EXTENDED ABSTRACT   ISCST

Web-fluid interactions during coating and printing.

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Summary

Roll and blade coating involves the application of a fluid to a web. This web is pulled away from the fluid layer. While the analysis of these coating flows are well developed, the influence of parameters associated with the web, such as web tension, are not well understood.

An experiment is proposed to measure the forces that are generated when a web is pulled away from a solid surface. Models are developed to predict the forces. A surprising force is found during the initial movement of the surfaces that seems to be caused by the need for air to be pulled into the region between the web and the lower solid surface. The experimental results compare well with the model predictions for most cases. An empirical expression is found that correlates the results for a wide range of situations.

Introduction

During coating and printing using a roll to roll process, the fluid exerts a force on the web at the nip exit. If this force is too large, it can lead to damage to the web by delaminating components of the web. For example, during printing, a common issue is called “linting” or “picking”: these events lead to unprinted spots in the image and a buildup of material on the ink roll. One method to prevent this is to increase the binder level in a paper coating. However, this leads to increase cost of the paper. Conditions to decrease this force during printing are not often of value.

The magnitude of this force, often called tack force, is an important parameter in understanding linting or picking. Tack is expected to dependent on pressure, viscosity, and velocity, but a good understanding of this force is not clear in the literature. Printing forces experienced by the paper web during printing and coating are critical to understand in order to avoid various printing defects such as linting and picking. In the paper industry, there are a number of common tests that measure ink tack (Zang et al., 1991; Gane and Seyler, 1994, and Xiang *et al.* 1998) but there is not a good understanding of the parameters that determine the magnitude of this tack value. Tack tests between a solid and a web under tension are also lacking in the literature; this is the situation at the exit of a printing nip.

The force of interest here is also similar to a peeling force. Studies of peeling force are also important in the adhesives literature. Zhao and Pelton (2003) show low peel rate of an adhesive can result in cohesive failure while high rates can result in delamination, similar to picking. Most analyses of peeling force treat the fluid layer as an elastic solid, not a fluid.

The force required to separate two rigid plates is common in the adhesion industry (Dubois et al., 2009). Stefan's Law describes the cohesive force to separate two parallel surfaces where the gap between the surfaces is much smaller than its width. Others have shown that cavitation and other effects are important. However, few have studied the situation where one boundary is a tensioned web. Here, experiments and models are used to understand the peeling away of a web from a fluid layer that is in contact with a solid.

Experiments and Model

In order to measure tack of a fluid between a solid and a web under tension, a simple apparatus consisting of an adjustable weight hung from a web attached to a frame across two rollers is constructed as shown in Figure 1. The top plate is attached to a load cell in a mechanical tester (Instron). Fluid is applied in consistent fashion to the web, which is subsequently compressed between two rectangular plates. At the start of the test, the top plate is accelerated upward to a target velocity. The web will deform upwards to some extent before the fluid is split. When the web is pulled upward, the forces on the top plate increase. Various fluids and webs are included in the experimental program. Newtonian silicon oils 60.8Pas and 12.5Pas are used as well as a typical offset cold set ink. Fluids were applied with a template to get an initial rectangular patch or as a drop to get a circular fluid shape on the web.

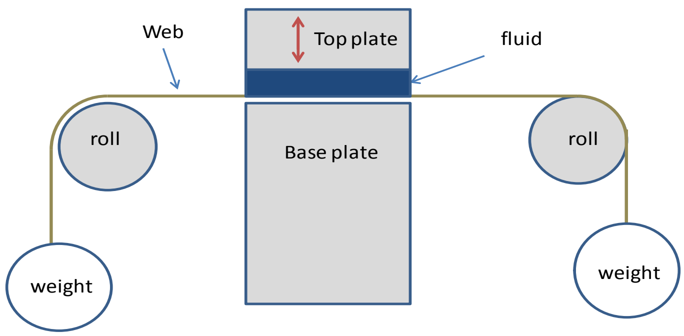

Figure 1: Schematic of the apparatus to tension a web on a base plate. The top plate contacts the fluid and is then moved upward at a known velocity.

A numerical model is developed that takes into account the web movement and vertical force balance between fluid and web interactions, nodal mass acceleration, and continuity. Figure 2 shows the important geometrical quantities. The web deflection is coupled to the fluid mechanics and is predicted by a force balance on a number of nodal points that represent the web position. The web sees forces from the tension applied, the fluid, and also from an air layer between the web and the bottom plate.

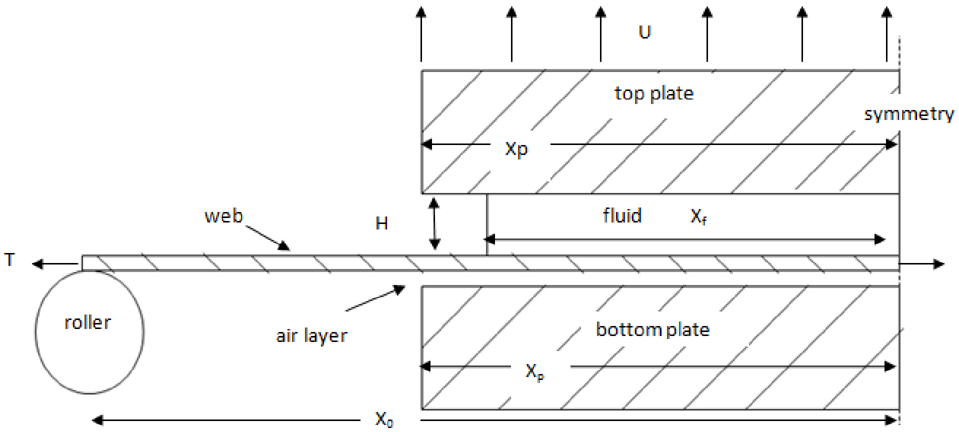

Figure 2: Parameters in model showing the initial gap H, the length of the fluid patch X_f and the presence of an air layer on the other side of the web.

Nodal points are fixed in the tangential direction to the plates and the number of nodal points is adjusted to satisfy continuity for the non-flooded model. Every node point will feel a vertical tension force based on the relative position of its neighboring nodes, as shown in Figure 3. Fluid forces F_f pull the web nodes in an upward direction as the top plate is moving and peeling forces are predicted. These fluid forces are estimated from lubrication expressions as

$$\frac{dP}{dx} = \frac{12\mu Q(x)}{h^3} \quad (1)$$

$$Q(x) = \int v dx \quad (2)$$

$$F_f = \int P dx \quad (3)$$

Where P is pressure, m is viscosity, Q is the flow rate per unit width, h is the local distance between the web and the top plate and v is the local average velocity. The pressure field in the film is obtained by solving Eqs (1) and (2) with finite difference methods. The integration of the pressure gives the fluid force at every node point.

Experimental results show that a force must exists that is caused by fluid forces of air as the web tries to move relative to the bottom plate. The same set of equations (1-3) are solved for an air layer on the other side of the film to generate air fluid forces F_a. A stiffness force F_s is also included in the model. These are predicted by solving a local bending problem of local nodes relative to the node of interest. The force balance on the nodes is shown in Figure 3. Web deflection is predicted by moving the web node points as they respond to local forces. A flooded version of the model does not account for the retraction of the fluid layer into the gap. A non-flooded version of the model adjusts the number of nodes and accounts for this retraction.

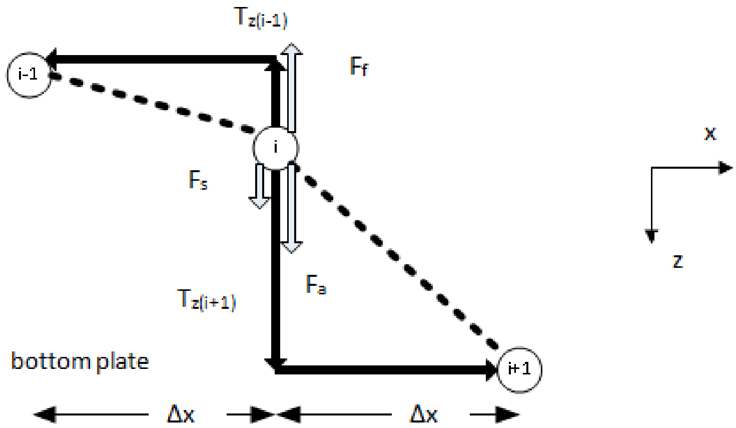

Figure 3: Nodal force balance shows tension forces on the node, fluid forces, air forces, and web stiffness forces.

Results

The models have four key input parameters that are the initial gap H, the target velocity of the top plate U, the viscosity of the fluid layer μ, the web tension T,the web elastic modulus E, and the length of the fluid layer in the direction of peeling X_f. Because this is a two dimensional model, the width of the fluid layer into the paper in Fig. 2 is assumed to be large. When accounting for an air layer on the other side of the web, the initial air layer thickness and the acceleration to the target velocity were also parameters. Dimensionless groups were formed. The key groups were dimensionless tension $T^* = T/\mu U$, fluid path length $X_1^* = X_f/H$, dimensionless stiffness $k^* = kH/\mu U$, and dimensionless force per unit width $F^*=F/\mu U$.

Finite difference methods solve for the pressure distribution in the fluid layer. This couples with the web deformation as described above. Figure 4 shows a node point being pulled upward on the left and how that pulls other node points upward that have a fluid layer under them. At high tension, the web acts more like a solid boundary instead of a peeling event.

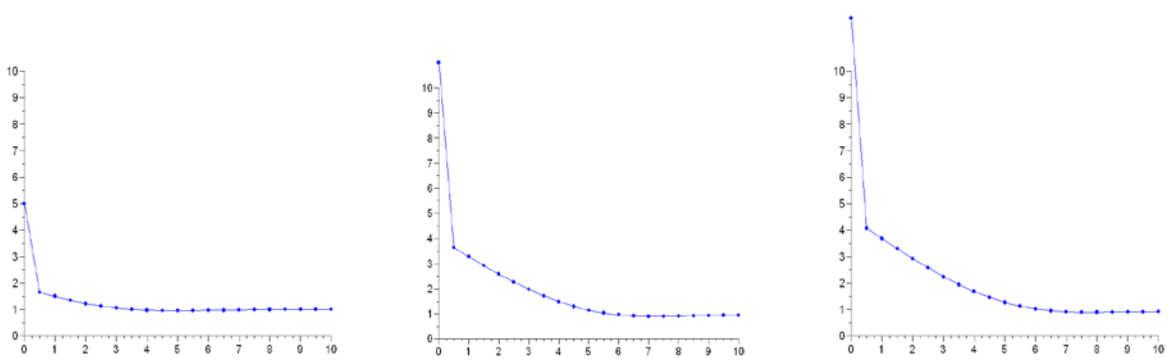

Figure 4. Example shape of web as a function of time, with time increasing left to right, with a fluid layer between the web and the x axis, and the node at zero location moving upward at a constant velocity.

Figure 5 shows the typical data from the experiment for 33 g/m^2 wood free paper as the web and 5ml of a 60 Pa.s silicon oil as the fluid. A real surprise is the initial forces that are generate even before the web has much opportunity to deform. This initial force exists even for aluminum foil and plastic films. This initial force seems to be caused by the need for air to flow into the gap between the web and the bottom plate before the web can deform. Therefore, this initial force seems to be controlled by the smoothness of the web and the web-solid interactions. When a thin tissue paper or power is placed between the web and the bottom plate, this force is reduced to a large extent; this is demonstrated in Figure 6. Force is made dimensionless with viscosity, velocity and the initial gap. Time is made dimensionless with the gap and velocity.

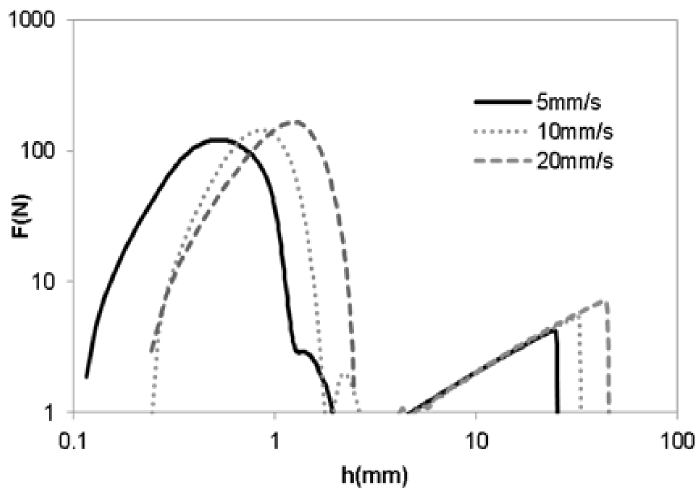

Figure 5: Force-gap results for a wood free paper at 91 N/m tension have different separation velocities.

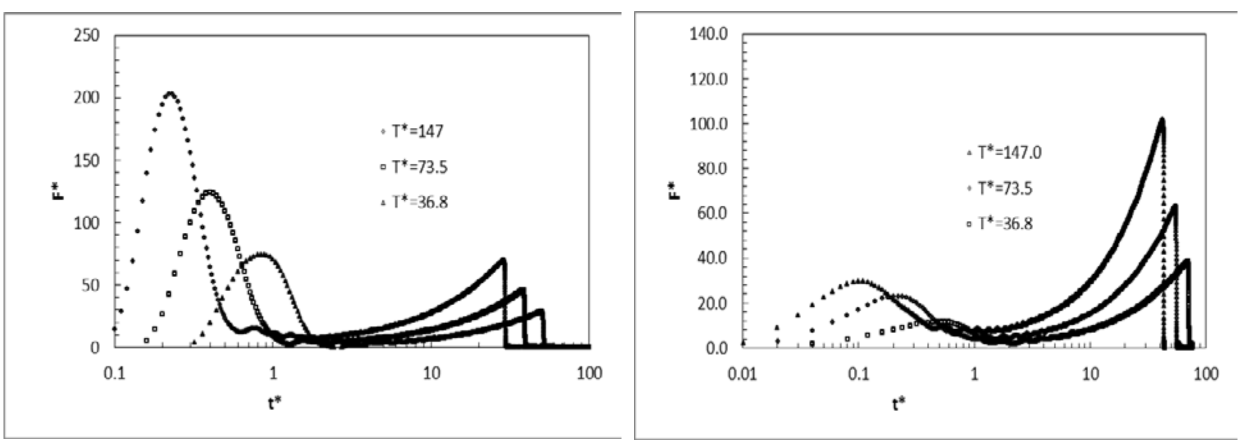

Figure 6: no tissue paper (left); tissue paper (right)

This model predicts the maximum average force, tack force, seen by the web. Consideration is given to different velocities, web tensions, fluid patch sizes, and air gaps between the web and baseplate. Figure 7 shows sample data for dimensionless force vs. time peeling curves assuming negligible suction forces for a 1x4 patch(left) and 4x4 patch(right) compared to numerical models.

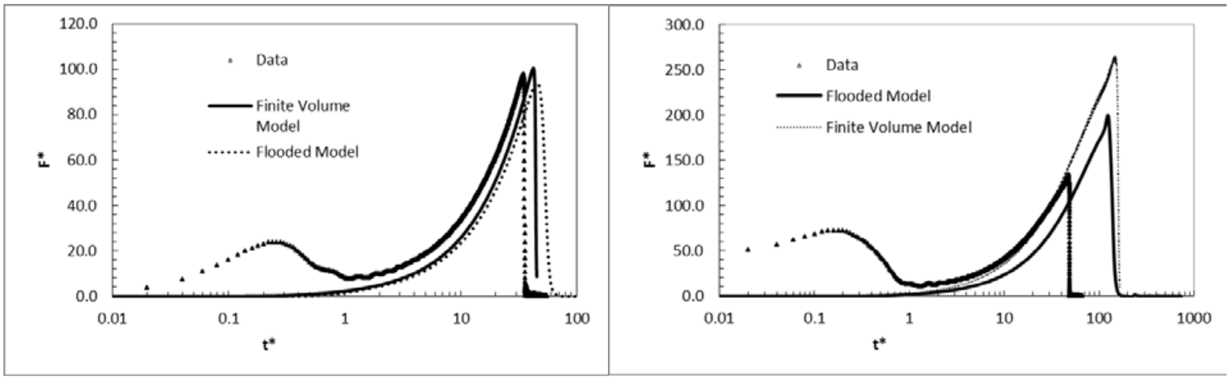

Figure 7: Results from patches of fluid compared to the models. Left is a 1x4 patch and right is 4x4 patch. Tissue paper is used to reduce the initial force.

Figure 8 shows model predictions of suction and peeling forces. Initially for both flooded and non-flooded models, the initial air gap is adjusted to fit the magnitude of the suction force. No parameters are adjusted to predict the peeling forces. Both models gives quite similar predictions of the peeling force and are quite close to the experimental results.

Figure 9 shows model predictions of maximum force for different patch geometries. The parameter X_1^* is half the length of the patch in the peeling direction divided by the initial gap. Patches were 24.5x100 mm in area for the X_1^*=12.7 (gap was 1mm) and 100x100 mm for X_1^*=63.5. For the smaller patches in the peeling direction, both model predictions are excellent with no adjustable parameters. However, for the larger patches, the models predict an increase in force, but this is not seen in the experiments. Examination of the patches of fluid show a distinct finger formation in the peeling direction. This fingering is linked to the ribbing instabilies in roll coatings and must lead to a lower force than what is predicted by a two dimensional model.

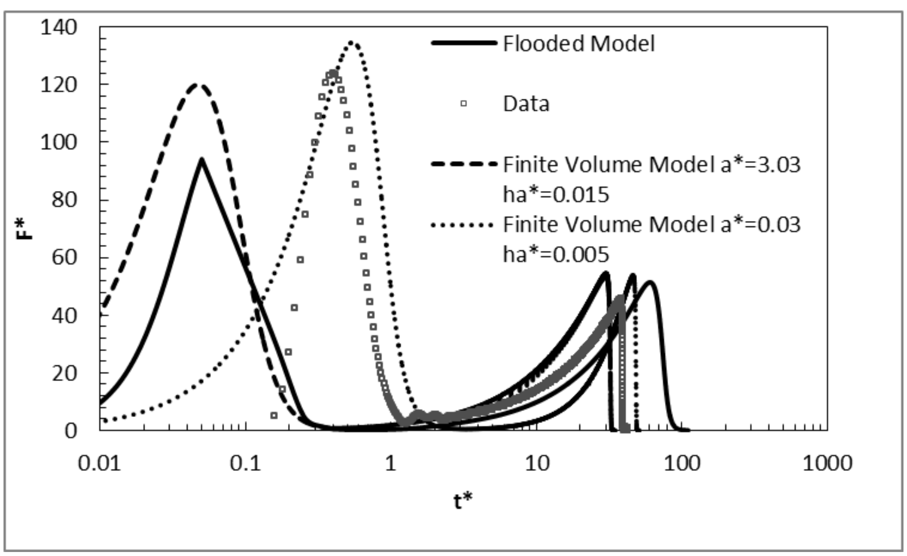

Figure 8: Suction force and peeling forces compared to model predictions.

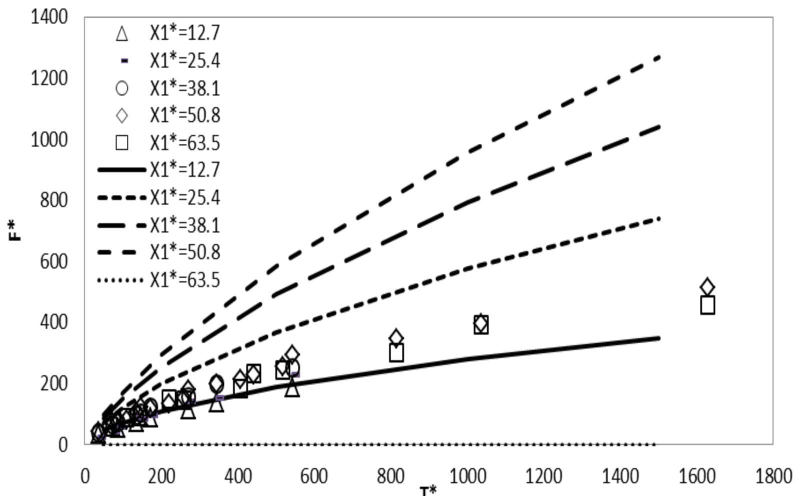

Figure 9: Maximum force for different patch geometries

Figure 10 shows a powerlaw fit for the patch data and for circular patch data. These simple expressions of dimensionless parameters seem to capture well the behavior. The tension is made dimensionless with velocity and viscosity as $T^* = T/\mu U$.

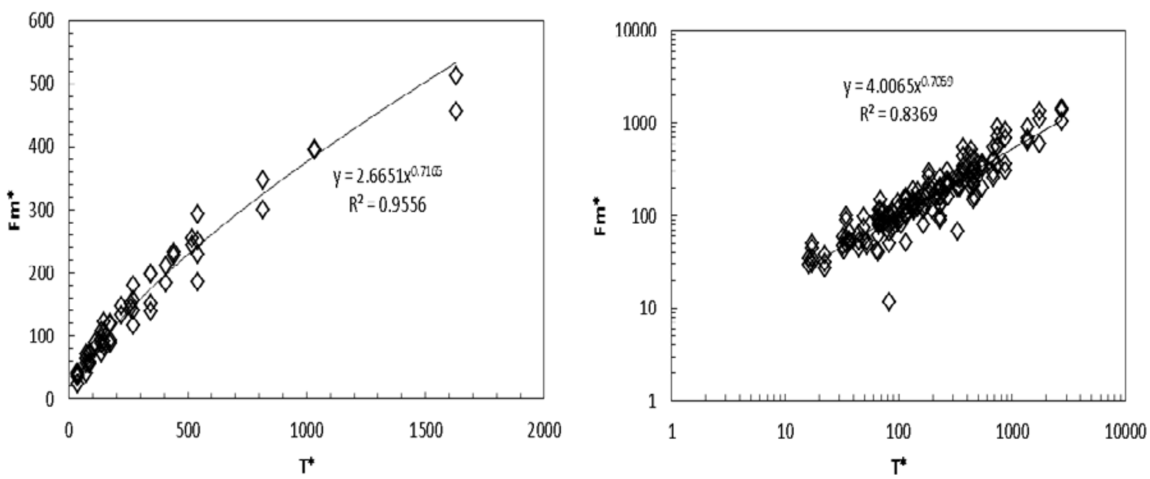

Figure 10: Empirical fit of dimensionless parameter for patch data (left) and circular data (right).

Conclusions

Experiments were conducted to quantify the forces that are generated when a web under tension is separated from a solid surface. An unexpected force is found in the first motion of the top plate that seems to be caused by the need for air to be pulled into the fine gap between the web and the bottom surface.   Models based on lubrication expressions coupled with a force balance were able to predict the results for most cases except for situations where a patch of fluid that is long in the peeling direction. The difference may come from a fingering event that reduces the forces due to three dimensional flows. Empirical models for suction and peeling forces are developed and compared to experimental data for different web materials, tensions, velocities, and fluids. A simple power law expression is found to be sufficient in predicting peeling forces.

Acknowledgements

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