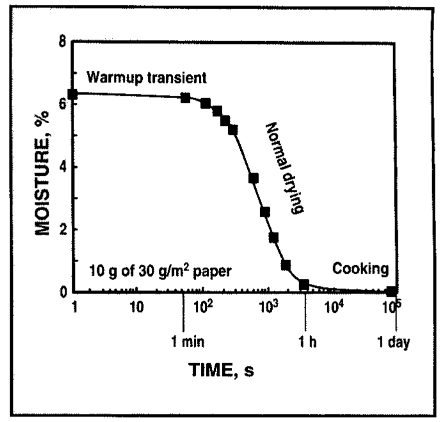
As with weight, vendor and customer must agree on a common definition of length, width, and thickness, which necessarily includes a statement on moisture content (and as we will see later, whether this moisture content was reached most recently by drying or wetting).

A simple example of width changes is the splice offset (*10*). During the splicing operation, the web is exposed for some time on both sides to the ambient humidity. If the web is not at equilibrium moisture content in the wound roll, it will take on or give up moisture until it reaches equilibrium, causing the web to shrink or grow in width. The several minutes the web is exposed to the air is more than sufficient for non-board grades to change significantly in moisture content. However, the roll is only exposed on the outside, and even those layers are constrained from contraction or expansion by the bulk of the roll. As a consequence, the tail spliced onto the roll may be several centimeters narrower or wider than the roll for a very wet or dry web on a wide machine.

A different set of concerns develops in converting if the moisture content of a web or roll is not uniform across its width or length. The high-moisture areas will expand more than the neighboring low-moisture areas. This will almost inevitably result in out-of-plane buckling of one of several types.

Buckling of a free web is best demonstrated by spilling water droplets onto a sheet of paper. On close inspection, one will see that the wetted area expands out of the plane of the web. More typically, the high-moisture area is a streak that buckles into a trough, as seen in **Fig. 3**. If the trough is severe enough, it can fold over into a crease when it crosses a roller.

1. Moisture loss vs. time during oven drying



On a wound roll, buckling is caused when the outer layers are wetter than the inner layers, and can form moisture welts (*10*) or roll cockle (*11–12*). Just as with the splice offset, the bulk of the roll will restrain free expansion or contraction of the outer layers. This is best observed when a thin paper grade is overdried in manufacturing and then stored in a humid room. Sometimes all it takes is a thunderstorm moving through the area to trigger these skin-deep blemishes.

Constrained CD expansion, caused by moisture increase and several other web-handling parameters, can be identified as having a cross section with a wavelength determined for an isotropic web by Eq. 4 (*13*):

$$\lambda = (2)^{1/2} L \{ [\pi^2 E (t/L)^2] / [3(1 - \upsilon^2)\sigma_l] \}^{1/4} \qquad (4)$$

where

L = length of web span between rollers

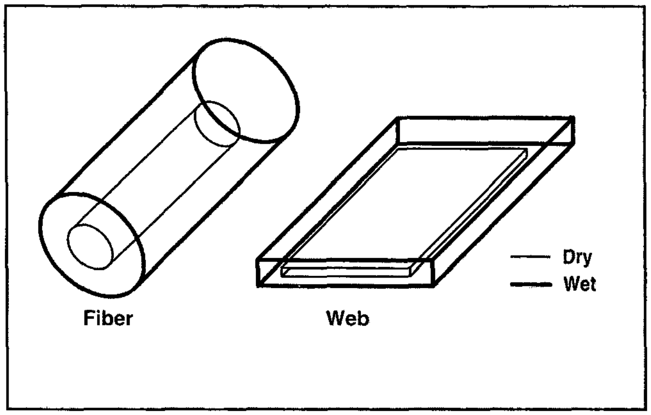
E = Young's modulus for the isotropic material

t = web thickness

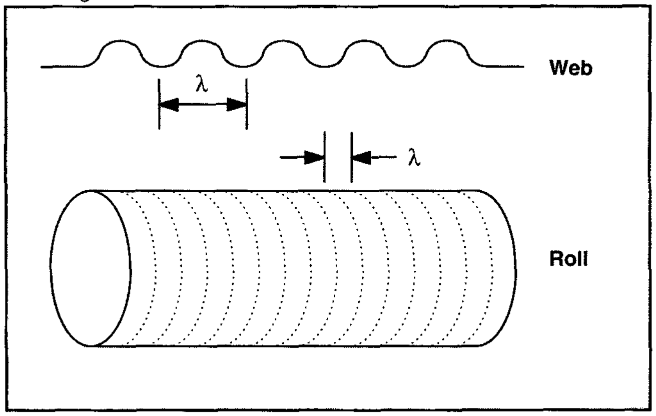
υ = Poisson's ratio

σ_l = stress caused by web tension

2. Hygroexpansivity in a fiber and in a sheet



3. Buckling caused by constrained hygroexpansivity has a predictable wavelength



The wavelength of constrained CD expansion in a wound roll is determined similarly, as seen in Eq. 5.

$$\lambda = [2\pi(Rt)^{1/2}]/[12(1-\upsilon^2)]^{1/4} \quad (5)$$

where

R = radius of wound roll

Another type of out-of-plane moisture-induced behavior is warping, where the best documented example comes from liner grades (*14*). Here, a board with flat plies can still warp with changes in moisture if the top and bottom plies have slightly different principal directions (i.e., polar directions). As moisture changes, each ply will experience an unbalanced bending stress that may warp along one of three axes. It would not be surprising if flat paper grades also could experience this difficulty if the principal direction of the fibers varies throughout the thickness of the sheet.

Strength

While the effect of moisture changes on strength properties depends on the particular test, web grade, and moisture content, a few generalities can be made. Web tensile strength decreases with increasing moisture content, as seen in **Fig. 4**, although it has been suggested that peak strength occurs at 30% RH rather than at zero moisture (*15*). Similarly, modulus and stiffness decrease with moisture. In contrast, web stretch increases with increasing moisture content. Similarly, tearing resistance and fracture toughness also increase with moisture.

Moisture content can also have a profound effect on the dimensional stability of load-carrying paper products, such as corrugated containers. It is well known that wood products are easier to bend and can be set into a new shape with addition of moisture, particularly at elevated temperatures. The effects of moisture on dimensional stability and paper strength are why moisture barriers must be applied to paper products such as drinking cups and milk cartons.

What may not be as well known is that the dimensional stability of wood products is also reduced by cyclic changes in humidity. Thus, while a corrugated container may withstand a given load at a given moisture content, it may fail if the moisture content is cycled (*16–19*). Cycling of moisture occurs in unconditioned storage under daily changes in moisture and temperature, under changes in weather, and under seasonal changes.

Converting

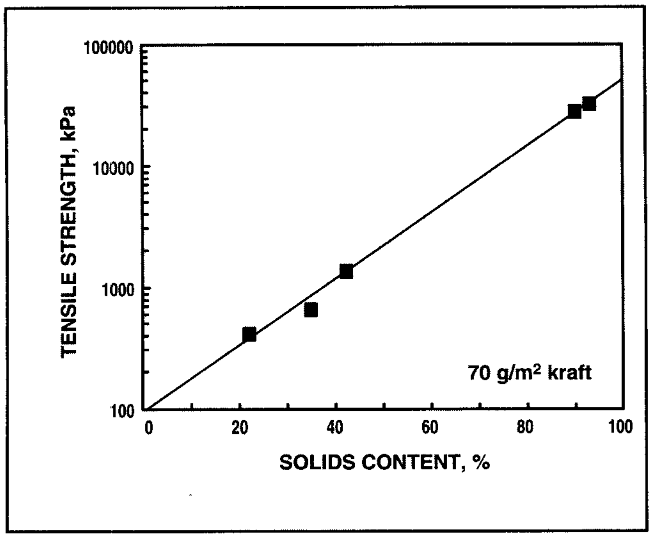
How does moisture affect web runnability in converting? We might expect that because the web has weaker tensile strength with more moisture, runnability would also decrease. However, web breaks are most influenced by fracture properties, so that breaks will tend to be reduced with wetter webs running in humid converting rooms (*20*). Thus, it has been found that printing presses operate with fewer breaks during the humid summer months (*21*).

Sometimes, however, converting efficiency may be better during the dry winter season. Some folders and sheeters can operate more efficiently when manipulating paper that is drier and stiffer. Another example is shown in **Fig. 5** for a particular kind of unwinding defect. Here, the problem mechanism is theorized to be related to a reduced stiffness and reduced interlayer friction. Nonetheless, the tendency is to fewer defects during winter, and diagnosing seasonal trends should always include humidity effects.

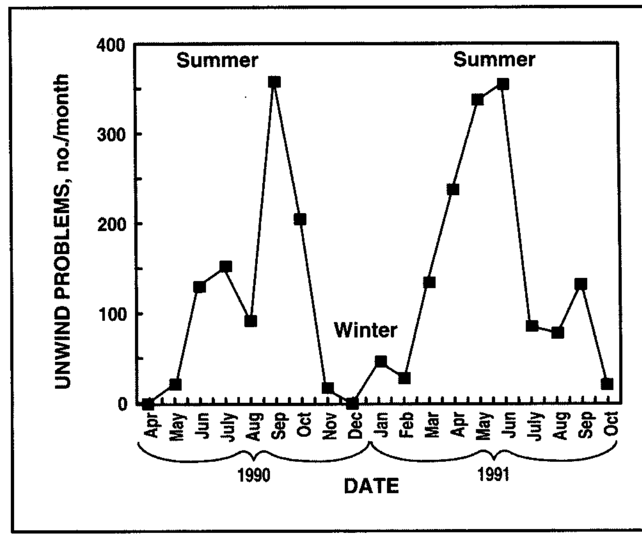
Just as moisture affects the strength of paper, it also affects the strength of fiber cores. It has been found that doubling the moisture content of cores can cut strength almost in half (*22*). Thus, the core would have an increased tendency to crush both axially and radially. Similarly, it would not be able to carry as much torque on center driven/braked unwinds.

Other problems can be seen with dimensional changes of high-moisture cores. A core cut precisely to 2 m at 10% moisture will shrink by 12 mm in length and undergo a 0.5-mm reduction in diameter if it is dried to 7% moisture (*22–24*). If this wet core were allowed to dry after being wound with paper, it might shrink enough to completely lose its radial pressure against the inner layers of the roll. Such a roll could not be unwound because brake

4. Ultimate MD tensile strength and moisture



5. Seasonal effects on converting problems may be related to humidity



and acceleration torques could not be applied without core/roll slippage. The roll also would be prone to telescoping.

Excessively dry webs and rolls are also prone to electrostatic problems (*25*). First, the generation of static electricity is increased because of higher rubbing frictions on dry webs. Secondly, the static cannot dissipate by conduction to metal rollers because dry paper is a very effective insulator. Similarly, if the air is dry (often associated with dry webs), it also will not be able to dissipate static very well.

While there are many outcomes from static, the chief concerns are web handling and operator safety. Light webs that are charged are attracted or repelled from charged rolls. Thus, the webs are likely to follow around a rubber roller rather than continue to the next roll. Similarly, charged unwinds can increase the force required to separate the top layer from the remainder of the roll, above and beyond the blocking and aerodynamic forces already present.

Dry webs are also very prone to dusting. Looser fibers near the surface are stiffer and brittle. Consequently, they are more easily separated from a web rubbing against stationary members, such as folding boards, guard boards and pans. Slitting also is a high-dust-generating operation. Thus, one of the advantages of water-jet slitting is reduced dusting.

In closing, we will just mention a few more of the many effects of moisture. Moisture can affect the processes—and consequently the products—of calendering (*26*), corrugating (*27*), and printing (*28*). Moisture also affects machines, as excessively high or low humidities can affect modern electronics because of condensation and static, respectively. Last but not least, operators and workers will feel more comfortable in an environment where humidities are in a range between 30% and 70%.

With all of these effects of humidity and moisture, we can no longer neglect their consideration when designing and diagnosing converting operations. The following describes the time-dependent diffusion mechanism and how it can be mathematically modeled.

Modeling moisture diffusion

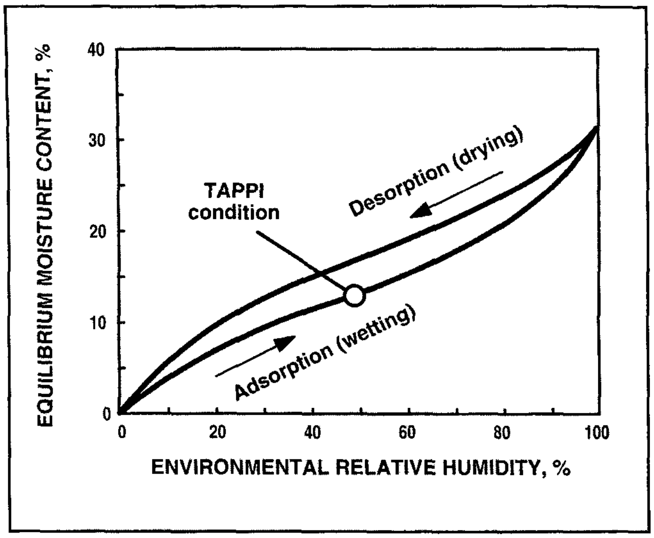
Sorption curves

The first concept necessary to understand the mechanics of moisture content is that of equilibrium. Given sufficient time, a cellulose web will reach a given moisture content depending on several parameters, including environmental moisture, temperature, the grade of paper, and finally whether equilibrium was achieved by drying or wetting. Equilibrium is reached when the moisture in the material is in balance with its environment and has no further tendency to take on or give up moisture.

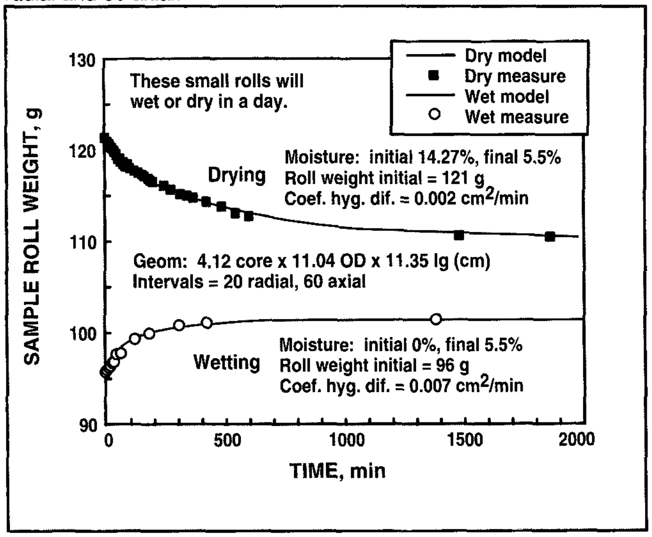
The single most important parameter determining moisture content is environmental relative humidity. As seen in **Fig. 6**, the moisture content varies from almost zero for a 0% RH on all grades to a grade-dependent 25–40% for a 100% noncondensing relative humidity. While these curves are unique to a particular material, they do not vary considerably between wide ranges of cellulose products in typical environmental relative humidities. For example, all start at 0,0 and they pass to as low as 12% for acetate rayon and surgical cotton, to 16% on sulfite pulp, and as high as 22% on viscose rayon at 90% RH (*29*).

Also note that there are two curves, where the bottom is the adsorption (wetting) curve and the top is the desorption (drying) curve. Thus, one could obtain two different values for material moisture content depending on

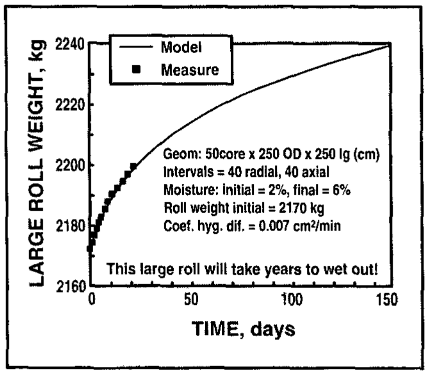
6. Moisture content vs. environmental humidity for drying and wetting conditions



7. Diffusion constants are obtained by weighing a sample small enough to wet or dry in a day (in this case, a roll of 11.35-cm length, 11.04-cm OD, with a 4.12-cm core), Values are adjusted until the model converges with the measurements. Modeling intervals were 20 radial and 60 axial.



8. Predicting moisture content for a large roll (in this case, a roll of 250-cm length, 250-cm OD, with a 50-cm core). Modeling intervals were 40 radial and 40 axial. The curve is for a wetting condition.



whether equilibrium was obtained by wetting or drying. Additionally, the locations of the curves depend slightly on ambient temperature.

Hysteresis and lab test conditioning

These equilibrium behaviors have several major implications for lab test conditioning, with analogous considerations for converting and storage. The first is that if one desires a consistent moisture content for a particular grade, then environmental RH (and to a lesser extent temperature) must be controlled. For lab testing, the standard is to control test lab environmental conditions to 50% ± 2% RH and 23°C ± 1°C (*30–31*).

The hysteretic separation of the adsorption and desorption curves also implies that a convention must be established there as well. The convention is to use the adsorption (lower, wetting) curve by ensuring that the material is brought for testing drier than test condition standards. If the material is manufactured either wetter or takes on moisture in a wetter storage environment, it must be preconditioned. This involves bringing the test specimens down to equilibrium at 30% RH prior to equilibrating at test conditions (*3*).

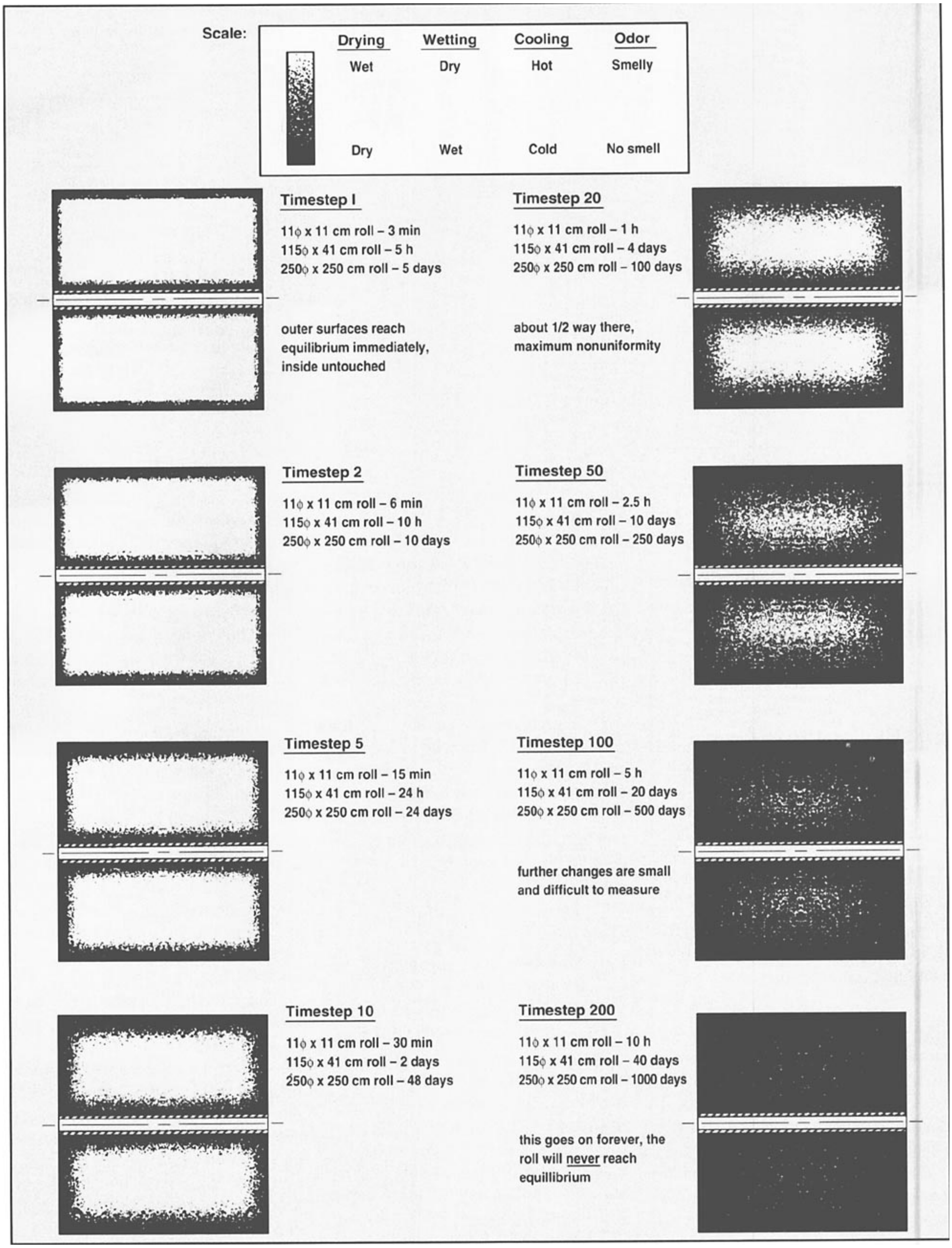
Diffusion

Paper taken from a machine reel and wound on a winder has a moisture level that is not necessarily in equilibrium with its storage environment. Similarly, the web, roll, or box may be moved from one environmental relative humidity to another in its passage from manufacture to end use. In all of these cases, the web, roll, or box will take on or give up moisture or heat with time until it reaches equilibrium with its environment. Thus, whether we are involved in converting, storage, or testing, the time-dependent nature of moisture diffusion must be considered. These equilibrating times vary from a few seconds for a web of light tissue exposed on both sides, to several years for a large jumbo reel. Thus, how long a material takes to equilibrate is most strongly dependent on the mass/area ratio of the web, roll, or box.

Additionally, as we will see, the moisture content of an object is not uniformly distributed. The outer surface equilibrates almost immediately, while the interior will take the longest to reach equilibrium. This has several implications for quality control and runnability when a web, roll, or box is only partially equilibrated, because properties such as weight, tension, and length are guaranteed to be nonuniform.

The effects of moisture on paper have been widely discussed. The primary purpose of this article is to show that the time-dependent change in moisture content by diffusion can be modeled quite simply for almost any product or situation (*32–33*). The three ingredients necessary are a model, a material property called the (hygroscopic or thermal) diffusion constant, and a computer program.

9. Moisture distributions for wound rolls. Time steps are arbitrary; time scale is typical for wetting or drying of unwrapped cellulose rolls.



Diffusion modeling

A model for the diffusion problem was first developed for one-dimensional heat conduction by the French mathematician Fourier in 1822. This model is presented in Eq. 6, which states that the heat flux, Q (energy/area/time), is equal to a material property, k, called the thermal conductivity, times the temperature gradient.

$$Q = -kA\,(dT/dx) \qquad (6)$$

Later, Fick developed his law of diffusion, which is mathematically identical to the thermal problem except that the equation was posed in terms of a diffusivity constant instead of a conductivity, and in terms of concentrations (i.e., moisture content) instead of temperature.

While the diffusion law in one dimension can be applied directly to a uniform flow of moisture in the ZD of a web, far more interesting problems can be solved in two dimensions for a roll, and in three dimensions for a box or stack. In the following analysis of a rewound roll, we will apply and extend Fick's Law in two dimensions and cylindrical coordinates in r, z, and t variables (*34*) as follows:

$$\partial^2 C/\partial r^2 + [(1/r)(\partial C/\partial r)] + \partial^2 C/\partial z^2 = [(1/D)(\partial C/\partial t)] \qquad (7)$$

where

C = moisture content, %, or temperature T, °C

r = radius, cm

z = CD position, cm

t = time, s

D = hygroscopic diffusion constant, %/cm²/s, or thermal or chemical diffusivity

Implicit here is the assumption that there is no moisture generation and that there is radial symmetry and isotropy. Isotropy means that the diffusion constant is the same in all three principal directions. While the formulation can easily be extended to include anisotropy, the measurement of the two or three diffusion constants will be considerably more difficult.

Using a forward finite-difference approximation for the temporal derivative and a central finite-difference approximation for the spatial derivatives, Eq. 7 becomes (8)

$$\frac{\left(C^{t+}_{r,z} - C^{t}_{r,z}\right)}{D\Delta t} = \frac{\left(C^{t}_{r-,z} - 2C^{t}_{r,z} + C^{t}_{r+,z}\right)}{\Delta r^2} + \frac{\left(C^{t}_{r+,z} - C^{t}_{r-,z}\right)}{2r\Delta r} + \frac{\left(C^{t}_{r,z-} - 2C^{t}_{r,z} + C^{t}_{r,z+}\right)}{\Delta z^2} \qquad (8)$$

t = superscript denotes current time

$t+$ = superscript denotes current time plus dt

r = subscript denotes current radius

$r+$ = subscript denotes current radius plus dr

$r-$ = subscript denotes current radius minus dr

z = subscript denotes current CD position

$z+$ = subscript denotes current CD position plus dz

$z-$ = subscript denotes current CD position minus dz

Solving Eq. 8 for future moisture at node r,z and collecting like terms gives: (9)

$$C^{t+}_{r,z} = \left(\frac{1}{\Delta r^2} - \frac{1}{2r\Delta r}\right)(D\Delta t)\,C^{t}_{r-,z} + \left(\frac{1}{\Delta r^2} + \frac{1}{2r\Delta r}\right)(D\Delta t)\,C^{t}_{r+,z} + \left(\frac{1}{z^2}\right)(D\Delta t)\,C^{t}_{r,z-} + \left(\frac{1}{z^2}\right)(D\Delta t)\,C^{t}_{r,z+} + \left[1 - \left(\frac{1}{\Delta r^2} + \frac{1}{\Delta z^2}\right)(2D\Delta t)\right] C^{t}_{r,z} \qquad (9)$$

Additionally, for numerical stability, the last term in Eq. 9 must be nonnegative. If we let the mesh size be the same in the r and z directions, then for a given mesh size ($dx = dr = dz$), the maximum time step interval dt is given by Eq. 10.

$$\Delta t_{max} \leq \Delta x^2/4D \qquad (10)$$

or, for a given time step interval, dt, the minimum mesh size dx is given by Eq. 11.

$$\Delta x_{min} \geq (4D\,\Delta t)^{1/2} \qquad (11)$$

Thus, Eq. 9, with the constraint imposed by either Eq. 10 or Eq. 11, defines the solution of moisture distribution of the interior points of the roll in the next time step given the current moisture at the current and adjacent nodes. However, in addition to the interior equation, the exterior boundary conditions must also be defined. The two mathematical possibilities are a fixed or gradient moisture.

Strictly speaking, the moisture distribution is convective for both moisture and temperature. However, in the case of moisture, the convective hygroscopic rate is so large that the outer layer of a paper product very quickly reaches equilibrium and is maintained there. This is analogous to a well-insulated wall that is near room temperature on the interior and at outdoor temperature on the exterior. Thus, for expediency, and with no serious compromise of accuracy, we will fix the outer surfaces of the roll to be the equilibrated moisture content at the ambient environmental conditions.

In the case of temperature, rolls of film and paper often feel warm to the touch, so that a convective boundary condition should be used. Though a convective boundary condition is easy to implement on the given finite-difference model, determining the convective constant could be difficult in practice.

The computer solution of the model is quite easily performed by predicting the moisture distribution of the next time step based on the current distribution and Eq. 9. This is implemented in three nested loops. The outer loop merely increments the time, calculates roll weight, and stores/prints results. The middle and interior loops scan across the nodes in the r and z directions, respectively. All of this is written in "Basic" language on a single page of computer code, which will run on virtually any computer.

Obtaining the diffusion constant

Thus, we have two of the three necessary ingredients to solve the diffusion problem: a model and a computer program. Now we need to obtain the diffusion constant. While there may be a variety of ways to measure this value experimentally, we will do this in a straightforward manner by periodically weighing a roll and using the computer model to "reverse engineer" what the diffusion constant must have been by adjusting the value until the model and the measurement converge.

First, a conveniently small roll is obtained of the particular grade of interest. By convenience, we mean one that will wet or dry most of the way to equilibrium within a few days. In the case of wetting, the roll is first dried out completely in an oven and then placed on a scale in a conditioned lab. In the case of drying, the roll is first wetted in a saturated closed container (sitting on a screen above open water) and then weighed periodically in a conditioned lab.

The next step is to run the model while adjusting the diffusion constants until a good match is obtained between the roll weights as calculated by the computer program and as measured on a scale. Examples are shown in **Fig. 7.** Notice how the diffusion constant is somewhat different for wetting from 0% RH and drying from 14% RH. Thus, it is best to measure diffusion constants for the small sample over the range of application interest.

Once the diffusion constant is obtained for a particular material over the range of moisture content of interest for a conveniently sized sample, we are free to model just about any condition we would expect to see in manufacturing, converting, or storage. **Figure 8** shows how the diffusion constant can be used to predict weights and moisture contents accurately for a roll 20,000 times more massive than the test sample. Thus, instead of monitoring moisture in large parent rolls over the course of months or years, we model it in minutes.

In addition to modeling behavior of different sized rolls, we can model geometry changes such as for a rectangular stack or ream. Also, we can model changes in environmental humidity with time, e.g., over changing seasons. Finally, we could model the effectiveness of different wrapping materials or of openings (such as tears) in boxes or wrappers.

Moisture distributions

As mentioned earlier, a web, roll, or box that is in the process of wetting or drying to equilibrium is guaranteed to have a nonuniform moisture distribution. Not only is this distribution available at any location or time, it is an integral part of the calculation. We can plot these distributions for a cross section of a roll using a grey scale, as seen in **Fig. 9.** A wet roll dries, as expected, from all exposed edges. At first this rate of change is very high, gradually becoming slower as more of the roll approaches closer to equilibrium.

The interesting generality about these moisture distributions is that the pictures look exactly the same whether one is wetting or drying, heating or cooling, or adding or removing solvents or odors. In addition, the pictures are valid from any starting point (moisture, temperature, odor, etc.) to any ending point. The only differences between all of these cases are the two labeled values on the ends of the scales. However, as seen in the time labeling, the time scale for these pictures varies enormously with the size or mass of the roll.

Additional applications of this temperature/moisture modeling are in stress/strain distributions. The drying roll will be tighter at the outer surfaces, implying baggy centers when unwinding, and will tend to be barrel shaped as opposed to cylindrical. The converse is true for a wetting/cooling roll. This model can also be coupled with wound-roll models or finite-element modeling to quantify stress/strain changes resulting from moisture nonuniformities. Finally, nonuniform distributions, coupled with creep and stress relaxation, could result in webs that are permanently nonuniform in camber.

Summary

We have seen just a few of the variety of responses that webs, rolls, and boxes have to changing moistures and temperatures. These include changes in size and shape, changes in tensions and strengths, as well as convertibility (calendering, corrugating, and printing). The diffusion model allows us to easily quantify these effects for a variety of converting and storage situations.

Also, we have seen that webs, rolls, and boxes will take on or give up moisture until reaching equilibrium. However, the time it takes to reach equilibrium varies considerably with size and shape, and to a smaller extent the material's diffusion constant, which can be easily obtained experimentally.

Once the constant is determined, we are free to model mathematically and predict moisture distributions for a wide variety of converting situations. These moisture/temperature distributions are very nonuniform throughout the wetting/drying/heating/cooling process. Knowing these resultants of physical law, we are better armed to diagnose and solve many humidity-dependent converting problems. TJ

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