A method to model web trajectory and release in forward roll coating

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Abstract
A method is proposed to describe the web trajectory and the pressure distribution in the fluid at the exit of a forward roll coater. Lubrication equations are coupled to a force balance on web node points. The fluid pressure in the coating layer generates forces on the web. These forces deflect the web. Integration in time gives the web dynamics. The angle that the web is pulled from the nip and the tension are found to influence the pressure pulse in the nip to a large extent. Low tensions lead to a second pressure pulse followed by a sub-ambient or tack pressure. Pulling the web at various angles from the nip can cause the tack pressure to increase or decrease. Pressure pulses are predicted that compare to a laboratory device.

Introduction
The release of a web from a coating roll at the exit of the nip is often the last contact of the coating with a solid. High tack forces can damage the web in the case of printing. For some coating application, the web can oscillate between two rolls, generating defects. While this is a critical part of many coating systems, the physics are not well understood. Simple models are needed to help understand unstable conditions and the forces that are placed on the web during this release.

The interactions of a fluid with a deformable web has been the subject of a number of studies, first initiated by Blok and Rossum (1953). Some simple expressions can be developed based on the tension of the web, the viscosity and speed. Kistler and Scriven (1984), Sakinger et al. (1996), Feng (1998) and others have shown some finite element methods that predict the deformation of the web during coating solving for the fluid flow in conjunction with the web deformation equations. Pranckh and Coyle (1997) summarize the topic of elastohydrodynamics in coating systems. Lin et al. (2008) show a method to couple the fluid flow with the tension web equation to understand tensioned web slot coating.

Carvalho (2003) shows a method to solve for the web deformation and fluid flow in tensioned coating systems. Finite element methods are used to solve the fluid flow and the cylindrical shell deformation equations are used to describe the web deflection. Park (2008), Nam (2009) and Nam and Carvalho (2010) followed up this work looking at various methods and conditions to describe the web over slot situation. These methods are robust and could be used to describe the situation of interest here. However, the methods are complex, the computational costs can be large and it is not clear how commercial software could be used. A simpler method is of interest if a large number of parameters are to be studied.

While finite element methods can produce an excellent description of the situation, a simpler method may be of value, especially if the dynamic response is of interest. Here, a method is proposed to describe the web deflection at the exit of a forward roll coating geometry. The method is similar to Lin et al. (2008)

except that the web deflection is found by integrating the equations in time to find a solution. The fluid flow is described by lubrication methods. The web deformation is found by solving dynamically a force balance that gives rise to the web deflection equations. The results are compared with experiments. The method may be of value in coating methods that involve a tensioned web.

Theory

Figure 1 shows the exit region of a forward roll coater. At this point, coating is assumed to be applied to the top side of the web. The web enters wrapping the bottom roll that has a radius R. The gap between the top surface and the web will determine the coat weight applied. In reality, the rolls are usually loaded with a force that will interact with the fluid dynamics to determine the coat wieght. The web will stick to the roll that has fluid for some distance before the web tension forces will pull the web away from the roll surface. What likely would be known is the distance away from the roll where the web is forced to turn or will contact a different roll. Here this take off point is labeled x_p. The angle of this point with the center of the nip is also something that can be set. Here a positive take off angle α, is shown in the figure.

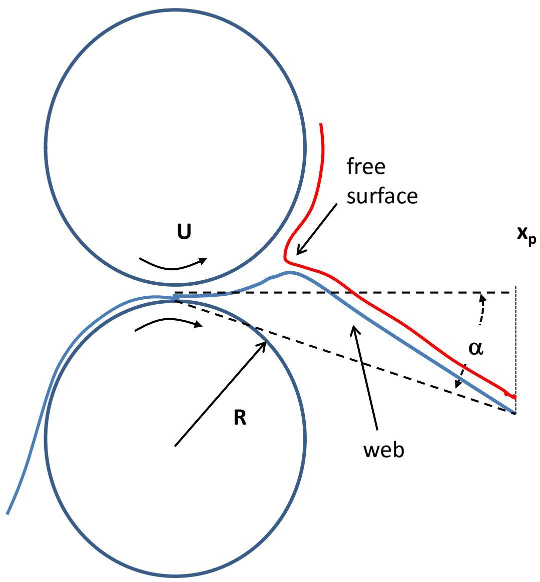

Figure 1. Configuration at the exit of a forward roll coating nip. The web can deform before the coating layer splits. α is the take off angle of the web and xp is the distance away from the nip that this point is applied. The center of the nip is taken as x=0.

The standard lubrication expression for flow in the nip and between the web and the top roll surface when the web velocity is the same as the roll surface velocity U is

$$\frac{dP}{dx} = 12\mu \frac{(Uh - Q)}{h^3} \tag{1}$$

where P is pressure, μ is viscosity, Q is the flow rate per unit width and h is the local distance bewteen the web and the top roll. The flow rate is constant at every location and would represent half of the coat weight if the film splits in half. This expression is easy to modify if the web is moving at a different velocity than the roll or if the rolls are not the same radius. Solving this equation with the geometry of the two rolls gives the typical pressure pulse between the rolls.

The web deflection is described by assigning a number of node points to the web, that are spaced at the same interval as the finite difference method that will be used to solve the lubrication equations. The net force on each node point in the vertical direction will determine if the node point moves up or down relative to its current position. The net force normal to the web travel direction is

$$F_n = F_a - F_f + T_n + F_s \tag{2}$$

where F_a, F_f, T_n and F_s are the force per unit width due to air pressure, fluid forces, tension and stiffness, respectively. For the results presented here, air pressure forces and stiffness of the web are assumed to be small, but these could be included. In some situations, the air layer that is trapped between the web and the bottom roll could create significant forces. If the web is coated on both sides, the air force would be replaced by a second fluid type force. The fluid force is the local pressure, in Eq. (1) multiplied by the node spacing; the negative sign here comes from the fact that a positive pressure would be pushing downward on the web for the geometry in Fig. 1. The tension force comes from node on either side pulling up or down on the node of interest. These tension forces are developed in Gates and Bousfield (2015). The expression is similar to a finite difference representation of the standard tension equation for webs or surface tension.

Once the net force on the node is calculated, Newton's law of motion is used to calculate the acceleration of each node in the vertical direction as

$$a_i = \frac{F_n}{m_n} \tag{3}$$

where m_n is the mass per unit width of the web. The acceleration is used to update the normal compontent of the velocity vector of each node. The velocity in the machine direction is assumed to be constant and that of the web velocity. The velocities are used to move the node positions. Web inertia was found to not play a major role for conditions of interest in printing of paper, but could be important in some situations. All of the nodes of interest are adjusted before another time step is taken. The position of the node at $x=0$ is known to be the top surface of the bottom roll. The position of the node at the take up point $x=x_p$ is also known. These positions serve as boundary conditions for the web.

The equations are solved by starting with some web profile, often undeformed web traveling to the take off point. For the inlet of the rolls, Eq. (1) is used to find the pressure profile to the center of the nip where the gap h is assumed to follow the geometry between two rolls. Here, the inlet of the nip is assumed to be flooded. Therefore, the pressure is set to zero at $x=-R$. After the nip center, Eq. (1) is still used to integrate the pressure distribution, using h as the distance between the web node and the top roll surface. A split location could be implemented, but the pressure decreases to a small value anyway and the web trajectory is controlled by the tension forces. The pressure condition is set to zero pressure at x=R. The flow rate of through the nip Q is therefore adjusted in order to satisfy the pressure boundary conditions. Once the pressure distribution is found, the net force on each node point is calculated. The force determines the acceleration, and the new vertical velocities of the node points as a time step is taken. The time for the web to reach a new condition is found, but the emphasis here is just the final steady state web trajectory and pressure distribution.

A number of assumptions still are involved in this description. First, the machine direction inertia is not taken into account. This could be implemented by doing a two component force balance on the node points, letting node points move from the calculation domain and adding points as needed. Other issues such as cavitation, non-Newtonian rheology, and capillary forces near the film split are neglected in this initial model. Also, inertia in the fluid layer is neglected when using the lubrication expressions.

Parameters are made dimensionless as in Table 1 using the roll radius R, viscosity, and the web velocity U to form the groups. The key parameter of interest here is the web tension and the take off position.

Table 1. Dimensionless parameters involved in the model.

Dimensionless parameters	**Equation**
Web Position	$H^* = h/R$
Tension	$T^* = \frac{T}{\mu U}$
Pressure	$P^* = \frac{PR}{\mu U}$
x-coordinate	$x^* = \frac{x}{R}$
Acceleration	$a^* = \frac{a_i R}{U^2}$
Gap at x=0	$h_i^* = \frac{h_i}{R}$
Nodal web mass per width	$m^* = \frac{mU}{\mu R}$
Take off point	$x_p^* = \frac{x_p}{R}$

Results and Discussion

Figures 2 and 3 show the pressure distribution and web trajectory, respectively, when the take up point is at $x_p^*= 2$ and the angle is zero. This would be the case when the web is pulled straight out of the nip. When the tension is high, the normal pressure distribution between two rolls is predicted with a positive pressure peak followed by a negative peak. This pressure distribution is not quite symmetric because for the inlet, the gap follows the equation between two rolls, but on the outlet, the gap is between a flat web and the top roll. As the tension decreases, the pressure pulse initially increases, but then decreases, to give a second but small positive pulse. What is happening is that the web starts to follow the top roll surface and is peeled away from the surface at some take off or peel point. As the web is traveling along with the web, the pressure distribution is rather flat. For T*=10, the pressure returns to a small constant value after the pressure pulse, but then has a small pulse followed by a negative pressure value at x*= 0.35. As can be seen in Fig. 3, for this case, the web follows parallel to the top roll surface before making a sharp turn at the peel location.

The deflection of the web, shown in Fig. 3 is not that large, less than 10% of the roll radius. This deflection may not be that obvious in actual operation. However, as these results indication, a small amount of deflection can have a large influence on the pressure distribution.

The magnitude of the sub-ambient pressure is often called the ”tack” force. This force can be responsible for the damage that is seen during printing call picking. Figure 2 shows that as the tension of the web is reduced, the magnitude of the tack force is expected to decrease.

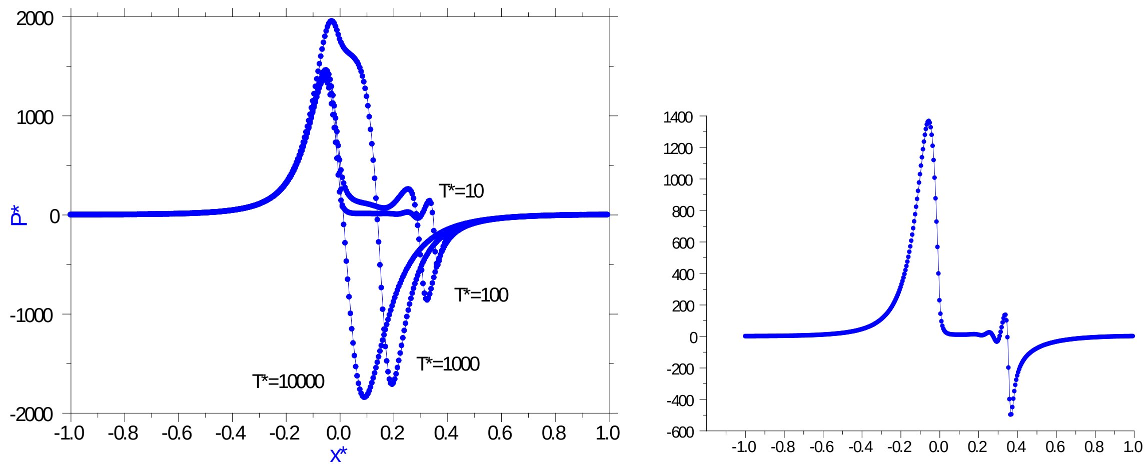

Figure 2. The pressure distribution predicted when the web is pulled straight from the nip for various tensions for h_i^*=0.01 and x_p^* = 2.0. On the right, the case for T*=10 by itself for clarity.

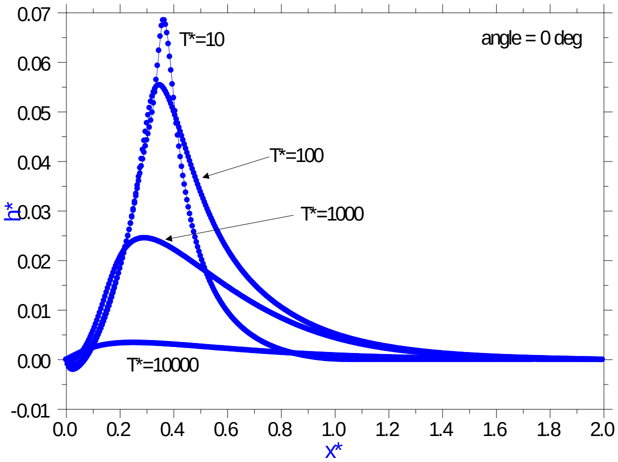

Figure 3. Web trajectories for various tensions when the web is pulled straight from the nip for various tensions and $x_p^* = 2$. Note that the y-axis is enlarged compared to the x axis.

As the web tension decreases further, the model predicts that the web will ride along the top roll surface even further. Figure 4 shows the pressure distribution as the tension is reduced below T*=10. The magnitude of the tack pressure seems to go to a constant value. There still is a small positive pressure pulse as the web releases from the roll surface.

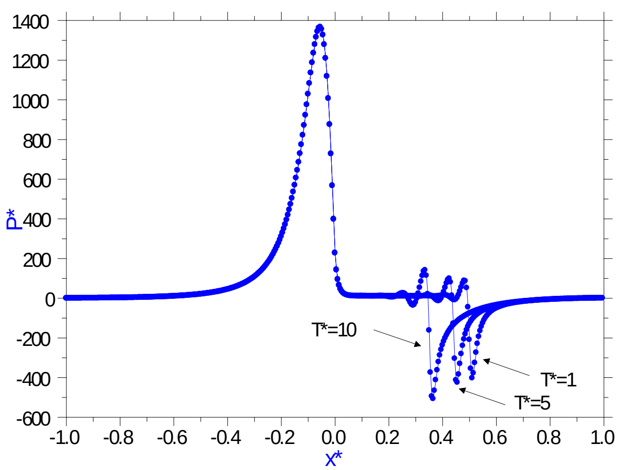

Figure 4. Pressure distribution for even lower web tensions for the same conditions as in Fig. 2.

The influence of the take off angle is shown in Figures 5 and 6. At high tensions and the web being pulled down, the web is pulled against the lower roll surface forcing a film split deep in the nip. This condition actually decreases the positive pressure pulse as well. As the tension decreases, the web is able to follow the top roll surface before it is peeled away. The peel location is decreased compared to the case where the web is pulled straight from the nip for high tensions, but for low tensions, it is similar.

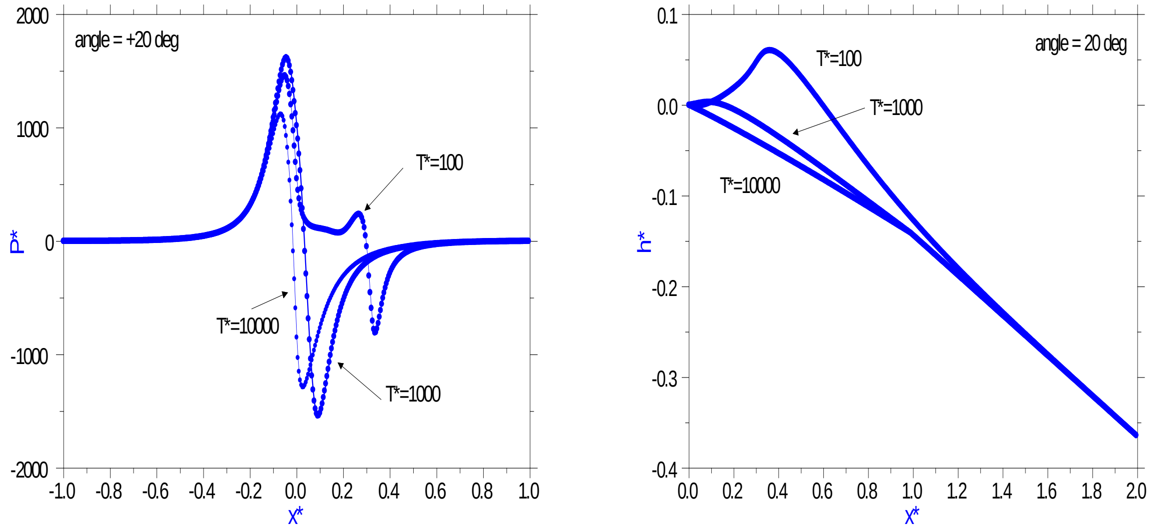

Figure 5. Results for positive (downward) take off angle of 20^o, with the take up point being x_p*=2.0 for hi*=0.01. Pressure profiles are shown on the left. Web trajectories on the right.

When the web is pulled upward, along the top roll surface, quite different behavior is seen. For high web tensions, the web is forced along the top roll surface, generating a large pressure pulse compared to when the web is pulled straight from the nip, as shown in Fig. 6. This angle and high web tension generates a converging nip situation that generates a large pressure; the web trajectories for this case shows the web much closer to the top roll surface than at low tensions in the right side of Fig. 6. As the tension decreases, the web again sticks against the roll surface, for quite some distance, before it is peeled away from the surface.

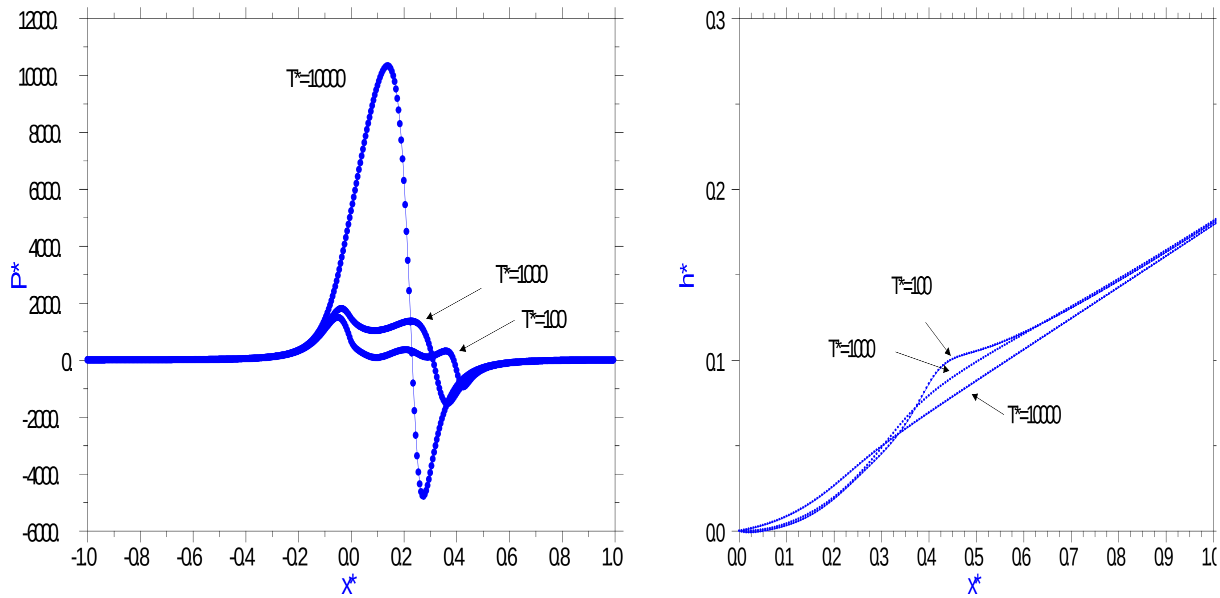

Figure 6. Same as Fig. 5 but for a negative angle of 20^{o}, with the web being pulled upward from the nip. Left side is the pressure distribution and the right side is the web trajectories.

The measured pressure distribution in a laboratory device confirms this general behavior. Figure 7 shows the pressure distribution of a 60 Pas silicon oil in the presence of a tensioned web. As the tension decreases, the location of the tack pressure moves away from the nip as well as it decreases in magnitude. Details of the experimental device and method can be found in Gates (2015).

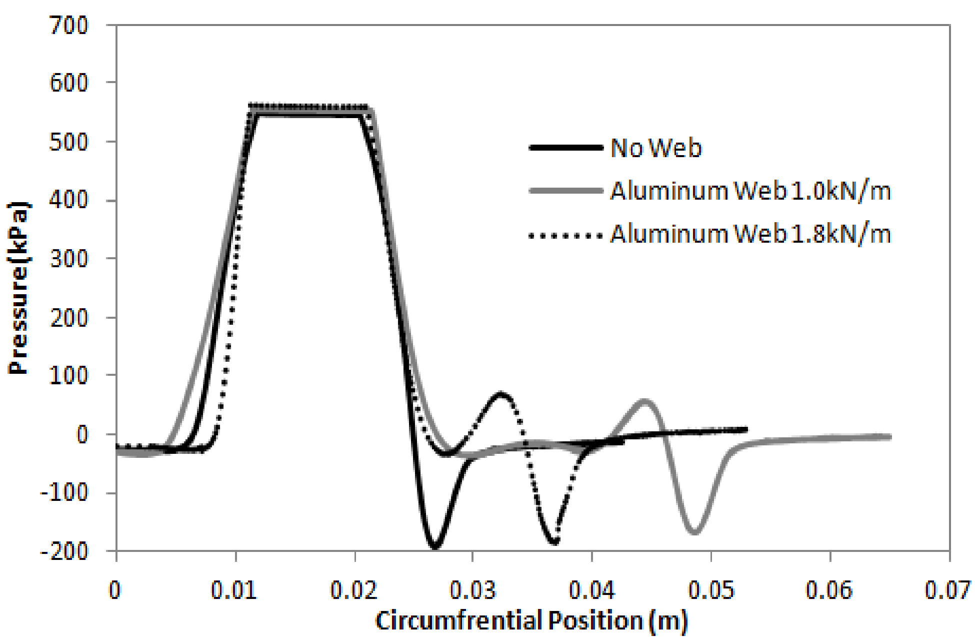

Figure 7. Measured pressure distribution in a laboratory device that had a tensioned web.

Concluding Remarks

A method is proposed to model the pressure distribution and web deflection at the exit of a roll coater. The method uses lubrication expressions to describe the flow field and a force balance on web nodes, to describe the web. The dynamics of the web are predicted as well as the final results. Webs are predicted to stick to the coated roll surface and peel away when the tensions are low. The web tension and take off angle influences the pressure distribution in the nip and the web trajectory. The results agree qualitatively with laboratory tests with a tensioned web.

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