Misting in forward roll operation compared to a filament stretching model

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Misting at the exit of a coating nip is a common problem in high-speed forward roll coating and printing operations. Misting can lead to serious health and housekeeping issues. While empirically this issue is generally understood, a good understanding of the fundamental physics is lacking in the literature. A recent PhD thesis made some advances at understanding the influence of process parameters and rheology on misting levels [1]. It is well known that as the operational speed increases, a transition of the film split at the exit of the rolls goes from a smooth split, to a ribbing pattern, and onto a “filament” region. The septa that form in the nip are stretched into filaments due to the roll surfaces separating at the exit. A key question remains: what conditions causes these filaments to break at one location to leave no drop, and what conditions cause filaments to break at two or more locations, leaving drops that would be ejected into the air? Figure 1 depicts that situation. Thinking about the physics, two limits of the stretching dynamics are possible: 1) the filament is stretched from one side and one boundary is stationary and as the experiments of James and Pouran [2], and 2) the filament is stretched from both sides. If inertial forces are not important, then these two limits would be the same, but the inertia of the fluid is expected to be important in these cases. These conditions are shown in Figure 2.

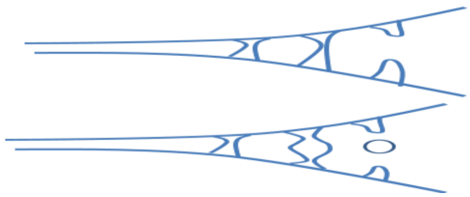

Figure 1. Filament breakage at nip exit.

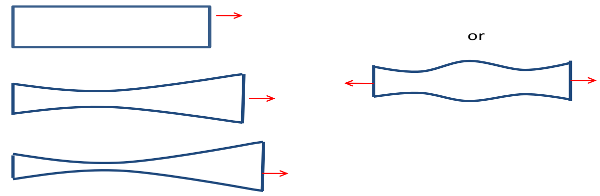

Figure 2. Two cases for stretching filament.

The thin filament or Cosserat equation is used to describe the dynamics of the filament that is being stretched. The equation accounts for inertia, viscous and surface tension forces. The conservation of momentum, that contains the local dimensionless velocity v is given by

$$\left(\frac{\partial v}{\partial t}\right) = -\frac{v}{R^2}\frac{\partial v}{\partial z} + \left[\frac{\partial}{\partial z}\left(R^2 P\right) + 2\left(\frac{1}{R\left(1+\frac{\partial R}{\partial z}^{2}\right)^{1/2}} + \frac{\frac{\partial^2 R}{\partial z^2}}{\left(1+\frac{\partial R}{\partial z}^{2}\right)^{3/2}}\right) R\frac{\partial R}{\partial z} + 2\frac{\partial}{\partial z}\left(R^2\frac{\partial v}{\partial z}\right)\right]\frac{Oh^2}{R^2} \qquad (1)$$

where R is the local radius of the filament made dimensionless with the initial radius, P is the dimensionless pressure, and $Oh = \mu/(R\sigma\rho)^{1/2}$ is the Ohnesorge number with σ is surface tension, ρ is density and μ is viscosity. The pressure is given by the Laplace equation that links the local curvature of the filament surface to the pressure difference as

$$P = \frac{\partial v}{\partial z} - \left(\frac{1}{R\left(1+\frac{\partial R}{\partial z}^{2}\right)^{1/2}} - \frac{\frac{\partial^2 R}{\partial z^2}}{\left(1+\frac{\partial R}{\partial z}^{2}\right)^{3/2}}\right) \qquad (2)$$

More complex rheology, including viscoelastic fluids, is not difficult to use within this framework. The other parameter that influences the results is the acceleration rate of the boundary. This can be calculated for the surface-surface separation of two roll surfaces. The acceleration rate A is a function of the roll radius and operation speed and can be made dimensionless as $A^{*}=A\mu^{2}R_o/\sigma^{2}$, where R_o is the initial radius of the filament. Only two parameters control the results, Oh and A* as well as how the filaments are stretched as in Fig. 2. This equation has been used in the past in various ways in the past, but what is unique here, is the stretching boundary condition that mimics the accelerated filament stretch at a nip exit.

The shape of three different viscosity levels is shown in Figure 3, for the same acceleration of A*=0.1. As the Ohnesorge number increases, the filament stretches to a thin thread and would change from breaking at two positions to eject a drop, compared to one position with no drop. This agrees well with recent experiments in our laboratory where the collected amount of misting decreases with increasing viscosity.

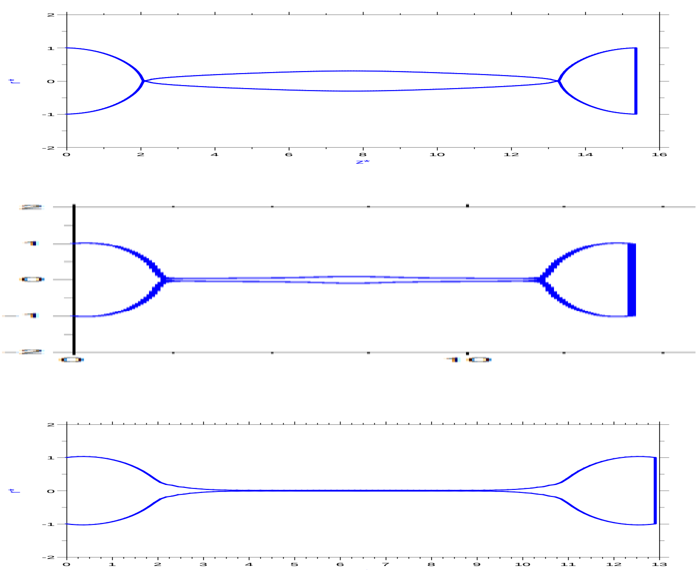

Figure 3. Final filament shape at breakup for Oh=1.0 (top), Oh=10, (middle) and Oh=100 (bottom).

The location of breakup can be influenced by what boundary is moving relative to the fluid. If only one boundary is accelerated, then the results in Figure 4 are obtained: breakup happens first near the boundary that is accelerated. The breakup moves from being symmetric, as in Fig 3. (top), to breaking first on one side. This is caused by the fluids inertia, trying to accelerate the mass of the fluid only in one direction. This shape is similar to what is reported by James and Pouran [2] where only one boundary is accelerated away from another. If the acceleration is in both directions, the filament breaks at two places at the same time, leading to the formation of a drop of fluid.

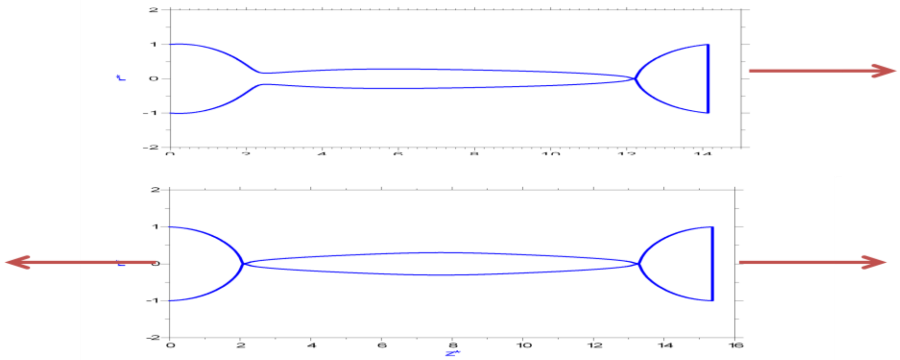

Figure 4. Results for A*=0.1 and Oh = 1.0.

As the acceleration increases, more mass is left in the potential drop. Figure 5 shows the predictions for a higher acceleration rate. The filament stretches to a larger extent, but the amount of fluid in the potential drop is increased. This agrees with recent experiments, and as commonly known, that the amount of misting increases with increasing speeds.

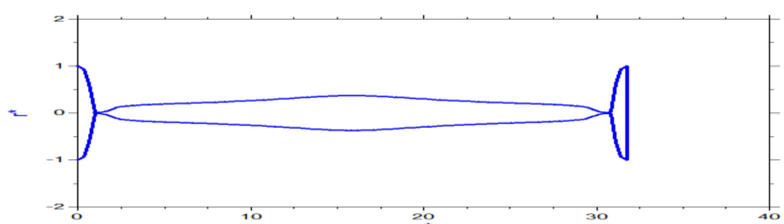

Figure 5. Shape predictions for Oh= 1 and A*=1.

The filament stretching model seems to be helpful in understanding and quantifying the physics around filament stretching at the exit of a coating nip. Drops are formed at low viscosity and high acceleration rates.

1. Owens, Michael, 'Misting in Forward Roll Coating: Structure, Property, Processing Relationships", PhD Thesis, University of Minnesota, 2005.
2. James D. F., and M. Pouran, "Droplet formation in quickly stretched liquid filaments", Rheol. Acta, 48:611-624 (2009).