Industrial Film Drying

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1. Introduction

Drying processes have been with us for a long time. During the Roman Empire, for example, the sun was used as a heat source in the convective drying of bricks, while during the industrial revolution, moist ceramic products were carried into and out of steam heated rooms by child labourers since it was deemed more cost effective to maintain a constant room temperature than to cool the room down in order to remove the products in a safe and healthy manner.

Drying is the removal of volatile substances (moisture) by heat from a mixture that yields a solid product.[1] The volatile substances or solvents used in the coating process can range from simple to handle materials such as water to active organic materials where the active ingredients may be polymers, binders, dyes, hardeners etc. The heat supplied during the drying process vaporizes the solvent and the solvent removal must be performed without adversely affecting the coating formulation or interfering with the physical uniformity of the coating. Note that although drying may involve solvent removal, chemical reactions may also aid solidification and it is possible also to accelerate solidification by using a catalyst or an outside energy source such as ultra-violet radiation. This is also called *curing* to differentiate it from drying although most coatings experience some form of reaction in the dryer.

From Keey[1] it may be observed that drying processes for web type substrates can be categorized into conduction, radiation, and convection style processes. Conduction processes are characterized by high levels of solid contact and the subsequent high material temperatures associated with this contact. Radiation style processes are generally limited to the drying of thin films as impinging radiation rarely penetrates beyond the immediate surface of a material. The most efficient and hence most frequently implemented drying method is based on convective drying. In this method a carrier gas is heated before being passed over or through the wet material. The convective method is the only method to simultaneously increase the heat transfer coefficient and the mass transfer coefficient.[2] This paper focuses on the convective style of drying. The following figure shows a schematic of two popular air convection drying processes. Figure 1(a) shows a typical air impingement drying process[3] where hot air jets pass over a coated film and transfer heat into the coating to vaporize the solvent. Figure 1(b) shows a schematic of a air floatation dryer,[4] which is used to support webs on an air cushion, thereby avoiding possible damage to the web substrate.

Although most coatings are applied in the fluid state, they are used in the dried state. Thus the drying process is as important as the coating process since it may either improve or degrade the properties of the coating. In practice, drying is also important since it may restrict the optimization of a coating process since in drying sensitive applications drying considerations may dominate over coating ones in limiting possible line speeds. Drying must be performed without adversely affecting the coating formulation or interfering with the physical uniformity of the coating.[5]

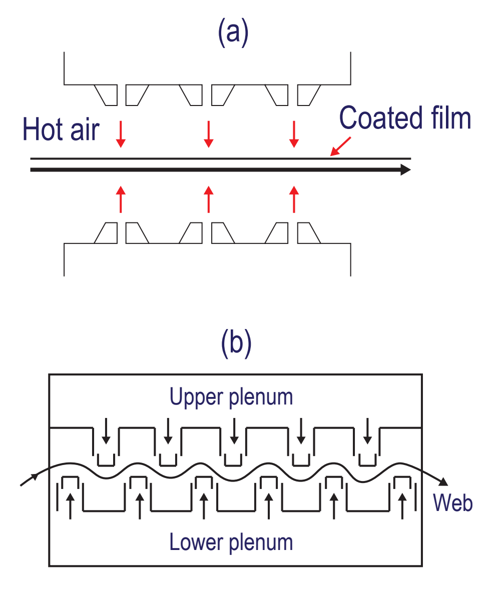


Figure 1 Schematic diagrams of (a) air impingement and (b) air floatation drying processes[3, 4]

2. The Drying Curve

In drying two processes must occur simultaneously:

(a) The transfer of energy (heat) from the surrounding environment to the product in order to evaporate the surface moisture.

(b) The transportation of solvent held within the product to its surface where it can be removed by process (a).

Drying can be

- Heat transfer limited—when there is an inability to supply enough energy to vaporize the solvent.
- Diffusion limited—limited by process (b)
- Mass transfer limited—environmental conditions prevent solvent vapor from being removed from the surface of the coating, e.g. humid conditions prevent sweating.

Convective heat transfer is the most important mechanism in industrial drying since it also enhances the transport of solvent vapor away from the coating surface, thereby providing environmentally favorable conditions for solvent removal from coating surfaces.

Air convection film drying processes often occur in three distinct regimes: the *rising rate*, *constant rate*, and *diffusion* modes, as described below. For aqueous systems most of the drying takes place in the constant rate mode of operation, however for solvent coatings, most of the drying takes place in the diffusion mode. Each of these is described briefly below.

2.1. The Rising Rate Mode

In this regime, the heat transferred into the coating mainly goes towards heating up the web rather than in drying (i.e. vaporizing the solvent from) the coating. The temperature generally increases linearly from the entrance temperature to the wet bulb temperature for single sided coating.[6]

2.2 The Constant Rate Mode

In this regime, drying is very different. Here the solvent concentration in the coating is large enough that there is little resistance to its motion through the coating to the surface where it can be evaporated. In this regime the rate of evaporation is limited by external mass transfer resistances, discussed below. Most of the heat input is available to evaporate the solvent which can move freely to the surface boundary layer where it can be carried away. In this region, increasing the heat input increases the drying rate and reducing it lowers the drying rate. Two important features of the constant rate period are that:

- The surface coating temperature is steady
- most of the heat load goes towards evaporating free solvent from the surface.

2.3. The Diffusion Mode

Sooner or later, the solvent(s) gradually become depleted by its/their evaporation from the coating. Generally the diffusivity of the solvent (i.e. its ability to diffuse through the coating) decreases rapidly as solvent concentration reduces so that less solvent than could be evaporated by the heat input to the coating can actually migrate to the surface of the coating. Ultimately, the internal resistance of solvent motion to the surface becomes dominant. This is the *falling rate* or *diffusion* regime since the rate of solvent evaporation continually falls from the value in the Constant Rate Regime and it follows that an increasing proportion of the heat transferred to the coating by convection goes to heat the web and coating up towards the dryer air temperature. In fact the transition point from the Constant Rate to the Diffusion regimes can be found simply by measuring when the web temperature begins to rise towards the drying air temperature.

The web surface temperature in each of the three periods is shown schematically in Figure 2.

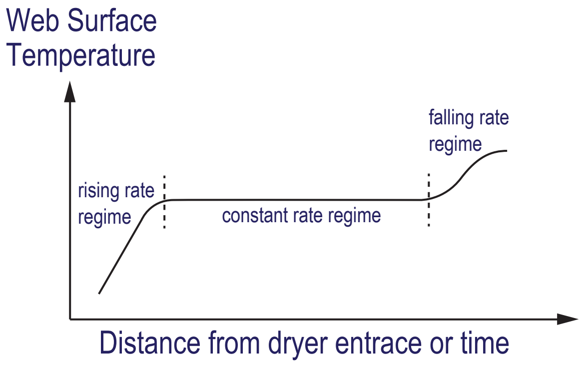


Figure 2 Web surface temperatures in the rising rate, constant rate, and diffusion regimes of film drying

The corresponding drying rates in each of these regimes are shown in Figure 3.

The efficiency of convection dryers is characterized by the heat transfer coefficient, h, which is defined by $Q=h\ A\ \Delta T$, where Q is the rate at which heat is transferred to the coating, A is the surface area of the coating, and ΔT is the temperature difference between the coated film and the drying air. This leads to the solvent evaporation rate=Q/λ, where λ is the latent heat of vaporization.

Since the ultimate goal in drying is to supply energy to the

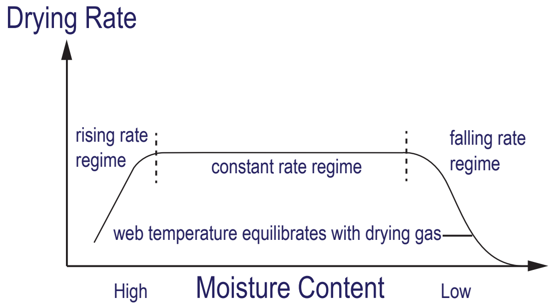


Figure 3 Drying rates in the rising rate, constant rate, and diffusion regimes of film drying

coating in order to evaporate the solvent, the efficiency of convection dryers is often characterized in terms of the heat transfer coefficient as it measures the ability of the dryer to supply energy for a given applied temperature difference and surface area between the drying air and the coating. The units of *h* are W/m^{2}K.

Since the heat transfer coefficient, *h*, is a key dryer design parameter, it provides a convenient measure of drying efficiency—as the heat transfer coefficient increases dryers become more effective: solvent is removed faster, thus shortening drying times and dryer lengths. The heat transfer coefficient is often a complicated function of the drying air velocity and the dryer geometry. Generally speaking, a larger relative air velocity at the surface of the web leads to a greater heat transfer coefficient and hence drying rate. However it is also important to be aware that using air velocities that are too high can lead to defects such as mottle in photographic coatings and are particularly liable to cause unacceptable defects for low viscosity coatings.[5]

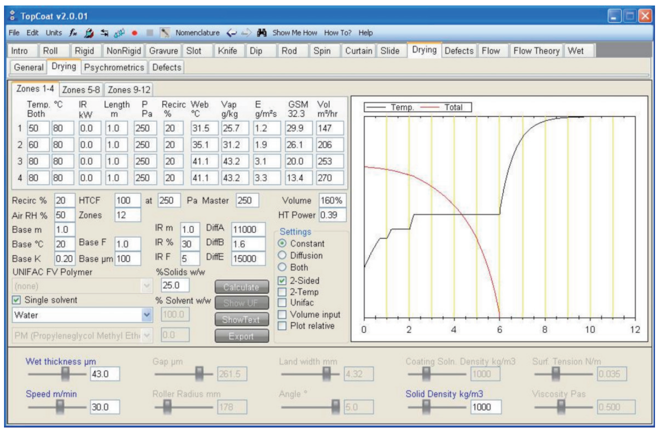
3. Modeling Film Drying

Several models of film drying have been presented, which have modeled drying in the Constant Rate and Falling Rate regimes. The models of Gutoff [6, 7] are particularly useful. There is insufficient space to describe these in great detail so we focus on the use of such models instead.

3.1 Modeling Constant Rate Drying

In the Constant Rate regime we assume that all the heat supplied to the coating is balanced by evaporative loss into the air. The key requirement of the models is to find the heat transfer coefficient, *h*, and the wet bulb temperature, T_W. The models of Gutoff [6, 7] have been implemented in the following illustrative results.

It is possible to calibrate the heat transfer coefficient, *h*, on the basis of a simple experiment on the production line. Imagine that we have a complex 12 zone oven and are drying a water-based product. You enter the things you know (% solids, web speed, wet thickness, zone temperatures) into the modeler and you make an estimate guess of heat transfer coefficient as 100 W/m^{2}K. You get the prediction in Figure 4.

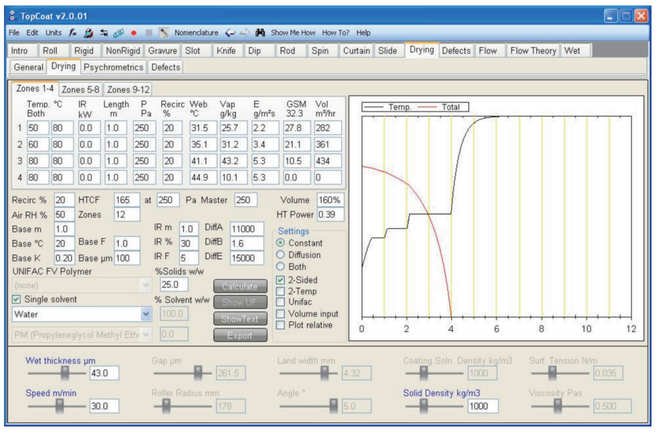


	Temp. °C Both		IR kW	Length m	P Pa	Recirc %	Web °C	Vap g/kg	E g/m²s	GSM 32.3	Vol m³/hr
1	50	80	0.0	1.0	250	20	31.5	25.7	1.2	29.9	147
2	60	80	0.0	1.0	250	20	35.1	31.2	1.9	26.1	206
3	80	80	0.0	1.0	250	20	41.1	43.2	3.1	20.0	253
4	80	80	0.0	1.0	250	20	41.1	43.2	3.3	13.4	270

Recirc % 20 HTCF 100 at 250 Pa Master 250 Volume 160%
Air RH % 50 Zones 12 HT Power 0.39
Base m 1.0 IR m 1.0 DiffA 11000
Base °C 20 Base F 1.0 IR % 30 DiffB 1.6
Base K 0.20 Base μm 100 IR F 5 DiffE 15000
UNIFAC FV Polymer (none)
%Solids w/w 25.0
☑ Single solvent
% Solvent w/w 100.0
Water
PM (Propyleneglycol Methyl Eth 0.0
Settings
● Constant
○ Diffusion
○ Both
☑ 2-Sided
☐ 2-Temp
☐ Unifac
☐ Volume input
☐ Plot relative
Wet thickness μm 43.0
Speed m/min 30.0
Gap μm 261.5
Roller Radius mm 178
Land width mm 4.32
Angle ° 5.0
Coating Soln. Density kg/m3 1000
Solid Density kg/m3 1000
Surf. Tension N/m 0.035
Viscosity Pas 0.500

Figure 4 Initial constant rate regime drying prediction

The modeler predicts that drying will be complete just at the end of zone 6. Suppose you find that the temperature rises suddenly just at the end of zone 4. Clearly the modeler's predictions are wrong. But we can easily fix this by increasing the heat transfer coefficient—the larger the value, the faster the heat gets transferred into the coating so the faster it dries. By trial and error, you find that a value of 165 W/m^{2}K gives you the graph in Figure 5.

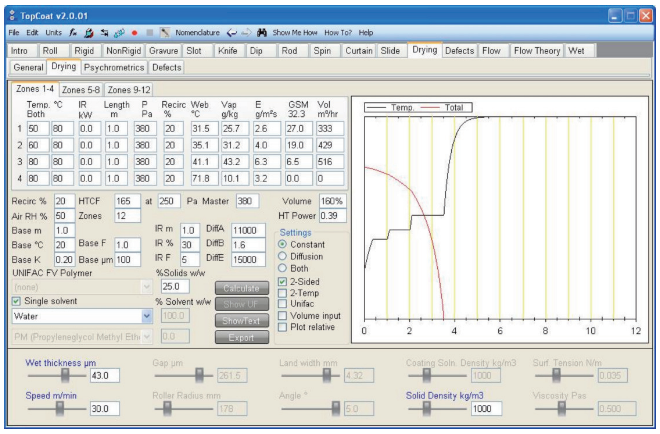


	Temp. °C Both		IR kW	Length m	P Pa	Recirc %	Web °C	Vap g/kg	E g/m²s	GSM 32.3	Vol m³/hr
1	50	80	0.0	1.0	250	20	31.5	25.7	2.2	27.8	282
2	60	80	0.0	1.0	250	20	35.1	31.2	3.4	21.1	361
3	80	80	0.0	1.0	250	20	41.1	43.2	5.3	10.5	434
4	80	80	0.0	1.0	250	20	44.9	10.1	5.3	0.0	0

Recirc % 20 HTCF 165 at 250 Pa Master 250 Volume 160%
Air RH % 50 Zones 12 HT Power 0.39
Base m 1.0 IR m 1.0 DiffA 11000
Base °C 20 Base F 1.0 IR % 30 DiffB 1.6
Base K 0.20 Base μm 100 IR F 5 DiffE 15000
UNIFAC FV Polymer (none)
%Solids w/w 25.0
☑ Single solvent
% Solvent w/w 100.0
Water
PM (Propyleneglycol Methyl Eth 0.0
Settings
● Constant
○ Diffusion
○ Both
☑ 2-Sided
☐ 2-Temp
☐ Unifac
☐ Volume input
☐ Plot relative
Wet thickness μm 43.0
Speed m/min 30.0
Gap μm 261.5
Roller Radius mm 178
Land width mm 4.32
Angle ° 5.0
Coating Soln. Density kg/m3 1000
Solid Density kg/m3 1000
Surf. Tension N/m 0.035
Viscosity Pas 0.500

Figure 5 Constant rate regime drying prediction with calibrate heat transfer coefficient

Now the sudden temperature rise is exactly where you found it—you now know that the heat transfer coefficient is 165 W/m^{2}K. This is the intrinsic value of the heat transfer coefficient for your machine and you can now rely on it for all your simulations. For forced convection dryers, measurements indicate that the heat transfer coefficient, h, depends on the plenum pressure, Δp, according to $h=h_0\ (\Delta p/\Delta p_0)^{0.39}$, [6] where h_0 is the reference heat transfer coefficient at the reference plenum pressure Δp_0. If we decide to change plenum pressure from 250Pa to 380Pa then the prediction is (and the reality will be) that the coating will dry half way through zone 3, as shown in Figure 6.



	Temp. °C Both		IR kW	Length m	P Pa	Recirc %	Web °C	Vap g/kg	E $\mathrm{g/m^2s}$	GSM 32.3	Vol $\mathrm{m^3/hr}$
1	50	80	0.0	1.0	380	20	31.5	25.7	2.6	27.0	333
2	60	80	0.0	1.0	380	20	35.1	31.2	4.0	19.0	429
3	80	80	0.0	1.0	380	20	41.1	43.2	6.3	6.5	516
4	80	80	0.0	1.0	380	20	71.8	10.1	3.2	0.0	0

Recirc % 20 HTCF 165 at 250 Pa Master 380 Volume 160%
Air RH % 50 Zones 12 HT Power 0.39
Base m 1.0 IR m 1.0 DiffA 11000
Base °C 20 Base F 1.0 IR % 30 DiffB 1.6
Base K 0.20 Base µm 100 IR F 5 DiffE 15000
UNIFAC FV Polymer (none) %Solids w/w 25.0
☑ Single solvent Water % Solvent w/w 100.0
PM (Propyleneglycol Methyl Eth 0.0
Settings ● Constant ○ Diffusion ○ Both
☑ 2-Sided ☐ 2-Temp ☐ Unifac ☐ Volume input ☐ Plot relative
Wet thickness µm 43.0 Gap µm 261.5 Land width mm 4.32 Coating Soln. Density kg/m3 1000 Surf. Tension N/m 0.035
Speed m/min 30.0 Roller Radius mm 178 Angle ° 5.0 Solid Density kg/m3 1000 Viscosity Pas 0.500

Figure 6 Increased heat transfer coefficient leads to quicker drying

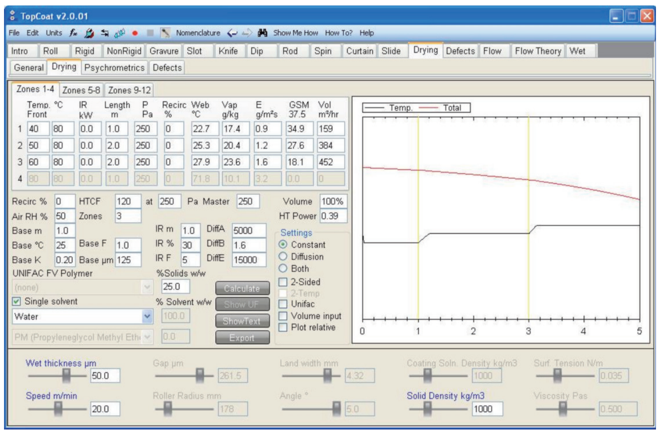
3.2 Modeling Diffusion Mode Drying

In solvent systems, most drying is in the Diffusion mode and the drying rate is limited by the ability of solvent to diffuse to the surface so that the rate of solvent evaporation from the coating is the rate of diffusion of solvent to the surface. In Gutoff's models of diffusion mode, solvent diffuses through the coating according to Fick's law (analogous to Fourier's law of heat conduction) where the solvent diffusivity, D, which takes the form:

$$D = A\ \exp(-B/(1+2\ h_{solv}/h_{solids}))\ \exp(-E/RT)$$

where A and B are constants. B models the reduction in diffusivity as the solvent concentration decreases, h_{solv} is the thickness of solvent in the coating and h_{solids} is the thickness of solids in the coating. E is an activation energy for diffusion where typically 12,000 J/mol $\leq E \leq$ 21,000 J/mol.

As an illustrative example of the effect of the diffusion mode of solvent evaporation, consider the following case of an aqueous coating with 25% solids by weight, with single sided drying in 3 zones with temperatures of 40°C, 50°C, and 60°C, and a heat transfer coefficient h=100 W/m^{2}K in each zone. If we first assume that drying is modeled in the Constant Rate mode we get the result in Figure 7, where the black line indicates web temperature and the red line indicates the solvent concentration during drying. In this case we get three constant product temperatures in each zone (Fig. 7).



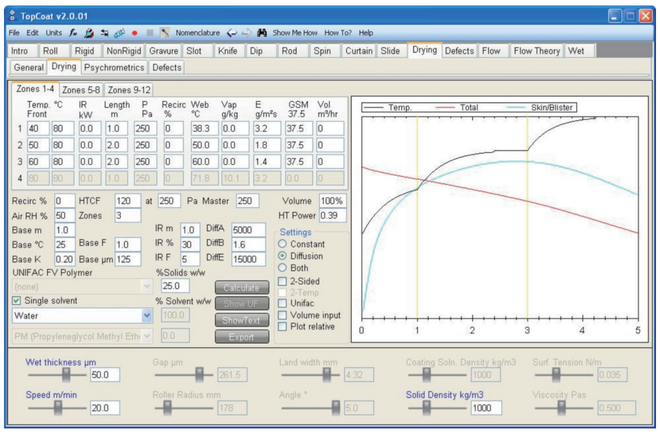
	Temp. °C Front		IR kW	Length m	P Pa	Recirc %	Web °C	Vap g/kg	E $\mathrm{g/m^2s}$	GSM 37.5	Vol $\mathrm{m^3/hr}$
1	40	80	0.0	1.0	250	0	22.7	17.4	0.9	34.9	159
2	50	80	0.0	2.0	250	0	25.3	20.4	1.2	27.6	384
3	60	80	0.0	2.0	250	0	27.9	23.6	1.6	18.1	452
4	80	80	0.0	1.0	250	0	71.8	10.1	3.2	0.0	0

Recirc % 0 HTCF 120 at 250 Pa Master 250 Volume 100%
Air RH % 50 Zones 3 HT Power 0.39
Base m 1.0 IR m 1.0 DiffA 5000
Base °C 25 Base F 1.0 IR % 30 DiffB 1.6
Base K 0.20 Base µm 125 IR F 5 DiffE 15000
UNIFAC FV Polymer (none) %Solids w/w 25.0
☑ Single solvent Water % Solvent w/w 100.0
PM (Propyleneglycol Methyl Eth 0.0
Settings ● Constant ○ Diffusion ○ Both
☐ 2-Sided ☐ 2-Temp ☐ Unifac ☐ Volume input ☐ Plot relative
Wet thickness µm 50.0 Gap µm 261.5 Land width mm 4.32 Coating Soln. Density kg/m3 1000 Surf. Tension N/m 0.035
Speed m/min 20.0 Roller Radius mm 178 Angle ° 5.0 Solid Density kg/m3 1000 Viscosity Pas 0.500

Figure 7 Effect of diffusion drying mode—initial constant rate predictions

Now suppose that we have the same conditions but now analyze the drying in diffusion mode with the diffusivity parameters A=5,000, B=1.6, and E=15,000. The Figure 8 shows that there is a gradual increase in web temperature (the black line) as the coating passes through the dryer zones.

Now, in practice the actual evaporation rate in the dryer is the minimum of the evaporation rates under constant mode



	Temp. °C Front		IR kW	Length m	P Pa	Recirc %	Web °C	Vap g/kg	E $\mathrm{g/m^2s}$	GSM 37.5	Vol $\mathrm{m^3/hr}$
1	40	80	0.0	1.0	250	0	38.3	0.0	3.2	37.5	0
2	50	80	0.0	2.0	250	0	50.0	0.0	1.8	37.5	0
3	60	80	0.0	2.0	250	0	60.0	0.0	1.4	37.5	0
4	80	80	0.0	1.0	250	0	71.8	10.1	3.2	0.0	0

Recirc % 0 HTCF 120 at 250 Pa Master 250 Volume 100%
Air RH % 50 Zones 3 HT Power 0.39
Base m 1.0 IR m 1.0 DiffA 5000
Base °C 25 Base F 1.0 IR % 30 DiffB 1.6
Base K 0.20 Base µm 125 IR F 5 DiffE 15000
UNIFAC FV Polymer (none) %Solids w/w 25.0
☑ Single solvent Water % Solvent w/w 100.0
PM (Propyleneglycol Methyl Eth 0.0
Settings ○ Constant ● Diffusion ○ Both
☐ 2-Sided ☐ 2-Temp ☐ Unifac ☐ Volume input ☐ Plot relative
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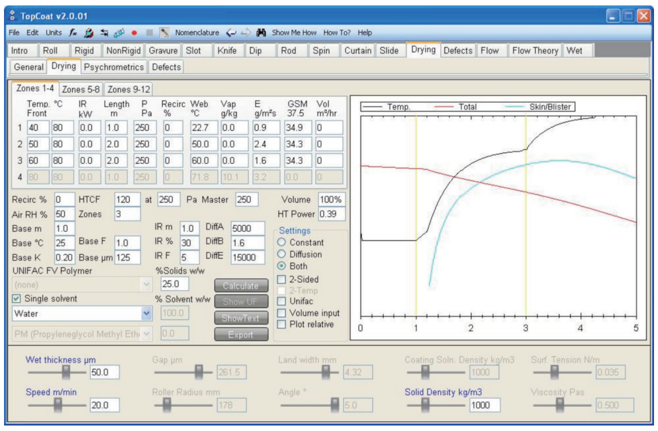
Speed m/min 20.0 Roller Radius mm 178 Angle ° 5.0 Solid Density kg/m3 1000 Viscosity Pas 0.500

Figure 8 Diffusion drying mode predictions

drying conditions (heat transfer limitation on drying rate) and diffusion mode conditions (mass transfer limitation on drying rate). The Figure 9 shows the actual drying behavior that would be expected. This shows constant rate drying for the first dryer zone (indicated by the constant web temperature—the black line) before the diffusion mode starts to become more important, as indicated by the non-uniform web temperatures in the other two zones.



	Temp. °C Front		IR kW	Length m	P Pa	Recirc %	Web °C	Vap g/kg	E g/m²s	GSM 37.5	Vol m³/hr
1	40	80	0.0	1.0	250	0	22.7	0.0	0.9	34.9	0
2	50	80	0.0	2.0	250	0	50.0	0.0	2.4	34.3	0
3	60	80	0.0	2.0	250	0	60.0	0.0	1.6	34.3	0
4	80	80	0.0	1.0	250	0	71.8	10.1	3.2	0.0	0

Recirc % 0
HTCF 120 at 250 Pa Master 250
Volume 100%
Air RH % 50
Zones 3
HT Power 0.39
Base m 1.0
IR m 1.0
DiffA 5000
Base °C 25
Base F 1.0
IR % 30
DiffB 1.6
Base K 0.20
Base μm 125
IR F 5
DiffE 15000
UNIFAC FV Polymer (none)
%Solids w/w 25.0
☑ Single solvent
Water
% Solvent w/w 100.0
PM (Propyleneglycol Methyl Eth 0.0
Settings
○ Constant
○ Diffusion
● Both
☐ 2-Sided
☐ 2-Temp
☐ Unifac
☐ Volume input
☐ Plot relative
Wet thickness μm 50.0
Gap μm 261.5
Land width mm 4.32
Coating Soln. Density kg/m3 1000
Surf. Tension N/m 0.035
Speed m/min 20.0
Roller Radius mm 178
Angle ° 5.0
Solid Density kg/m3 1000
Viscosity Pas 0.500

Figure 9 Actual drying predictions: solvent evaporation rate is minimum of constant and diffusion mode predictions

Although not discussed here due to space restrictions, other important features of film drying such as the use of mixed solvents to alter vapor pressures significantly or the use of infrared radiation to provide thermal energy to evaporate solvent and to raise the web temperature to promote some form of reaction, can also be analyzed in such drying models.

4. Conclusions

Film drying plays a vital role in industrial coating processes and can have the dominant influence on production rate and product quality. Drying models can provide valuable insight into drying processes and can be used to minimize energy consumption and avoid defects during industrial drying operations.

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