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Drop Size Modification in Black Liquor Sprays from Commercial Nozzles Using Vibratory Assist

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DROP SIZE MODIFICATION IN BLACK LIQUOR SPRAYS FROM COMMERCIAL NOZZLES USING VIBRATORY ASSIST

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ABSTRACT

Improvement of spray nozzles for black liquor injection into kraft recovery boilers is expected to result from knowing how to obtain a controlled, well-defined droplet size distribution. Black liquor drop size data were obtained from an environmentally acceptable spray facility capable of delivering liquor at normal firing temperatures using commercial nozzles. Image analysis techniques were developed from high-speed video images which gave good two-dimensional representations of black liquor sprays. Previous work showed that black liquor sprays have a characteristic size distribution which is determined by the fluid mechanical forces breaking up the spray sheet issuing from the nozzle. This work has centered on applying vibratory assist as an independently controlled force on the sheet breakup process in an attempt to change the drop size distribution. Experiments are described which featured vibratory assist applied in the axial direction. Results are presented which show the dependence of median drop size on pulsation frequency up to 450 Hz.

INTRODUCTION

The most important unit operation employed in the recovery cycle of the kraft pulping process is combustion of black liquor in the recovery boiler. This step is initiated by spraying the concentrated liquor through one of several types of commercial nozzles, the most common being the splashplate, the V-jet, and the swirl cone. The liquor issues from the nozzle as a thin sheet, which subsequently breaks up into droplets whose diameters are predominantly in the one- to four-millimeter range. These droplets then go through the sequential processes of drying, pyrolysis and gasification, combustion, chemical reduction, and smelt coalescence (1). The rates at which these physical and chemical processes occur are highly dependent upon the size and size distribution of the droplets formed from the spray. The smaller the droplet, the greater the surface area per unit mass of liquor and hence, the greater the rates of heat and mass transfer per unit mass. While this is desirable for increasing capacity, it is offset by higher droplet entrainment and carry-over, which are characteristic of small particles in an upward flowing turbulent gas stream. Inevitably, this results in accelerated fouling of the relatively cool boiler tubes and more rapid plugging of the heat transfer section of the boiler.

An applied research program under U.S. Department of Energy sponsorship was undertaken to identify the optimum black liquor delivery system for the kraft recovery boiler. Because the preferred drop size distribution for optimum recovery boiler operation is not known, the fundamental objective was to develop ways to control droplet formation such that, once the optimum combustion conditions are actually known, the specified drop size and size distribution can be obtained and optimal operation achieved. A recovery boiler modeling project is currently underway at the Institute of Paper Science and Technology (IPST) to help determine the black liquor droplet size and velocity distribution which optimizes use of the furnace volume.

Potential benefits from this applied study can be found in improved energy efficiency and increased process productivity. Thermal efficiency gains are projected up to 500,000 BTU per ton of pulp, or about 3×10^{13} BTU/yr for present U.S. pulp production. The recovery boiler is a pulp mill operation which can often claim that improved unit productivity will result in increased millwide productivity. A 1% gain in production industrywide can result in a $200-300 million per year increase in profits (2).

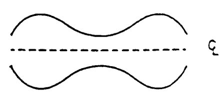
Previous testing with V-jet and splashplate nozzles showed a weak dependence of median drop size on liquor velocity and fluid properties, the most important parameters being nozzle diameter and liquor density and velocity (3). At high solids levels, liquor viscosity also became important. Furthermore, the drop size distribution model to best fit the experimental data was the square root-normal distribution. The extensive experimental database showed that the normalized standard deviation, defined as the ratio of the standard deviation to the square root of the median diameter, has a constant value of 0.19, implying the square root-normal model for black liquor sprays can be characterized by one parameter.

These findings suggested that gaining any degree of control over drop-size distribution would require some external force, independent of the viscous, momentum, and surface tension forces which fundamentally control the droplet formation process. Such an independently applied external force is vibratory assist. Vibration of the liquor flow can be done either in-line with the flow (i.e., axially) or normal (i.e., transverse) to it. The resulting waves in the liquor sheet issuing from the nozzle should be in the dilational and sinuous modes, respectively (cf. Figs. 1 & 2).

Figure 1 - Vibratory Assist

Dilational Wave Generation

- Wave-like Disturbances to Upper and Lower Surfaces of the Sheet Are Out of Phase

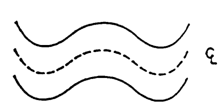


- Vibration in Direction of Liquor Flow

Figure 2 - Vibratory Assist

Sinuous Wave Generation

- Wave-like Disturbances to Upper and Lower Surfaces of the Sheet Are in Phase



- Vibration in Direction Normal to Plane of the Sheet

Conceptually, the dilational mode would be expected to give a narrower drop size distribution, since the breakup of the sheet into ligaments should occur at the lines of minimum thickness. These are not randomly placed but are determined by the pulsations imposed on the flow. This reduces the randomness in the drop formation mechanism and should cause a narrowing of the drop size distribution, even though the subsequent breakup of ligaments into drops will still be a random event.

Vibrations normal to the plane of the sheet should give sinuous waves in the liquor sheet and not effect a significant change. This is because, conceptually, the sheet thickness is constant throughout, maintaining the mechanism of sheet breakup as a random phenomenon going to ligaments, which then randomly break up into drops. Limited experimentation using an air vibrator oriented normally to the plane of the spray sheet gave a 15-30% increase in median diameter and distribution width but no change in either spray parameter using a mechanical vibrator (4).

NOMENCLATURE

D	droplet diameter	ℓ	length of ligament
F	volumetric liquor flow rate	R	radius of ligament
f	pulsation frequency	v	sheet velocity
h	sheet/ligament thickness	w	width of ligament
L	sheet breakup distance	θ	spray sheet angle

THEORY

For vibratory assist to work effectively, it must be done at the proper frequency and amplitude. Otherwise, the natural frequency of the sheet will dominate, giving a square root normal distribution of drop sizes. A model of droplet formation under the influence of axial vibratory assist based on fundamentals should reveal the effect of operating frequency on drop size at a given set of operating conditions.

Assuming that the velocity and the thickness of the spray sheet are uniform at a given distance from the nozzle, wave theory stipulates that an unstable sheet breaks at every half wave length. The bands of liquor thus formed then break up into droplets. Knowing the volumetric liquor flow rate, the subtended angle of the spray sheet, the breakup distance from the nozzle, and the desired radius of the bands of liquor (i.e. ligaments), the length and thickness of a ligament can be calculated:

$$\ell = 2\pi L\theta/360 \qquad (1)$$

$$h = F/(v\ell) \qquad (2)$$

At the point of sheet breakup, a ligament will have width w and thickness h; this ligament will then assume an approximate circular cross section having an area of πR^2. Therefore,

$$w = \pi R^2/h \tag{3}$$

Substituting (2) into (3),

$$w = \pi R^2 v\ell/F \tag{4}$$

According to wave theory, an unstable sheet breaks at every half wavelength (w). Therefore,

$$f = v/(2w)$$

$$= F/(2\pi R^2\ell) = 90F/(\theta L(\pi R)^2) \tag{5}$$

Rayleigh's instability theory predicts that an unstable strand is most likely to break at nine times its radius (5). Hence, a ligament will break up into $\ell/9R$ droplets, each having diameter D. From a mass balance on a ligament,

$$\ell/9R = \pi R^2\ell/(\pi D^3/6)$$

or

$$D = 3.8R \tag{6}$$

Substituting Eq.(6) into Eq.(5),

$$f = 132F/(\theta LD^2) \tag{7}$$

Assuming typical values for the process parameters ($F = 76$ ℓpm, $L = 1$m, $\theta = 120°$), the estimated vibrational frequency to produce a drop diameter of 2.5 mm is:

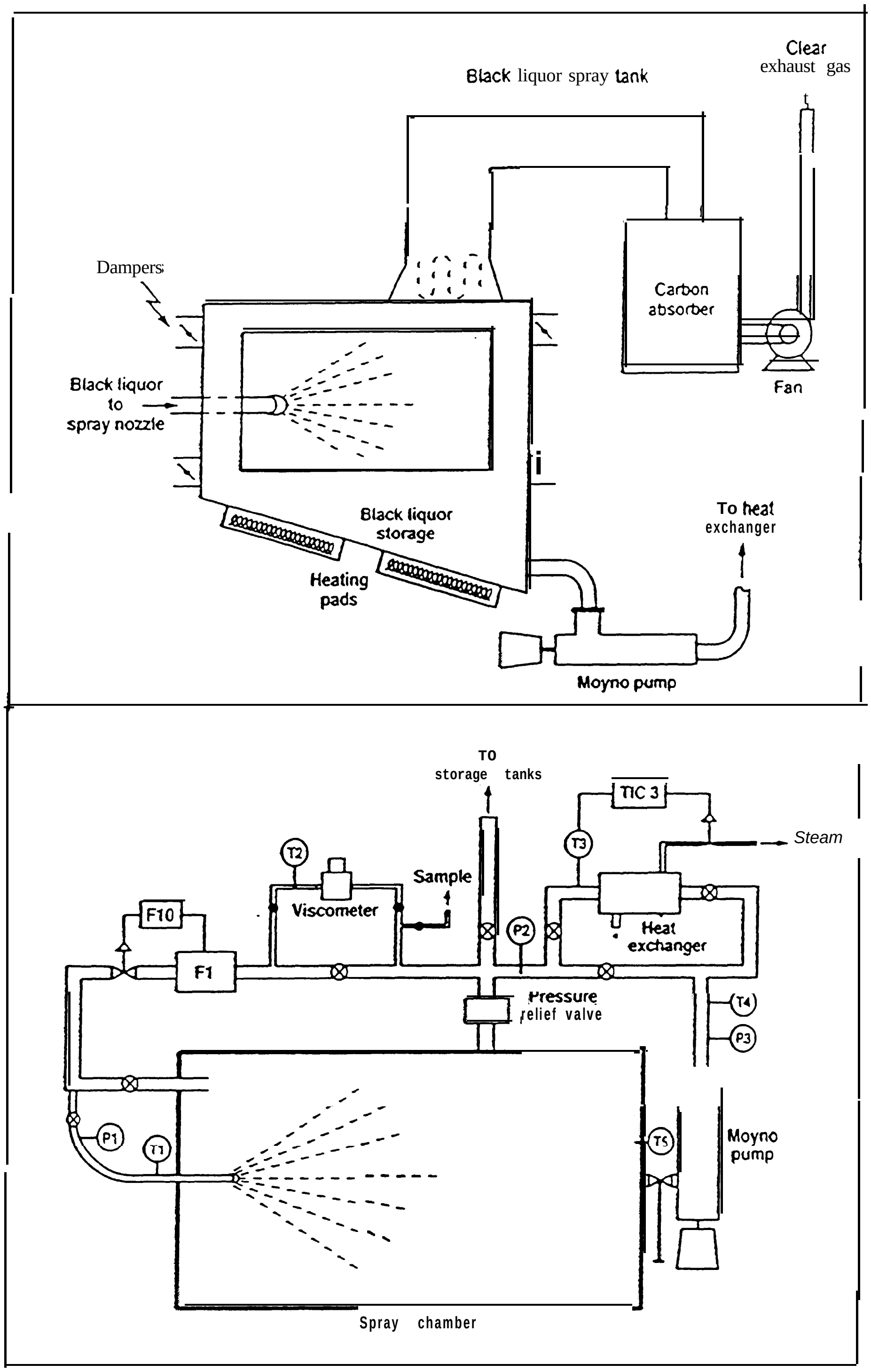
$$f = (132\times76/(120\times1\times6.25))\times17.9$$
$$= 240 \text{ Hz}$$

The analysis above is highly simplified, with a key assumption being that the sheet breaks up into discrete uniform bands with no interactions between adjacent bands. Also, if the ligament (or band) is wide and irregular, it may subdivide into several smaller ligaments. Nonetheless, the model does point out the important physical parameters, how they interact, and the magnitude of the vibrational frequency associated with a typical drop size.

EXPERIMENTAL

A spray facility (cf. Fig.3) was constructed to test both commercial spray nozzles and new experimental nozzle designs over a wide range of process conditions. The system was designed to be large enough that nozzle sizes compatible with present recovery boilers could be tested. The spray was contained in a large spray chamber (2.1 m by 1.8 m by 3.0 m) with tempered glass

Figure 3 - IPST Black Liquor Spraying Facility



windows which allowed videotaping of the spray pattern and drop distribution. Black liquor flow rates as high as 190 liters/min could be tested. A spiral heat exchanger and a direct steam injection system provided liquor temperatures as high as 135°C (275°F). Instrumentation and data acquisition hardware and software recorded operating conditions for each test, including temperature and viscosity of the liquor, nozzle pressure and flow rate, and liquor solids content.

The spray chamber had an off-gas scrubber system to prevent the release of odor due to reduced sulfur compounds from the black liquor. An induced draft fan maintained a slight vacuum on the chamber (similar to the firing zone of the recovery boiler), and the exhaust gas was drawn through an activated carbon adsorber (donated by Westvaco Corporation) before being released to the atmosphere.

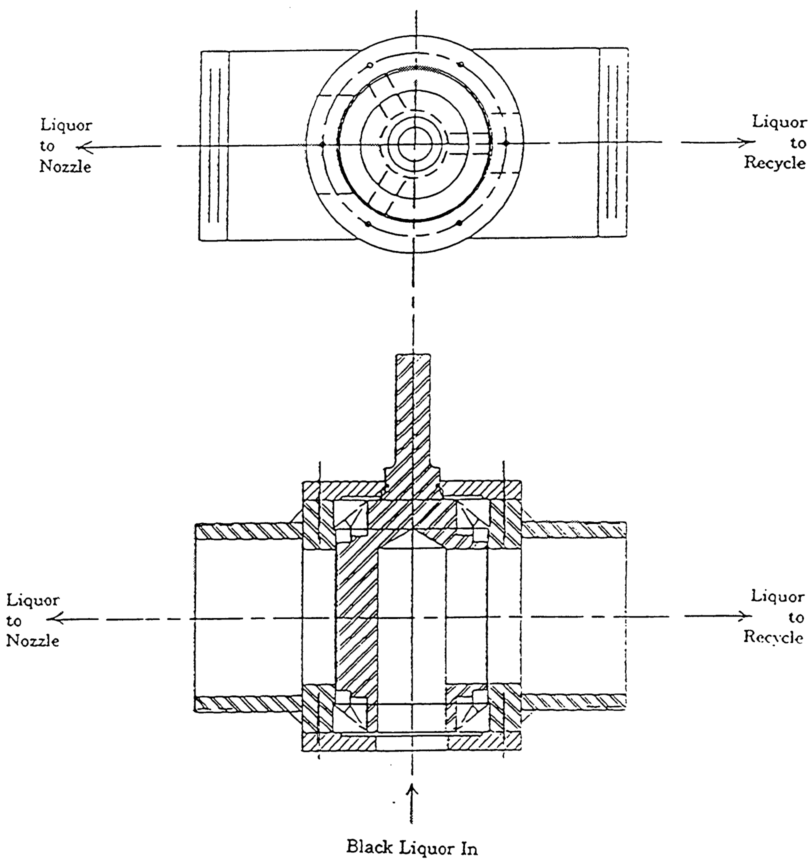
A high-speed video camera manufactured by Xybion Electronics Systems (Model ISG-250) was used to record the spray pattern and the drops which formed. The camera has an adjustable image capture gate range (shutter speed) of 25 nanoseconds to 20 milliseconds. By using a Micro Channel Plate Intensifier and a charge coupled device image array, the camera is able to operate at light levels down to 1 millionth foot candle. Camera resolution was 768 $\times$ 493 pixels. Drop size data were obtained with a Tracor Northern TN-8500 image analyzer.

One mode of achieving vibratory assist in the axial direction is to use flow interruptions rather than direct pulsations. This was accomplished by using the design depicted in Fig. 4. In this design, continuous delivery of nozzle solids black liquor with vibratory assist in the axial direction is accomplished by a cylinder rotating within a stationary pipe section. The outer pipe contains two outlets that are diametrically opposed. One outlet on the outer pipe is connected to the nozzle orifice, while the other outlet is connected to a recycle line. Black liquor is fed continuously to the inner cylinder which is rotating at a rate set by a drive motor assembly.

The rotating cylinder wall contains three or more holes that are positioned such that, at any one instant in time, only one of the holes is lined up with either of the two openings in the outer pipe. Liquor flows out to the nozzle or to the recycle line, as dictated by whether or not a hole in the rotating cylinder lines up with one of the two openings in the outer pipe. Thus, when liquor flows to the nozzle orifice, it doesn't flow to the recycle, and vice versa. Leakage through the annular space between the rotating and stationary bodies is minimized by providing a tight clearance between the bodies.

The net effect of this concept is to provide a pulsed flow to the nozzle orifice while not deadheading the black liquor pump. The frequency of pulsation is determined by the angular rotation speed provided by the drive assembly and the number of holes in the rotating piece. Additional holes could be drilled in the rotating cylinder to increase the frequency of spray interruption. The amplitude of pulsation is a complicated function of the number of holes in the rotating body, the sizes of the two holes in the stationary piece, and the leakage between the rotating and stationary bodies. A Disclosure of Invention has been filed covering a nozzle to give a pulsed black liquor flow by the flow-interruption mode described above.

Figure 4 - Black Liquor Flow Distributor (Interrupted Flow Mode)

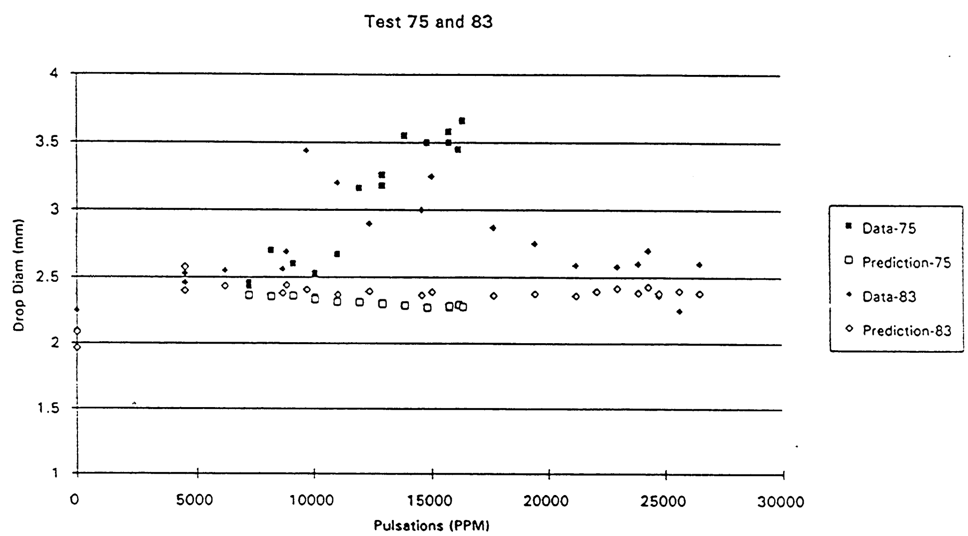


RESULTS

Testing with axial vibratory assist using the interrupted flow mode described above was carried out with 62% solids black liquor flowing through a 3/8-inch V-jet nozzle at 73°C and 30 ℓpm. Liquor viscosities ranged from about 100 to 160 cP.

The distributor design was machined so that liquor flowed to the nozzle orifice 1/4 of the time (3/4 time going to recycle). The frequency range extended from 0 Hz up to 450 Hz; liquor solids and temperature (∴ viscosity) were held constant. Interestingly, median drop size increased from 2.2 mm with no pulsation up to a maximum of 3.5 mm at about 230 Hz, then decreased steadily to 2.5 mm at 450 Hz. The shape of the drop diameter vs. frequency curve was nearly sinusoidal, supporting the expectation of harmonic behavior that should be characteristic of a vibratory process (cf. Fig.5). Also shown in Figure 5 are calculated values, based on earlier results (3), for the median diameters that would have resulted at the same process conditions with no pulsation. The normalized standard deviation of the drop size distribution did not show any variation with pulsation frequency.

Figure 5 - Effect of Vibrational Frequency on Median Drop Diameter

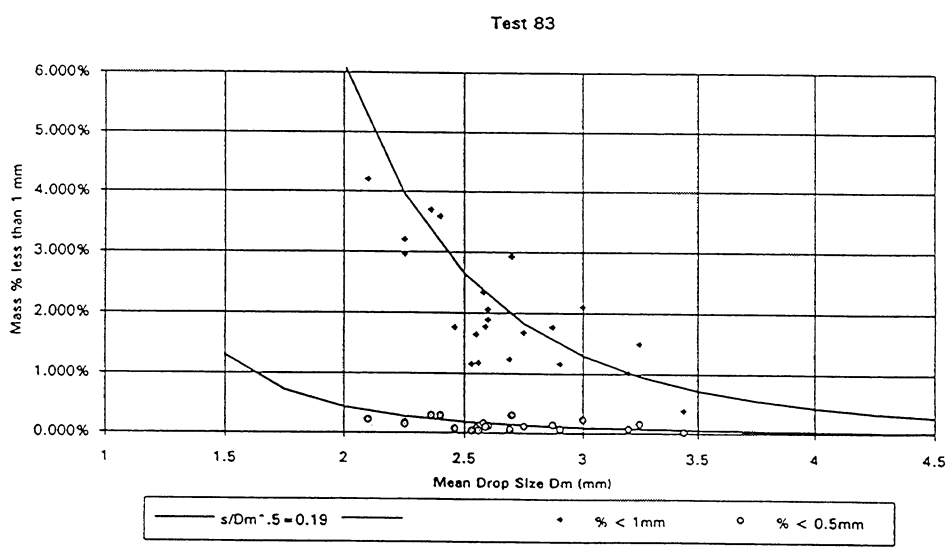


It is interesting to calculate the frequency that theory would predict to give a 3.5 mm diameter drop at the 30 ℓpm flow rate. The subtended angle for the V-jet nozzle was about 60°, and the breakup length (L) was about 1/3 m. Substituting the values into Eq.(7), the predicted frequency is 294 Hz. The agreement with the observed harmonic frequency reported above is better than could be expected.

The important question at this juncture is: What do these results mean with regard to optimizing recovery boiler performance? A major operational concern is droplet carry-over, and this study has not demonstrated any ability to narrow the drop size distribution which might result in reducing the fraction of small size droplets and thereby reduce carry-over. But narrowing the drop size distribution is not a necessity; what would seem to be necessary is a reduction in the fraction of "small" drops, or a skewing of the distribution toward the larger diameters. What has been shown in this work is a way of increasing median drop diameter without changing the size distribution and doing this independent of the normal process operating parameters (e.g., temperature, per cent solids, nozzle diameter). The only quantity that needs to be changed is frequency.

If these results are used to calculate the frequency dependence of the mass fraction of drops in a given spray that would be less than some small diameter, say 1 mm, 4% of the drops would be less than 1 mm at zero pulsation (median drop diameter 2.2 mm) and a little under 1% at the 230 Hz condition, which gives a median drop diameter of 3.5 mm (cf. Fig.6). Hence, the fraction of smaller drops in the spray would be reduced by a factor of four using the independently controlled variable - pulsation frequency. This may have interesting implications for reducing carry-over in recovery boilers. Predictions using the IPST recovery boiler model currently being developed will be generated to confirm this desired result.

Figure 6 - Effect of Median Drop Diameter on the Fraction of Drops Smaller than 1 mm



CONCLUSIONS

1. Gaining some measure of independent control over drop size distribution in black liquor sprays from commercial nozzles will require an independently-controlled external force, such as vibratory assist.

2. Vibratory assist in the axial direction, as applied to black liquor spraying, was accomplished with a novel nozzle design. Achieving a pulsed flow by inducing periodic flow interruptions showed some promise in changing the mean drop size without changing the normal process operating parameters. A harmonic frequency existed where a minimum of small size drops was made.

3. To what extent the drop size distribution should be narrowed or skewed to have a positive impact on recovery boiler performance is not known at this time. An estimate can be obtained by specifying different drop size distributions as input to the recovery boiler model currently being developed by the Institute of Paper Science and Technology and calculating the model predictions.

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