

Effects of air entrainment on coat weight distributions with an enclosed pond applicator

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ABSTRACT: *In-pond extraction of entrained air and excess coating through the use of an extraction tube substantially improves coat weight uniformity at high machine speeds.*

KEYWORDS: *Air entrainment, applicators, bibliographies, coating weight, enclosures, flow control, homogeneity, ponds.*

There is an industrial need for a high-speed coater which achieves improved coat weight uniformity while maintaining acceptable runnability at high machine speeds (>1372 m/min). Deterioration of the coat weight uniformity and coater runnability are anticipated with any coating applicator as the machine speed exceeds a critical level which we have defined as a *coatability speed limit*. This speed limit seems to be a strong function of the flow configuration of the coating applicator as well as the rheological properties of the coating.

In this paper, we limit our discussion to an enclosed pond applicator that has been widely used for paper coating because of its superior runnability and ease of operation. In general, the applicator contains a pond-type application zone, normally with one coating inlet and two coating outlets. The applicator provides a uniform transfer of the coating fluid onto the paper. The paper enters the pond

through an overflow region where it makes contact with the coating fluid inside the pond, and then exits the pond at a metering blade. The major problem associated with this type of applicator is the appearance of nonuniform cross-machine direction (CD) and machine direction (MD) coat weight distributions as the machine speed exceeds the coatability speed limit. These nonuniformities have a characteristic length scale of about 20–30 mm.

An order of magnitude analysis of the length and time scales characteristic of the flow suggests that this coat weight nonuniformity problem is primarily caused by the state of flow in the pond, but not necessarily the flow under the metering blade where a high shear-rate condition with small length and time scales is encountered. This condition may only significantly alter the microscale variations while having little or no effect on the macroscale variations. Previous researchers have

suggested that the nonuniformity coat weight distribution problem is largely attributable to flow instabilities resulting from the interaction of multiple events in the coater pond, such as: the existence of 3-D vortexes in the coater pond (1, 2) and entrainment of air at the three-phase dynamic contact line (3–5).

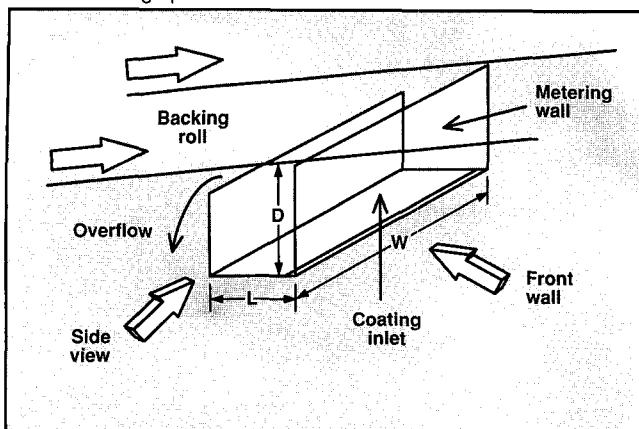
Numerical simulations have been carried out with a driven cavity (6–9) and recently with a system resembling the one used here (10–12). These analyses neglect the contribution of the instabilities which are induced by the free surface and the dynamic contact line due to the singularity problem (13, 14).

Scriven (3) addressed some of the fundamental issues of air entrainment in the coating process, and Aidun (4) discussed how the entrained air could affect the coat weight distribution on paper with an enclosed pond applicator. Experimental studies with a plunging tape (15–18) and a rotating roll partially immersed in a fluid (19–21), resulted in some empirical correlations which predicted the critical speed of air entrainment. It is apparent that even at low machine speeds, there is still a lack of understanding of how air is entrained at the dynamic contact line, how much air volume enters the coater pond, and where the entrained air goes.

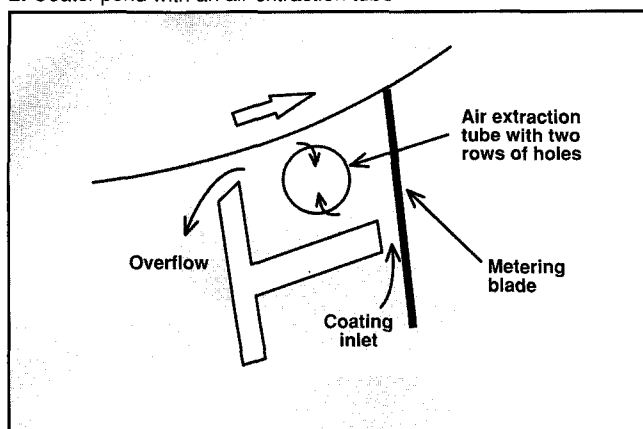
Mechanical means of preventing the air from entering the coater pond have been proposed, including: (a) the use of an additional blade next to the overflow region to cut down the incoming

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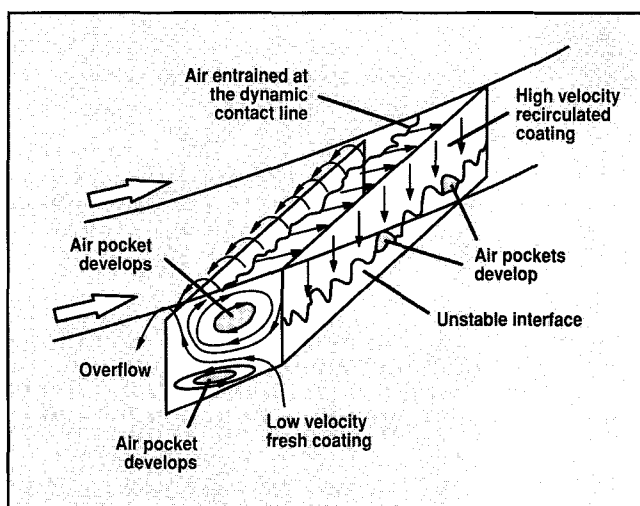
1. A see-through pond with overflow



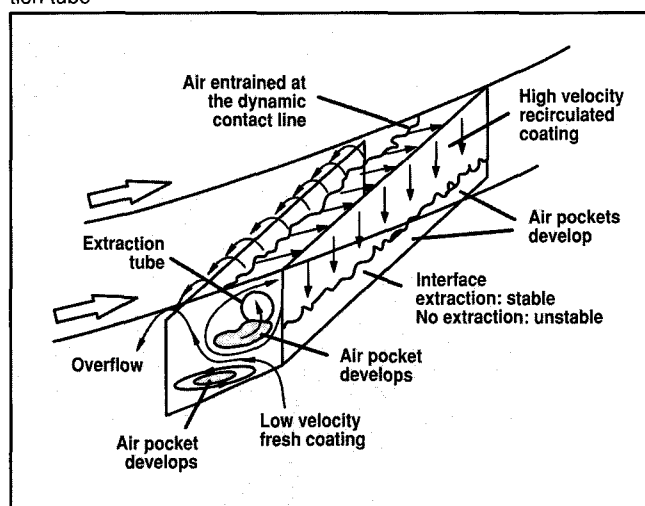
2. Coater pond with an air extraction tube



3. Observed flow pattern inside a see-through pond



4. Observed flow pattern inside a see-through pond with an air extraction tube



boundary layer of air (22), (b) supply the coating fluid under high pressure in the form of a jet to reduce the relative velocity between the moving substrate and the coating fluid (23), and (c) use of a partial vacuum to replace the gas phase, as commonly adopted in slot and slide coaters for use in the photographic industry. In general, runnability will be a problem with a two-blade design because of an increased frequency of paper breaks. Matching the velocity of a high viscosity coating fluid to that of the moving substrate is difficult at high machine speeds, and air tends to act as a barrier or shield for the substrate. Based on the experience with slot and slide coaters, the partial vacuum method may be limited to only low-speed coat-

ing applications. Since the prevention of air from entering the coater pond seems extremely difficult, the question of how to remove the entrained air has led to the use of a CD air extraction tube residing inside the coater pond (24).

Approach to the problem

It is still unclear how air is entrained at the dynamic contact line and how the entrained air affects the flow dynamics in the coater pond, and by consequence, the coat weight distribution on paper. Effective minimization of the coat weight non-uniformity with an enclosed pond applicator at high machine speeds will require a fundamental understanding of the relationships in-

volved. Our approach to this problem has included: (a) flow visualization experiment with clear fluids to determine the general flow pattern inside a see-through pond for various flow and geometry conditions, (b) coater trials with typical LWC coating formulations being applied directly onto a solid rotating backing roll to study the dynamic response of the coat weight distribution for similar flow and geometry conditions, and (c) pilot machine trials of coating onto paper to validate observations from both the flow visualization experiment and coating on the backing roll.

Experimental setup

Flow visualization experiment

A see-through pond with overflow was built for the flow visualization experiment, as shown in Fig. 1. The pond permits control of the coat weight on the backing roll and provides the ability to operate at machine speeds up to 1524 m/min. The characteristic aspect ratio, ϕ , for the see-through pond is 1.75, where ϕ is defined as:

$$\phi = D/L \quad (1)$$

and D and L are the characteristic depth and MD length of the pond. For better visualization, the actual depth and length of the pond are about 2–3 times larger than the pond size used for the research coater trials and pilot coater trials. The pond width, W , is 0.2 m.

Initial air extraction experiments were carried out with an extraction tube (OD = 12.7 mm) having one row of holes. The tube was arbitrarily located near the front plate (metering wall) and the roll surface. Two cases were considered: (a) an extraction condition where the extracted air/coating mixture was exited from the pond through the tube due to a pressure difference between the pond and the atmosphere, and (b) a no extraction condition where both ends of the tube were closed such that neither air nor coating were allowed to flow through the tube.

Research coater trials: coating on the roll

The characteristic aspect ratio of the research coater pond was 1.04 and the coating width was 0.4 m. A doctor blade was located at the side opposite the coater head to scrape off the coating film on the roll. A stainless steel tube (OD = 13.8 mm) having two rows of holes was placed in the coater pond at the position shown in Fig. 2. The tube was supported by two end dams made of styrofoam. Several sets of end dams were prepared for determination of the optimum tube position in the coater pond. In addition, the tube was rotated to optimize the hole orientation for

maximum air extraction. Both the extraction and no extraction conditions were investigated. For extraction conditions, the extracted air/coating mixture was allowed to flow into a separator which was connected to a vacuum pump. The vacuum level in the tube was adjusted through a control valve.

Pilot coater trials: coating on paper

The aspect ratio of the pilot coater pond was 0.29, and the coating width was 0.4 m. Due to a pond size difference between the research coater and the pilot coater, the air extraction tube was replaced with a smaller diameter tube (OD = 12.7 mm). The optimum tube location and hole orientation were determined from the results of the research coater trials. No vacuum was used for the extraction condition.

Coating formulations

For the flow visualization experiment, both water and a polyvinyl alcohol-water solution (18% solids by weight) were used as the coating fluids. The Brookfield viscosity of the polyvinyl alcohol-water solution at 100 rpm was 1300 mPa • s. This solution exhibited a weak shear-thinning behavior. At this low solids content, the polyvinyl alcohol-water solution could be considered to approximate a Newtonian fluid.

Different coatings were employed in the coater trials, including several typical European and North American light weight coating (LWC) formulations. The solids content was maintained at 58–59% by weight. Coating with solids higher than 59% created problems with quick drying of the coating film on the backing roll. These coatings exhibited a strong shear-thinning behavior. The Brookfield viscosity at 100 rpm was maintained in the range of 1000–1300 mPa • s. These coatings also contained a small quantity of an optical dye that fluoresced when illuminated under ultraviolet light for easy identification of coating patterns on paper.

Results

Flow visualization experiment

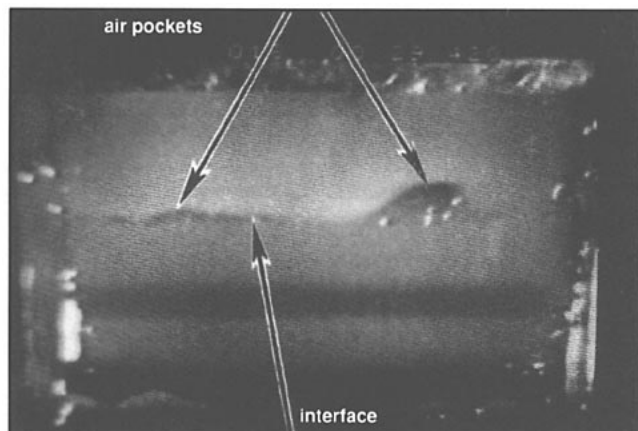
See-through pond. With water as the coating fluid, it was observed that air bubbles came in through the overflow region and eventually accumulated in the pond. A nonuniform air bubble distribution was observed with the maximum concentration occurring in the region of high flow recirculation. The volume of entrained air that accumulated in the pond was strongly dependent upon the machine speed. Increasing the machine speed increased the quantity of the entrained air. The placement of a pre-blade in the vicinity of the overflow region showed the ability to stabilize the dynamic contact line and an obvious reduction of the entrained air bubbles up to machine speeds of 914 m/min. At higher machine speeds, we were unable to maintain sufficient stiffness of the pre-blade to cut down the entrained air volume due to vibration or deflection by the high velocity air stream. These experiments also demonstrated that air did enter the coater pond through the overflow region due to the inability of the coating fluid to effectively and uniformly displace the boundary layer of air next to the moving roll.

With the polyvinyl alcohol-water solution, there were three regions where a high accumulation of air bubbles developed, eventually forming air pockets (Fig. 3):

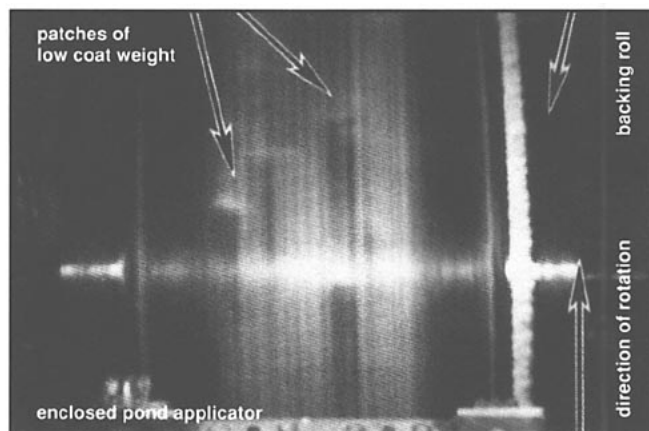
1. In the inner region of high flow recirculation (primary vortex)
2. At the bottom of the pond (flow separation at the edge)
3. At the interface where the fresh coating entered the pond from the inlet at the bottom and the recirculated coating from the tip of the metering wall first met.

The entrained air appeared to migrate across the streamlines toward the inner regions of flow recirculation zones. This was in contrast to the following tube flow situations: (a) par-

5. Front view of the see-through pond with a polyvinyl alcohol-water solution shows that the air pockets are formed in the region below the tube and eventually become noticeable at the interface for a machine speed of 1219 m/min.



6. Image of the coating pattern on the backing roll with an enclosed pond applicator at a machine speed of 1372 m/min



ticles in viscoelastic fluids migrate toward the center of the tube as the result of the normal stress effects (25, 26) and (b) particles in Newtonian fluids migrate to a narrow region at approximately 0.6 radius of the tube under the influence of the inertial effects (27). Air pockets were formed in a relatively short time. As the air pockets grew in size, they began to oscillate, becoming unstable and then breaking down. The maximum size of these air pockets is believed to be related to the interfacial tension at the air-fluid interface, the flow dynamics in the neighborhood of the air pocket, and the characteristic dimensions bounding the flow. An abrupt change of momentum induced by sudden air pocket breakdown might generate three possible situations: (a) the forcing of excess coating out of the pond through the overflow region leading to a subsequent low coat weight region, (b) the propulsion of a portion of the air toward the metering wall creating additional wall vibration, or (c) the contribution of the variability in the location of the dynamic contact line which could affect the boundary layer buildup and thereby the momentum transfer to the metering wall. However, there was no strong indication that air did pass under the metering wall, and it would be difficult to get definitive proof that air bubbles passed under the metering wall using this ex-

perimental setup and coating fluid.

In the case of water as the coating fluid, air pockets were not formed because of a sufficient level of turbulence which acted to break up large air bubbles. The dimensionless Reynolds number defined as:

$$Re = \frac{\rho v l}{\mu} \quad (2)$$

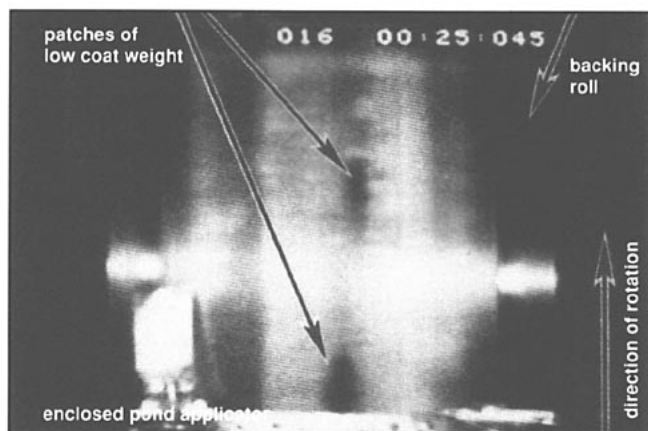
is about 3 orders of magnitude higher for water than the polyvinyl alcohol-water solution. Here, ρ is the density of the fluid, v characteristic velocity, l the characteristic dimension of the pond (D or L), and μ the apparent fluid viscosity.

Viewing the pond from the front revealed an unstable wavy interface which developed as the high velocity coating, recirculated from the tip of the metering wall, met with the low velocity fresh coating fed from the bottom (see Fig. 3). This fast moving coating mixed with the slow moving coating feed, generating additional viscous energy dissipation. The location of the interface depended upon both the machine speed and the feed rate. A higher machine speed or lower feed rate pushed the interface down away from the metering wall tip and toward the feed inlet. However, there was insufficient evidence to conclude that a higher feed rate would effectively eliminate the type of coat weight nonuniformity considered here.

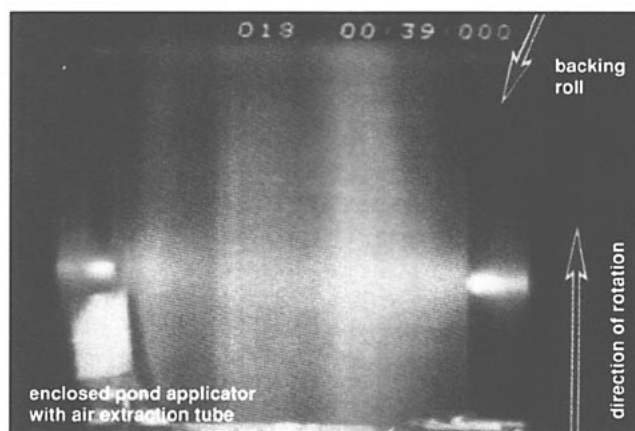
See-through pond with an air extraction tube. The extraction tube was arbitrarily mounted near the backing roll and the metering wall. For the initial extraction condition, no vacuum was applied to the ends of the extraction tube as both ends of the tube were open to atmospheric pressure. Flow patterns inside the see-through pond were recorded at machine speeds up to 1219 m/min. It was observed that the stability of the internal flow pattern in the pond was significantly improved as the air/coating mixture was extracted. The interface between the recirculated and feed flows was comparatively stable with no noticeable fluctuation. Air pockets were observed in the region below the extraction tube, as shown in Fig. 4. As the excess coating was doctored by the metering wall, it flowed rapidly down between the extraction tube and the metering wall. Flow was separated from the tube wall at some point, forming a high recirculation region (vortex). The maximum extraction of air volume was achieved when the holes were pointing into this region. Orienting the holes elsewhere resulted in the extraction of more coating fluid and less air. At a machine speed of 1219 m/min, no apparent enlargement or reduction of the air pocket size was observed from the end plate with continuous removal of the entrained air from the pond.

For the no-extraction condition, air

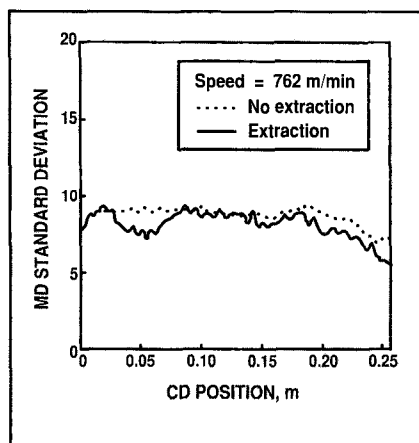
7. Image of the coating pattern on the backing roll for the no-extraction condition with the addition of an air extraction tube to the enclosed pond applicator at a machine speed of 1372 m/min



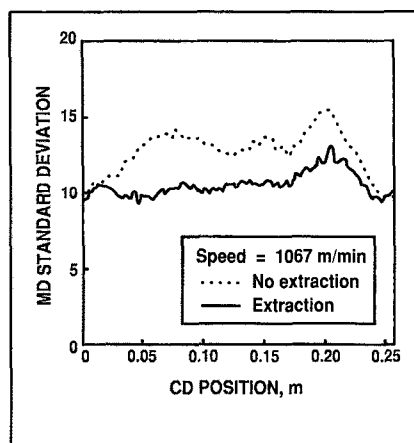
8. Image of the coating pattern on the backing roll for the extraction/vacuum condition with the addition of an air extraction tube to the enclosed pond applicator at a machine speed of 1372 m/min



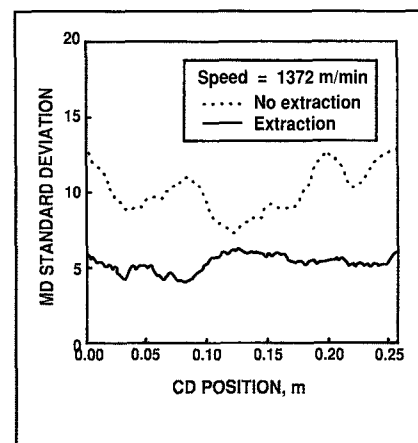
9. Plot of MD standard deviation as a function of CD position for the extraction/vacuum and no-extraction conditions at 762 m/min



10. Plot of MD standard deviation as a function of CD position for the extraction/vacuum and no-extraction conditions at 1067 m/min



11. Plot of MD standard deviation as a function of CD position for the extraction/vacuum and no-extraction conditions at 1372 m/min



accumulated in the coater pond and made the interface between the recirculated coating and the fresh feed very unstable at any machine speed. Distinct air pockets were formed in the region below the extraction tube and eventually became noticeable at the interface, as illustrated in Fig. 5. They were formed rapidly, grew to a critical size, and then broke down. This caused the interface to fluctuate vertically due to an unstable force balance at this interface. The overflow exhibited a low frequency pulsation which suggested that the flow rate of the excess coating fluid exiting the pond was nonuniform as a result of the air pocket formation and breakdown. At a machine speed

of 1219 m/min, the experiment showed that the time interval from the pocket formation to pocket breakdown was approximately 8–10 s. From the front and side views, the stability of the internal flow pattern seemed to improve, but only lasted for approximately 2–3 s after the air pockets broke down.

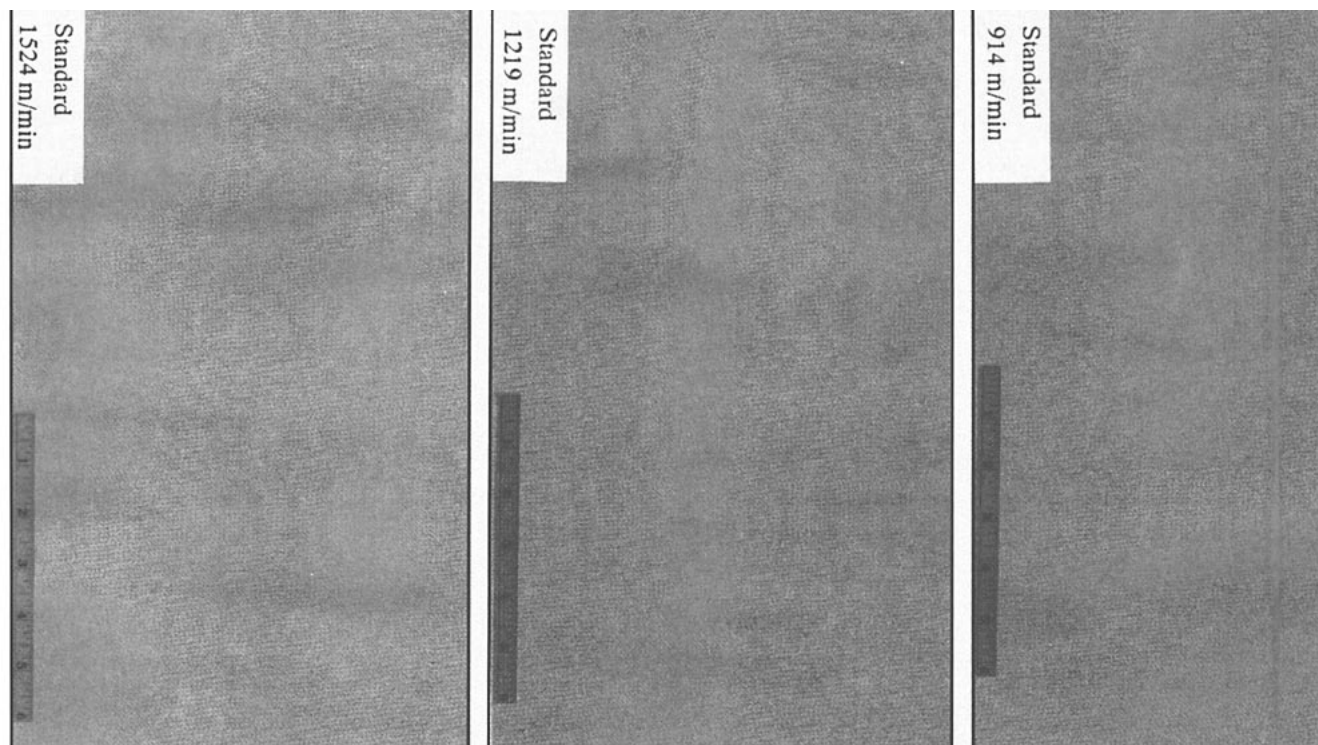
Research coater trials: patterns on the roll

In evaluating the uniformity of the coat weight distribution on the backing roll, we neglected the high frequency noises attributed to vibration of the metering blade, doctor blade, and machine. We also neglected the microscopic coat weight variations as-

sociated with the surface texture on the roll cover and the coat weight variation from known causes, such as grinding pattern or defects on the roll.

Coater pond. To illustrate the effects of air entrainment, data from a typical LWC formulation is presented. From Fig. 6, evidence of deteriorating coat weight uniformity is observed at a machine speed of 1372 m/min as the low coat weight patches emerge on the backing roll. There is no proof to suggest that these patches of low coat weight are caused by air passing under the metering blade. Increasing the machine speed enhances the patch distinctiveness, magnifies the patch size,

12. Coat weight distribution on paper with an enclosed pond applicator at various machine speeds



and increases the frequency of patch occurrence. In addition, an increase of the coating film thickness on the backing roll from 10 μm to 70 μm appears to have no significant effect. It is apparent that an extremely high coat weight is required to mask the nonuniformity.

Coater pond with an air extraction tube. The optimum extraction tube position in the coater pond was midway between the metering blade and the back wall, near the roll surface. Moving the tube too close to the roll surface or the blade generated skip coating. Moving the tube too close to the overflow wall tended to obstruct the flow and increase the overall pressure in the pond. The optimum hole orientation (two rows of holes, one on each side) was found to be normal to the roll and to the high flow recirculation region. Air and excess coating flowed through either the holes pointing toward the roll or the holes pointing to the high recirculation region.

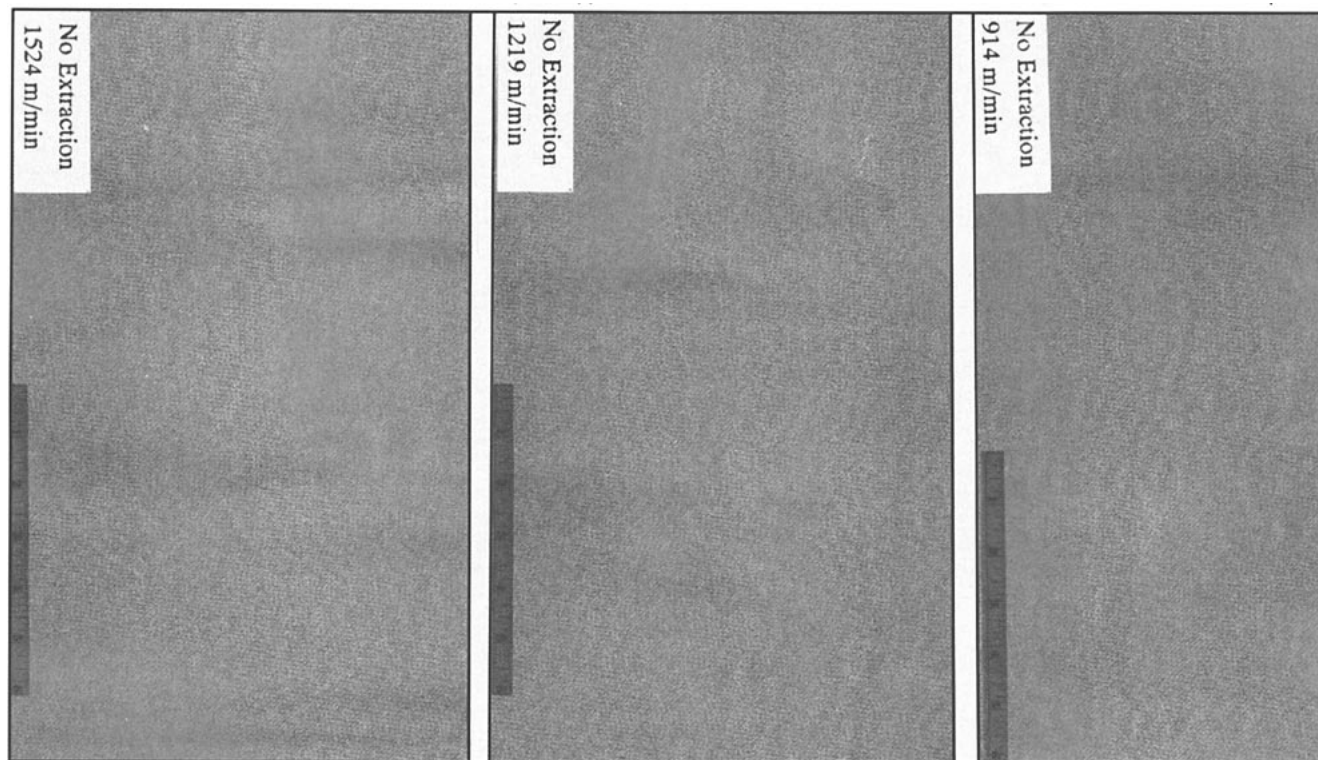
The dynamic behavior of coat weight distribution on the backing roll

at machine speeds of 762 m/min, 1067 m/min, and 1372 m/min was recorded for extraction/vacuum and no-extraction conditions. It appeared that extraction with and without vacuum generated indistinguishable coating patterns. Coat weight or film thickness on the backing roll was checked before the coating pattern was recorded with the high-speed video camera. The extraction/vacuum condition was performed immediately after the no-extraction condition. No significant changes in coating rheology was anticipated due to the short time interval between the two conditions. The main focus was only on the dynamic change of the coat weight distribution.

For the no-extraction condition, patches of extremely low coat weight were observed for machine speeds over 1067 m/min. An obvious reduction in the number and size of the low coat weight patches (stable coating pattern) was found for the extraction/vacuum conditions. It was observed that a small portion of the coating fed into the coater pond was extracted through the tube. The images of the

coat weight distributions on the roll at a machine speed of 1372 m/min for the extraction/vacuum and no-extraction conditions are shown in **Figs. 7 and 8**.

To provide a qualitative comparison of coat weight uniformity for these two conditions, the recorded patterns were digitized from the videotape with an image analyzer. The comparison is, however, limited to a qualitative nature. Due to the curvature of the roll and nonuniform light illumination at different MD positions, multiple scans from the same image would be meaningless. Consequently, a single scan per image at the same location on the roll was attained. A total of 128 scan lines were obtained from 128 sequential images. **Figures 9 to 11** show the local MD standard deviation of the gray levels as a function of CD position for the extraction/vacuum and no-extraction conditions at machine speeds of 762 m/min, 1067 m/min, and 1372 m/min. The standard deviation in gray level was insignificant at 762 m/min. The extraction/vacuum condition gave a smaller standard deviation than the no-extraction condition at 1067 m/



min and 1372 m/min. Due to minor differences in the film thickness at each machine speed, a direct comparison of the MD standard deviation of the gray scale for Figs. 9–11 could not be made. In general, the results indicated that improved coat weight uniformity was found for the extraction/vacuum condition.

Pilot coater trials: pattern on paper

Coater pond. Figure 12 shows photographs of the coat weight distributions on paper from the paper trials using an enclosed pond applicator with a typical LWC coating formulation at three machine speeds. The bright region indicates a high coat weight; the dark region a low coat weight. The appearance of patches of low coat weight is observed for machine speeds above 914 m/min. The apparent patch characteristics become more distinct, larger in patch size, and more numerous in quantity as the machine speed increases. The observed coating patterns on paper are similar to that found on the backing roll, indicating that coat-

ing on the roll is a suitable method for evaluating the coater performance.

Coater pond with an extraction tube. From the experiences gained from the research coater trials, the air extraction tube was located near the metering blade and the roll surface. The holes were oriented normal to the roll surface and toward the bottom of the pond. For the no extraction condition, we replaced the extraction tube with a solid rod. Our intention was to investigate the possibility of any smoothing action developing between the rod and the roll surface which might contribute to improved coat weight uniformity.

Comparisons of coat weight distributions on paper at various machine speeds under different conditions are shown in Figs. 13 and 14. Even though the tube location and hole orientation were not optimized for these trials and the pond aspect ratio was different, we still observed the same improvement in coat weight uniformity with the extraction condition over the no-extraction condition (or the coater

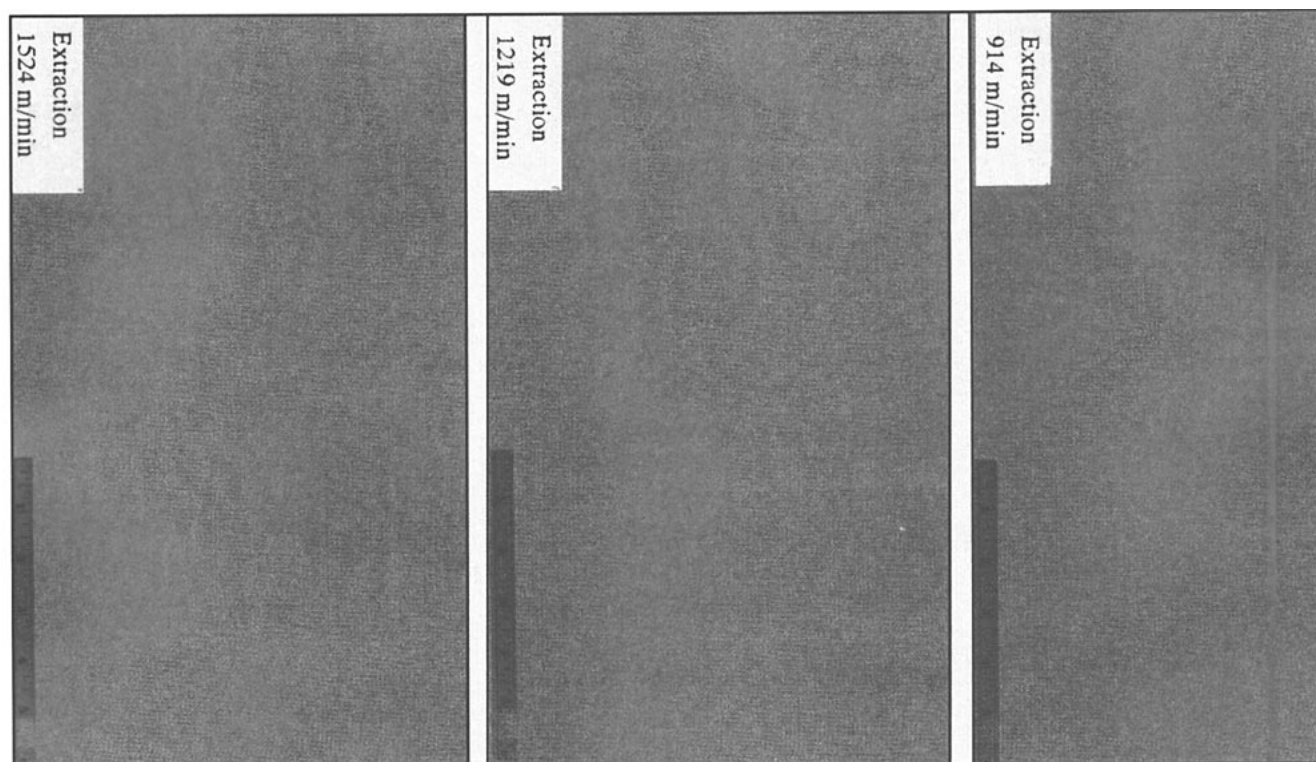
pond without an air extraction tube). This suggests that in-pond extraction of entrained air and excess coating can stabilize the internal flow as well as improve the coat weight uniformity.

Discussion

The air extraction method described here can effectively capture the entrained air bubbles and thereby facilitate air and coating separation in the designated low-pressure recirculation region. The capture of air bubbles from the coating is characterized by the simultaneous action of buoyancy, viscous, inertial, centrifugal, and normal forces, that act between the air bubbles and the low-pressure region. These combined forces govern the bubble trajectories which in turn determine whether the air bubbles will be transported to the low-pressure region. The fundamental concept behind this air extraction method is to (24, 28):

1. Create a high recirculation (low pressure) flow in the pond for inducing air/coating flow separation

14. Coat weight distribution on paper with an enclosed pond applicator/air extraction tube for extraction condition at various machine speeds



2. Force the entrained air bubbles to migrate toward and to be trapped within the low pressure region for accumulation
3. Remove the accumulated air through the holes of the extraction tube in the pond as a result of the pressure difference between the pond and the atmosphere
4. Dampen out macroscopic flow variations in the pond as a result of nonuniform feed and overflow.

Summary

Flow visualization experiments and coater trials with an enclosed pond applicator have demonstrated that air is entrained at the dynamic contact line and enters the coater pond. The accumulation of the entrained air results in the formation of air pockets in the inner region of flow recirculation. Formation and breakdown of these air pockets can significantly affect the state of flow in the coater pond and thereby the coat weight distribution.

The results are summarized below:

1. In-pond extraction of small quantities of air and coating through the use of an air extraction tube provides substantial improvement in uniformity of the coat weight distribution over the no-extraction condition (or the coater pond without an extraction tube).
2. A plausible explanation is the reduction of air volumes, the attenuation of macroscopic flow variations in the coater pond, and the stabilization of the dynamic contact line.
3. Coating on a backing roll is useful as a model for paper coating due to a macroscopic similarity between the coating patterns on both the roll and the paper.

Further work includes the determination of the driving forces behind the extraction process and the mechanisms leading to a stable internal flow pattern and a uniform coat weight distribution. ■

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