CURTAIN COATING TECHNOLOGY

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INTRODUCTION

Economies of scale occur when a coated product is manufactured wide, fast and in one pass. Substrates can be manufactured wide and multilayer coating can provided added functionality, but how do you make a coated product faster. The first hurdle is curing (typically the bottleneck of the process). Once you properly size the oven for the application, you need to consider the fluid flow dynamics within the coating system. As the fluid is coated faster and faster, the effects of film split, turbulence and air reek havoc on the coated product and leave a trail of coating defects in the path.

Some coating techniques, however, actually perform better under high speed scenarios. One coating technique that should be considered for high speed applications is curtain coating. Imagine taking a slot die, coating in close proximity, and raising it up in the air to allow the fluid to drop down onto the substrate. This rain shower of liquid can have some advantages, but the advantages can only be realized with higher speeds. Why is that?

The fundamental equation behind the success of a falling curtain of fluid is the dimensionless Weber number-

$$\mathbf{We = \rho Q V / \sigma}$$

We = Weber number

ρ = density

Q = volumetric flow rate

V = impingement velocity

σ = surface tension

The Weber number provides us with the height of the curtain that allows for success. A good starting point is to look for the coating conditions that allow for $We > 2$. This is considered a stability region for the fluid. As $We < 2$, the constant flow of fluid breaks up and disintegrates into droplets instead of a sheet. While it is possible to maintain a curtain under many conditions, this gets us started.

Let's break it down. The Weber number is a ratio of the density, volumetric flow rate and fluid flow rate to surface tension forces. The fluid flow rate is also termed the impingement speed of the fluid - the higher the fluid falls the faster the speed. Line speed and pump work together to develop the coat weight of the product - for a set pump speed (volumetric flow rate), a higher line speed creates a lighter coat weight product. Now, if the fluid is dropped at a high throughput, but the line speed is slow, the coat weight will be high. So if your product requires a light coat weight, you will need to adjust height or flow rate to meet our stability criteria ($We > 2$). Since density and surface tension are relatively set, volumetric flow rate or height of the curtain are the only variables that can be shifted to land the product in a reasonable coating window.

Now, there are many variables that affect the flow and stability of curtain coating a fluid, but the Weber number stability criteria is a good starting point. The coating window itself is a function of the Reynolds number and the web speed to impingement velocity-

$Re = \rho Q/\mu$

Re = Reynolds number

ρ = density

Q = volumetric flow rate

μ = viscosity

U/V

U = web speed

V = impingement velocity

If the U/V ratio is too low, disintegration of the curtain occurs (similar to a low Weber number). At a balance point between Re and U/V, the coating is stable. As U/V increases, we begin to see air be an issue because the line speed overcomes the fluid velocity.

With this handful of variables and simple equations, you can evaluate curtain coating to improve your speed and move into a new realm of coating capability.

ADVANTAGES

At its basic level, curtain coating differs from proximity coating only the distance from the substrate. Besides this distance, many of the basic physical characteristics apply. Both systems develop a meniscus, dynamic wetting line and free surface. Both require precision machined edges and faces of the slot die to perform well. Both techniques can coat as multi-layer systems to produce coated systems with multiple functional layers. Also, both proximity coating and curtain coating technique need proper development of the fluid substrate interface to reduce air entrainment.

For proximity coating, a slot die is positioned the wet coating thickness away from the substrate. For curtain coating, the gap is much larger and determined not only by the wet coating thickness, but the web speed, impingement velocity, density and viscosity of the fluid being coated. This extra distance allows for coating irregular surfaces that would not normally be proximity coated. Examples include nonwoven substrates and glass panels.

Hydrodynamic assist is a function of distance from the slot die exit to the substrate, gravitational orientation compared to direction of fluid flow, and momentum of the fluid at the impact with the substrate.

Whether coating a continuous sheet or a discrete part, curtain coating provides a speed advantage that may be a limitation for proximity coating. In the early years of curtain coating, the liquid was released in a fluid film over parts and pieces and any excess liquid was collected and recirculated for continuous use. This is still an option, but if solvents are released during operation, a recovery system should measure the density and viscosity to replace the proper amount of solvent during the recovery process.

So how fast do you need to run the line, how high does the slot die need to be from the substrate and how much fluid needs to be pumped through the slot die to form a stable curtain? Every fluid and substrate interaction is different because of rheology and interfacial dynamics, but a good rule of thumb is that the flow rate of 0.5 cm^3/s at a height of 250 mm (9.84 inches) works well for most applications.

Similar to proximity coating with slot die technology, finite element analysis can be completed to verify that the internal flow is appropriate for a stable cross-web caliper liquid curtain. This information can verify that the liquid curtain will be robust enough to develop flow that has the same velocity, same pressure drop and same volumetric flow at exit.

DISADVANTAGES

The lengthy fluid bridge that is created in a curtain coating technique is fundamentally different than the short fluid bridge created in proximity coating with slot die technology. Instead of needing to cover the wet coating thickness through the formation of a meniscus at the substrate and slot die interface, curtains that are formed need to be self-supported until they reach the point of substrate interaction where the hydrodynamic assist develops the meniscus as required in all coating systems.

This lengthy curtain of fluid can be disrupted by air flow or vibrations. To have the best possible flow control a couple items are required: sharp lips at the slot die exit to control the static contact line of the fluid; edge guides to control curvature of the fluid during flow from the slot die exit to the substrate; and air shields to control the environmental impact of air currents on fluid flow.

To maintain a stable film formed to the complete width of the slot die coating exit, edge guides are required. These can take the form of simple plates that the fluid rides from the slot die exit to the substrate or as complex as liquid fed tubes that help carry the curtain down. The key is curtain stability at the edges. Without mechanical edge guides, the liquid would neck in and have curvature in three dimensions. This is most troublesome at the edges of the liquid formation, causing the fluid to curl in on itself and form edge beads that would be thicker than the rest of the coated substrate.

Air shields protect the formed curtain from disruption during operation. A simple air current developed from an air duct or door movement can break up a stable curtain. These mechanical air shields need to be concerned with the fluid formation zones at the slot die exit, the curtain stability zone during the travel from the slot die exit to the substrate and the coated film formation zone at the substrate.

In addition to the air and vibration issues associated with an unsupported fluid curtain, the hydrodynamic assist function creates an operating limitation and a reduced coating window. The way the fluid develops a heel at the point of impact is important. This heel development is a function of the contact angle which is subsequently dependent on the line speed and the wettability of the fluid onto the substrate. This wettability can be encouraged through surface energy and surface tension match making between the liquid and the substrate, but is more powerfully controlled by the substrate speed and the volumetric liquid flow.

This ratio of volumetric flow (V) and substrate speed (U) is presented at the Reynolds number calculation. The ratio of U/V has a dramatic effect on the heel development of the impinged fluid flow. While heel development needs to meet a critical level of stability for the removal of air, too large of a heel (too low of a substrate speed for the fluid flow) can lead to turbulent flow in the impinged heel and air defects downstream. The exact Reynolds number and U/V ratio is empirically determined.

The Weber number calculation provides a great starting point to understand where the fluid will form a stable curtain, but this needs to be combined with the understanding of the hydrodynamic assist concept to produce a usable coated product. Past experience has shown that while the literature states that a Weber number greater than 2 should produce a stable curtain, a Weber number greater than 7 typically is required for a robust stable curtain. This theoretical versus reality based idea should be considered when designing equipment and coating liens with little empirical data.

Understanding the distribution of the liquid flow at the slot die exit is important for both proximity and curtain slot die coating operation. This can be completed through finite element analysis and verified through experimentation. However, developing a computer model of the flow external to the slot die in either arrangement is less simple. The boundary conditions are less controlled which leads to a reduced understanding and replication with empirical data. Navier-Stokes calculations provide a good starting point for a physics based concept of flow. To further develop mathematical models, understanding the liquid to substrate interface should be empirically measured and compared to the FEA models being developed.

In the observation of the heel formation in curtain coating projects, the hydrodynamic assist can lead to a stable meniscus and coated film or not. The worst case scenario looks like a pulled film without any heel formation while an intermediary flow looks like a heel is formed, but disrupted and unstable. In either case the issue is air entrainment. Air entrainment will lead to uneven flow and potential streaks developing in the coated surface. The volumetric flow needs to be increased or the substrate speed needs to be reduced. Keeping in mind that the ratio of the two develops the proper coat weight for the product.

CONCLUSION

Curtain coating slot die technology is an ideal solution for coating irregular surfaces at high speed. It should be considered an option whenever proximity coating is not an option or thinner coatings and higher line speeds are required to meet the economics of the coated product. With every equipment setup, however, considerations need to be reviewed. Balancing the advantages of increased coating gap, higher line speeds and thinner coatings, with the disadvantages of air disturbances, vibration disruptions and the minimum line speed and flow rate requirements, leads to a process equipment decision based on economics and capability. Curtain coating provides a strong case for precision coating from a distance.

REFERENCES

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