Curtain Coating Edge Control

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Precision curtain coating is heralded as the fastest of the thin liquid film coating methods that are capable of achieving accurate and extremely uniform coatings. In addition to these advantages, curtain coating has multilayer capability and a host of process benefits associated with its large applicator-to-substrate clearance. It is not surprising then that this coating method is being successfully adopted by technology-aggressive companies in a number of industries.

The practice of curtain coating superficially appears to be quite simple: form a liquid layer of the desired coating width and cause this layer to fall a sufficient distance onto the moving substrate. Indeed, this is the simple scheme in which crude curtain coatings of various 3-D objects from confections to electrical components conveyed on belts have been achieved for at least a century. However, commercially-viable precision curtain coating of webs is much more demanding. This discussion considers one of curtain coating's most important and challenging "reduction to practice" aspects - controlling the edges of the falling curtain. First, some of the basic curtain coating process characteristics will be briefly reviewed in order to appreciate the method's more important capabilities, then the technology applied to control curtain edges will be described.

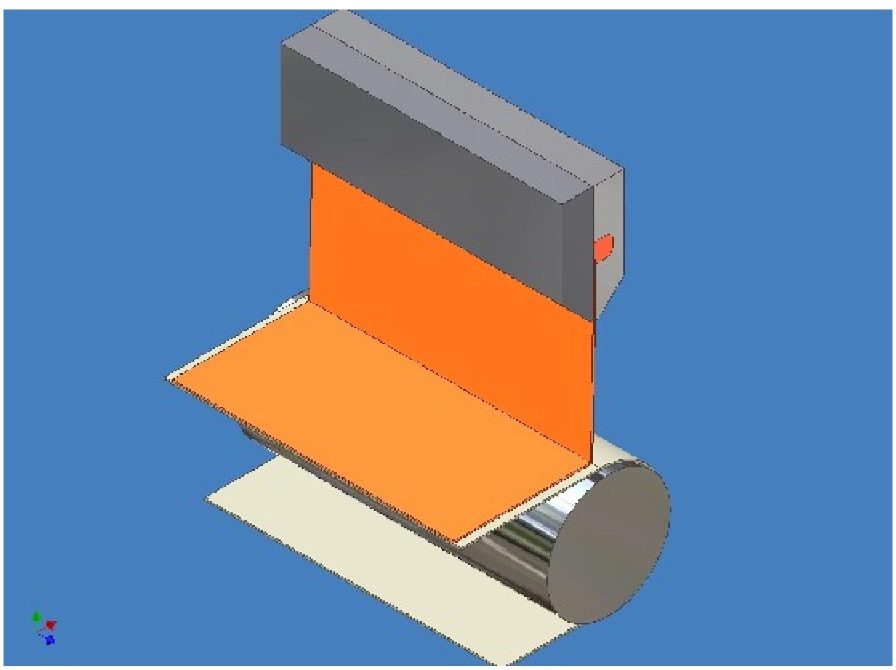

Figure 1. Curtain coating with a slot-curtain die
(Cutaway view displays slot die with single distribution manifold.)

Basic Characteristics
Curtain coating is a pre-metered method in that the coating liquid flow metered to the curtain applicator is directly and completely transferred to the moving substrate with the important result being that the coated thickness is simply determined by liquid metering rate and substrate speed. Curtain coating is also a die-coating method in which coating liquid flow pumped to the applicator via a pipe is transformed in the applicator's internal manifold into a thin flow of desired coating width prior to its transfer to the substrate. If the manifold is optimally designed and precisely fabricated, excellent cross-direction flow uniformity is achieved. Furthermore, if liquid metered rate and substrate speed are accurate, accurate coating thickness results. Two formats of curtain coater dies are slot-curtain and slide-curtain as shown in Figures 1 and 2, respectively. The slide-curtain die is distinctive in that multiple manifold plates can be assembled for multilayer applications.

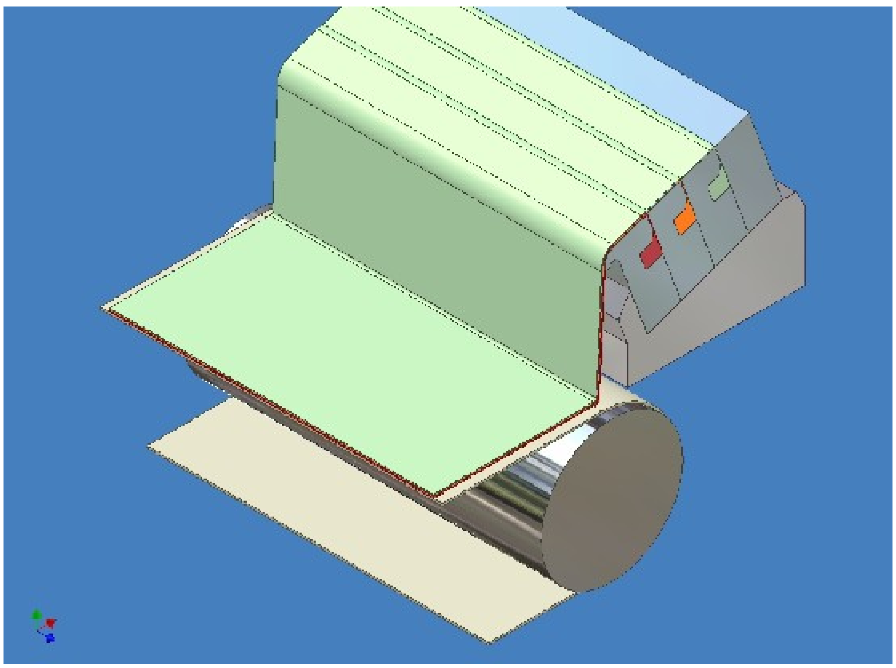

Figure 2. Curtain coating with a multilayer slide-curtain die
(Cutaway view displays slide format die with three manifold plates.)

Hydrodynamic Assist – Maximum Speed
Curtain coating's readily identifiable feature is its sheet of falling liquid, or curtain, in which a thin film flow is transferred from the applicator die to the web. Gravitational acceleration acting over this curtain height imparts relatively high momentum to the liquid as it impinges on the moving substrate. The correspondingly increased liquid stagnation pressure in the vicinity of the dynamic wetting line is able to exclude web-entrained air and thereby allow rapid liquid wetting in much the same manner as a squeegee's pressure spike at its tip excludes water on a glass surface. This mechanism is frequently referred to as "hydrodynamic assist"[1] and its resultant commercial benefit is that the method is able to coat at speeds of 2000 – to – 3000 fpm on smooth substrates and even 4000 – to – 5000 fpm and higher on certain rough surfaces. It should be noted that these maximum coating

speeds are very much dependent upon optimization of the coating liquid rheology, flow rate and curtain height.

Coating Window

Air entrainment onset is an example of a hydrodynamic instability that limits the parametric operational space of the coating method. Curtain coating, as with other coating methods, is subject to various hydrodynamic instabilities and further limited by practical considerations, the composite of these limits defining the method’s coating window. For instance, another important curtain limit is that a minimum flow rate in the range of 0.5-1.0 cc/sec per cm-width is required for sufficient curtain momentum to overpower surface tension and thereby maintain a stable curtain flow. This minimum flow rate is often the crucial hurdle for applying curtain coating because it requires fast coating when the applied thickness is thin.

Other Benefits

In applications within its coating window, curtain coating has many compelling process and product advantages beyond its high speed capability and precision laydown. The robustness of the curtain flow near the impingement location allows coating over uneven substrates including many splice geometries as well as coating beyond the edges of the substrate, i.e., overboard coating. Further, the substrate itself experiences minimal stress in the transfer zone which allows use of weak and vulnerable substrates. The large clearance between the curtain application die and substrate corresponding to the curtain height allows a relaxed geometric precision between applicator and substrate compared to the exacting clearance precision required with nip, gap and bead coaters. This large clearance also assures that no particles or bubbles can become entrapped and otherwise cause lines and streaks with tight clearance. Finally, curtain coating is a vertical projection coating and for customary web applications, the resultant coating uniformity is independent of web thickness variation and surface features.

Multilayer Capability

For sophisticated product and/or process applications, the most important capability of curtain coating is often its simultaneous multilayer capability. Slide-curtain format especially has practically unlimited capability for uniformly assembling many precise thin layers into a film flow ensemble on its slide surface for subsequent curtain transfer to the substrate. Because the flow is absolutely laminar throughout the coating process, these multilayer coatings are realized in high precision in the final product giving the inventive product scientist considerable flexibility for optimizing product characteristics and cost.

Reduction to Practice

The previous discussion focused on the general characteristics of the curtain coating method; however, there are a number of specific practical considerations that must be addressed with coating die design, attachments or devices when applying the method to an actual commercial production. Many of these devices are shown in the equipped slot-curtain coating station photo in Figure 3. For instance, a curtain liquid catch basin and a vacuum air baffle are displayed, in this case as an integrated unit. With the coating die positioned in a standby position over the catch basin as shown, the curtain flow can be established and thoroughly inspected prior to initiating coating. Upon repositioning the die over the web for coating, the vacuum baffle suppresses the boundary layer of web-entrained air which would otherwise be disruptive to coating at high speed. Additionally, a curtain deflection plate is present that can quickly and briefly interrupt the coating. Shielding of the curtain against spurious room air currents is also needed in many cases, but such a shield is not shown in this photo. Finally, curtain edge control devices are clearly displayed attached beneath and to each side of the die. As previously mentioned curtain edge control is one of the most important reduction-to-practice technologies. It is the focus of the remainder of this discussion.

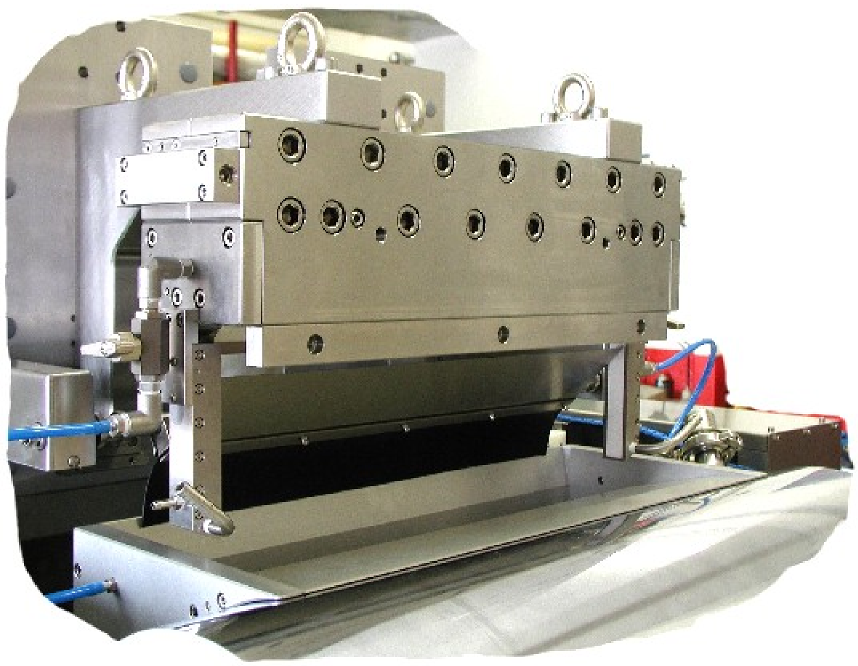

Figure 3. Slot-curtain die equipped for commercial production

Curtain Edge Control

The simplest option, of course, is to do nothing, i.e., to allow the hydrodynamics of each unimpeded curtain edge region to determine its own flow configuration. Each curtain edge will angle inwardly, driven by surface tension that contracts both curtain free surfaces toward the curtain interior. The angled-in edges become greatly thickened with high local flow rate relative to the curtain interior. This “free edge” coating mode is commercially used in special cases when coating overboard, i.e., wider than the web. Because the excess liquid edge flow is typically so great, the nominal supply width of the curtain must exceed the web width considerably in order to coat only the more uniform interior curtain onto the substrate. Economic considerations then establish the beneficial “free edge” applications as those in which the collected excess edge liquid can be dependably recirculated back to main coating delivery or as those in which the excess flow can be discarded.

As one may suspect, the situations that require active edge control are the majority of industrial curtain coating applications. These include all cases of inboard coating, i.e., coating within the width of the web, and also overboard cases in which the excess width flow must be minimized and/or carefully handled for minimum liquid physical deterioration. In addition, low flow rate applications require edge control to minimize the exposed curtain edge and thus avoid potential curtain rupture and disintegration.

Simple Edge Guides

Active edge control is achieved through the use of edge guides of various designs all of which accomplish the basic task of preventing curtain edge contraction. Ideal control would achieve this basic task while allowing edge region flow fields that perfectly match the curtain interior thus incurring no cross direction variations of velocity or curtain thickness. Unfortunately, ideal control is not achieved because practical edge guide systems utilize solid members as supports against curtain contraction. The less-than-ideal consequences of this fact all stem from the solid surface no-slip boundary condition. The challenge is then to achieve satisfactory edge control as close to the ideal result as necessary for the application. Depending on the application specifics, achieving this can range from being reasonably easy to exceedingly difficult.

The most commonly used edge guides have simple shapes such as cylindrical rods, wires or flat plates made of wettable materials. These typically have smooth and continuous surfaces from the start of the curtain at the curtain die lip all the way to nearly touching the web surface. These guides are obviously inexpensive to fabricate and are easy to set up and use. They can often be configured to be adjustable for different coating heights and coating widths. Cylindrical guides are the easiest to implement with rod-like guides of larger diameter being more robust for coating edge adherence, but causing more variation in curtain edge thickness and flow. Smaller diameter, wire-like guides give more uniform curtains, but carry an increased risk of curtain edge detachment that would result in a contracted edge. Not surprisingly, these wire-like guides also tend to require operator intervention to establish curtain attachment for low and even moderate flow rate applications.

Simple flat surface guides are even more robust for curtain attachment than rod guides and, in fact, tend to promote establishment of guided curtain edges automatically at lower flow rates. Flat surface guides are also preferable for the slide format of curtain coating. In this format, the liquid film flowing down over the end of the slide has an asymmetric flow field and consequently the start of the ensuing curtain usually deflects underneath the die lip. The flat surface guide allows this deflection in the curtain edge regions, whereas a cylindrical guide will cause some distortion of the curtain near the edge presuming that the curtain edge remains attached to the guide. The drawback with flat guides is that they tend to produce nonuniformity of the edge coating and in some extreme cases, cause a thin region just inboard of the edge that can be vulnerable to rupture.

The most important deficiency of these simple edge guides for high-speed coating is the guide’s retarding effect on the edge regions of the falling curtain. Recall that the curtain liquid accelerates from gravity and this acceleration in the interior of the curtain is approximately that of free fall. However, this is not the case for the liquid within the retarding influence of the no-slip condition at the guide’s surface. Here, a boundary layer exists and grows in thickness (curtain width) down the guide surface. At the impingement location on the web, the impinging curtain near the edge guide has a comparable deficit in impinging momentum. As a consequence, air entrainment will occur at the coating edge region at lower speeds than would occur in the interior of the coating thereby limiting the maximum attainable coating speed.

Edge Guides with Lubrication Layer

For high speed curtain coating a more capable edge guide system is provided via inclusion of a lubrication layer, usually a thin layer of water or low viscosity compatible solvent, between the edge guide and the higher viscosity curtain liquid. Ideally, most of the large velocity gradient is contained within the thin lubricating layer thus allowing the curtain edge to accelerate without severe restraint. In the best cases, the air entrainment onset speed at the curtain edges is only slightly less than that which would occur in the curtain interior. Encouragingly, additional benefits are realized as a result of the edge flow. For example, the presence of this interlayer on the solid guide promotes wetting attachment by the curtain edge. Additionally, since the presence of the edge layer also allows a higher momentum curtain edge liquid, automatic start of the guided edges occurs at lower curtain flow rates. Finally, the surface of the edge guide is continually flushed by water or solvent and this tends to protect the surface from contamination or even build-up from coating liquid ingredients.

This lubricating edge flow technology is greatly beneficial, especially for the more challenging applications of curtain coating. However, the implementation of curtain edge guide systems employing lubricating edge flow is often challenging. For instance, introducing the edge flow without causing a disturbance in the curtain can be difficult especially considering the small characteristic dimensions of the die lip region and the extreme sensitivity of the thin film free surface flow to disturbance. The resultant composite flow down the guide surface is complex and can be subject to secondary flow phenomena, especially with surfactants present. Further, disturbances here can lead to coating defects inboard that result from setting up stationary disturbance waves in the curtain. Finally, another considerable technical and design challenge pertains to the ultimate disposition of this excess edge liquid. Usually this excess flow is suctioned from the curtain edge region just above the impingement location on the substrate surface. The design of the extraction port geometry is challenging because close proximity to the substrate is desired with a minimum of retarding effect on the non-extracted coating edge.

Example

Now that the benefits of the edge-flow type of curtain-edge guiding systems and the challenges of implementing this technology have been described, it is instructive to consider an example of a capable edge guide system with this technology. Figure 4 displays the photo of a proprietary edge guide system by TSE Troller Schweizer Engineering AG. In this case, the edging flow is introduced onto the flat surface of an edge guide via permeation through a porous ceramic plate from a pressurized liquid reservoir behind this plate. This arrangement introduces the low viscosity liquid onto the surface of the edge guide in a very smooth and controlled way. The edge layer smoothly flows down the guide surface with increasing layer thickness as the adjacent curtain liquid increases in velocity. Just above the web surface, the edge flow is suctioned away via an extraction slot built into the lower edge of the guide structure. With appropriate attachment to the die and plumbing, this edge guide is easily set up and the edge flow system is easily controlled via an inlet flow-control valve and the suction vacuum level. The drawback of the system is that although the system is robust for set-up, lubrication layer control, establishing curtain attachment, and auto guided starts, the guide can compromise the edge uniformity of low viscosity curtains.

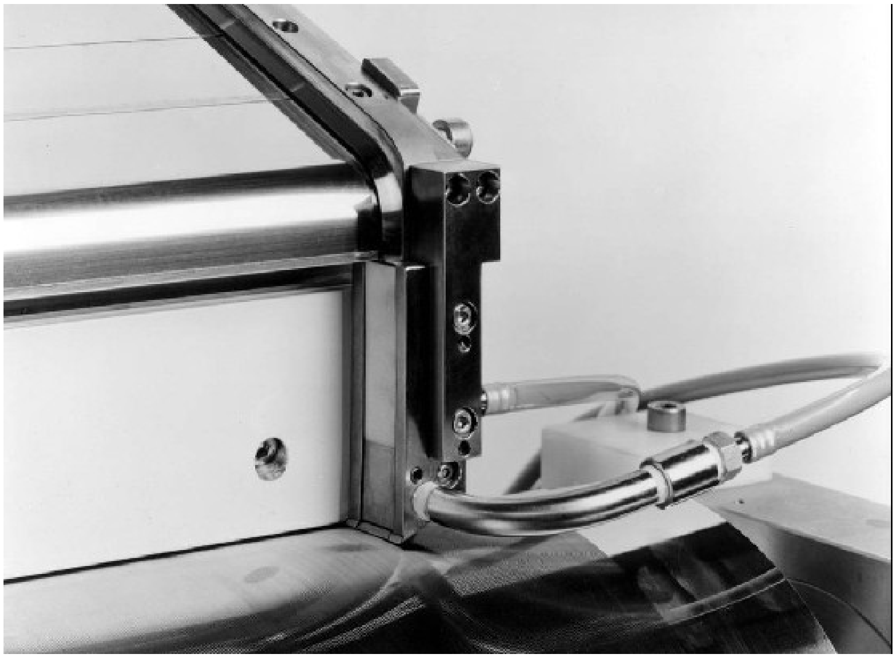

Figure 4. TSE proprietary curtain edge guide system utilizing lubricating edge flow

Concluding Remarks

We have considered the curtain coating method, arguably the most capable of all the thin liquid film coating techniques. This method superficially appears simple, but practical aspects of applying the method are challenging. One of the most important of these aspects is the control of curtain edges which is essential in most curtain coating applications. Although not ideal, current edge guide technology, especially with lubricating edge flow, can control curtain edges with satisfactory flow characteristics in order to achieve a successful coating application in most cases albeit with increased design and operational complexities.

Reference:
1. Blake, et al, "Hydrodynamic Assist of Dynamic Wetting", AIChE J., V40, n2, 1994, pp.229-242.

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