Parameters that Control Misting During Printing

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Motivation

- Misting often limits processing speeds and causes environmental issues.
- A number of parameters influence the results such as speed, rheology, and substrate.
- Still not well understood.
Phenomenological Facts about Misting

- Misting increases as
  - Temperature increases
  - Humidity decreases / electrostatic fields increase
  - Ink film thickness increases
  - Roller speed increases, misting = k (speed)^n
  - Air Entrainment increases

Misting Mechanisms

- Mist Formation
  - Film-Split
  - Film-Split + Air-Entrainment

- Sling Formation

![Diagram showing ink, misting, nip center, peak height, valley depth/tack value, pressure, time, and deformation types such as extensional and shear.]
Objective and Background

• fill the gap between the industrial press misting performance and the rheological characterization of inks
  – Misting data at similar conditions to commercial presses
  – Visual performance / misting data
• Results for 6 inks are provided in this presentation.

<table>
<thead>
<tr>
<th>Ink ID</th>
<th>Viscosity (Pa.s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>13.6</td>
</tr>
<tr>
<td>B</td>
<td>59.3</td>
</tr>
<tr>
<td>C</td>
<td>11.8</td>
</tr>
<tr>
<td>D</td>
<td>41.5</td>
</tr>
<tr>
<td>E</td>
<td>8.7</td>
</tr>
<tr>
<td>F</td>
<td>7.8</td>
</tr>
</tbody>
</table>
Pressure Profiles and Visual Representations

- Pressure pulse for ink A with roll speeds of 1 and 1 m/s. Different series are the same ink but repeated passes through the nip.

Gap held between rolls
To around 100 mm

**FIXED GAP RESULTS**

- Surface of roll corresponding to the above pressure profiles.
Dimensionless Groups: Definition

- Misting No., $Nm$
  
  $N_m = \frac{M_m}{2\pi RN_{Rev} \rho Wh}$

- Pressure No. $N_{\Delta P}$
  
  $N_{\Delta P} = \frac{(h/D)\Delta P}{\frac{1}{2} \rho U^2}$

- Reynolds No., $Re$
  
  $Re = \frac{\text{inertial force}}{\text{viscous force}} = \frac{\rho h U}{\eta}$

- Weber No., $We$
  
  $We = \frac{\text{centrifugal force}}{\text{surface force}} = \frac{\rho U^2 h}{\sigma}$

Note, this misting number is different than what Olsen’s thesis suggests.
Misting No. vs. Reynolds No.

- Mist number as a function of Reynolds number. The data is for six inks at three different speeds.
Impact of Centrifugal Forces on Misting Generation

• Criteria for a fluid surface to sling out droplets
  – To grow fluid surface defects, a modification of the analysis of Roper et al. (1997)

\[ We > \left( \frac{2\pi L}{\lambda} \right) \text{ where } L = (Rh)^{1/2} \]

- To breakup the filament from the coated fluid (sling) before the filament rotates a complete cycle and meet the nip again. So the time for the filament to break needs to be shorter than the following

\[ t_{\text{filament-break-to-sling}} < \frac{2\pi R}{U} \]
Lubrication analysis

Accounts for surface tension, centrifugal forces, geometry, and viscosity.

Axisymmetric around $r=0$

Particle differential equation for $h$ that is solved with finite difference methods
Growth of a Disturbance into a Filament

- Growth of a disturbance into a filament for a film thickness of 100 µm, a speed of 10 m/s, viscosity of 1 Pas, an initial disturbance of 50 µm, a surface tension of 30 mN/m, and roll radius of 0.1 m for a total elapsed time of 60 ms.
Impact of Initial Disturbance Size

- The difference in height between the highest and lowest points of the film for conditions above but for different initial disturbances.
- Large initial disturbance is needed to generate a spout in the time available.
Growth often too slow to generate drops.

Key finding – growth is slow if starting from small disturbance, but large if it starts from a filament remain.
Mechanism

- When do we break at one point and when two points?
Problem setup
A few issues

- How to move mesh.
- Boundary condition at surfaces.
- Initial velocity conditions.
- Initial radius or filament shape.
Thin filament or Cosserat equations

- Mass and momentum equation averaged in radial direction.

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

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

For a Newtonian fluid.
Other rheology not hard.
Other rheology

\[ \rho R^2 \left( \frac{\partial v}{\partial t} + v \frac{\partial v}{\partial z} \right) = \frac{\partial}{\partial z} \left( R^2 T_{zz} \right) + 2\sigma \left\{ \frac{1}{R \left( 1 + \frac{\partial R^2}{\partial z} \right)^{1/2}} + \frac{\partial^2 R}{\partial z^2} \left( 1 + \frac{\partial R^2}{\partial z} \right)^{3/2} \right\} R \frac{\partial R}{\partial z} \]

Axial stress. Term.
Work in dimensionless quantities.

- R (filament radius), L(initial length), U(velocity of roll surface normal), \( \mu, \rho, \sigma \) (fluid properties). Three units. Leads to three dimensionless groups that control.

- In the real case, the filament stretching starts at zero and increases linearly as \( A=U_w^2/R_r \) web speed and roll radius.
Quantities

- $r^* = \frac{R}{R_o}$  filament radius
- $z^* = \frac{L}{R_o}$  filament length
- $u^* = \frac{U\mu}{\sigma}$  velocity
- $t^* = \frac{t}{\sigma R_o}$  time
- $Oh = \mu / (R_o \sigma \rho)^{1/2}$
- $A^* = \frac{A \mu^2 R_o}{\sigma^2}$ where $A$ is the rate of increase.
- Velocity at end increases then as $A^* t$
- 3 parameters $z^*, A^*, Oh$
Key results

Initial length did not influence if it was less than the unstable wavelength $L < pR$

As Oh increases, filaments generated are thin and have a chance to break at one point.

As speed increases, much more fluid left in the middle.

Pulling from one end, instead of from both, promotes breakup at one point.
Oh = 10     A* = 0.1
$O_h = 1 \ A = 1$
Oh = 1 A = 0.1
Oh = 10  A = 0.1
**Other cases**

- **Oh = 100  A = 0.1**

- **Oh = 10  A = 0.01**
Pulling one boundary causes single point breakup

Oh = 1  A = 0.1

Fluid

James, 2009
Oh = 0.006
Oh = 10  A = .1

Only pulled to the right
James, Oh = 0.13
Breaking lengths

![Graph showing breaking lengths](image)

- **James et al. Newtonian**
- **Filament model**

The graph plots $\ln(Lb/Lo)$ against $Oh$, with data points marking the transition from one model to the other as $Oh$ increases.
Results agree with experiments

- High viscosity leads to thin filaments and longer breaking lengths. **Oh controls.**

- Increase speed leads to more fluid being left in drop --- relates to more misting in experiments. **Small A* reduces misting.**

- Initial thickness scales problem, but not the onset of misting. (nip loads in experiments).
Practical implications

- The only parameter that is reasonable to control is ink rheology. High viscosity inks linked with less misting. We still do not understand viscoelasticity of inks on misting.
- Control of the filament forming stage is important. Can additives me included to generate smaller scale filaments?
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