

Measurement of condensate depth in ribbed Yankee cylinders

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The depth of the condensate layer within the dryer shell can be determined with a simple probe that measures the electrical conductivity of the condensed liquid.

The heat on the outer surfaces of dryer drums and Yankee cylinders is obtained by injecting saturated steam into the interior of the dryer cylinder. As the steam condenses, the layer of condensate film that forms at the cylinder wall acts as a thermal insulator and disrupts the heat flow to the outer surface of the drum.

At low cylinder speeds, the condensate film flows down the walls and accumulates in a pool at the bottom of the cylinder. As speed increases, the condensate begins to rotate with the cylinder. When the dryer rotates at or beyond the rimming speed, a uniformly thick layer of condensate is formed around the entire circumference of the dryer shell.

The condensate is evacuated from the cylinder through siphon tubes whose inlets are placed in close proximity to the interior wall of the dryer shell. The live steam that flows through these tubes, called blow-through steam, entrains and transports the condensate droplets as a two-phase flow from the periphery of the dryer cylinder to its center.

The condensate's effect on heat transfer through the dryer cylinder is determined by such operating parameters as machine speed, blow-through steam flow, and siphon arrangement. Anyone attempting to model the heat transfer in the dryer cylinder must consider the effects of these parameters. This is especially true in dryers operating at high speeds, where rapidly growing centrifugal forces exert a significant influence on the behavior of the condensate film.

This article examines the effects of machine speed, blow-through steam flow, and siphon arrangement on condensate behavior in a full-size, ribbed Yankee cylinder with an outside diameter of 4.57 m and a length of 0.8 m. The experimental tissue machine used in this study is capable of speeds up to 2100 m/min and was designed to facilitate measurements of steam and condensate flows in the cylinder.

No one has yet quantitatively measured condensate depth in a full-size industrial dryer. Measurements have been performed either in laboratory units (without the usual steam atmosphere) or in full-size drums, where average condensate depths were obtained by stopping the cylinder and measuring the residual total condensate. White (1) presented data for 1- and 2-ft-diam. cylinders by measuring the total volume of water in the drum. Wahlström and Larsson (2) calculated the amount of water in a 1.5-m-diam., 3.5-m-long cylinder from the difference between the total amount of water added and the amount of water measured in the storage tanks.

Other techniques have been evaluated in an effort to measure condensate depths inside a ribbed Yankee cylinder. Gusev (3) presented a method using γ -radiation from the isotope Cs^{137} . The absorbance of the radiation through the cylinder was correlated to the amount of condensate in the cylinder. However, it seems uncertain whether this method is capable of measuring condensate-layer variations of a few millimeters in cast-iron cylinders with thicknesses up to 70 mm.

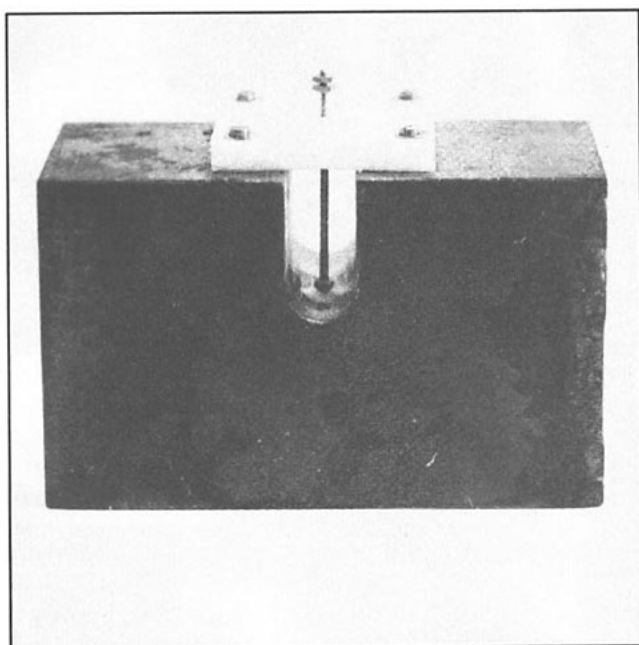
Appel and Hong (4) measured condensate depth with a set of electrically insulated probes positioned at progressive intervals of 0.125 mm from the cylinder surface. The layer thickness was obtained by electrically detecting contact between the layer and the probe. Quantitative data obtained on a laboratory drying cylinder indicated that condensate depths varied between 2.41 mm and 2.79 mm for 9 of the 11 measurements. For large variations in depth, the number of electrodes becomes unwieldy. In addition, the arrangement is difficult to implement in a ribbed cylinder.

Berthold (5, 6) suggested two methods of measuring the condensate depth, one for slowly rotating cylinders and another for cylinders rotating at high speed. At slow speeds, the electrical conductivity of the condensate was measured with two electrodes positioned on the inner surface of the cylinder. At higher speeds, the capacitance was measured between two slabs, with a varying condensate depth resulting in a corresponding change in capacitance. No quantitative measurements were presented.

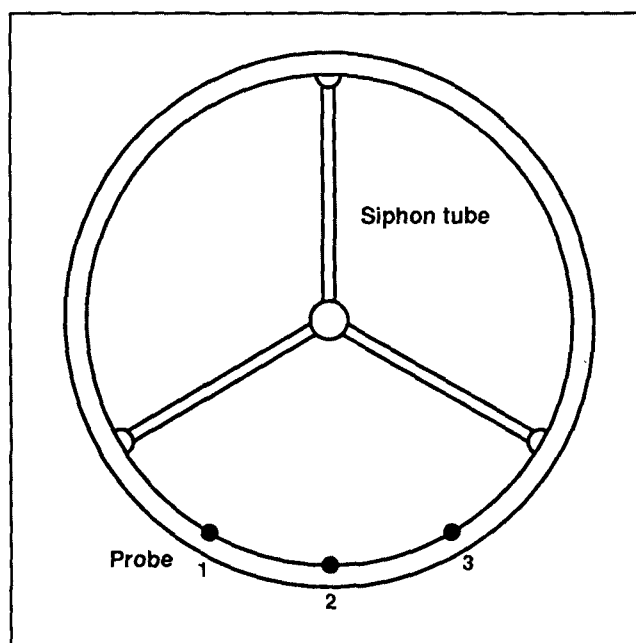
The use of direct-distance-sensing probes (either laser or ultrasound) to measure condensate depth was initially investigated in this work. These probes showed good results in tests on a rotating condensate layer in a model

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1. Conductivity probe in model Yankee groove



2. Arrangement of siphons and probes in dryer groove



1.5-m-diam. cylinder. However, temperatures up to 175°C and a very wet atmosphere mandate some kind of cooling and isolation of the probes. These problems appeared difficult to overcome. Instead, the decision was taken to design a probe with a more robust construction, i.e., one that did not need a voltage supply or contain sensitive electrical circuits. The probe was designed as an electrode capable of measuring the electrical conductivity of the condensate, as presented by Berthold (5).

Condensate probe

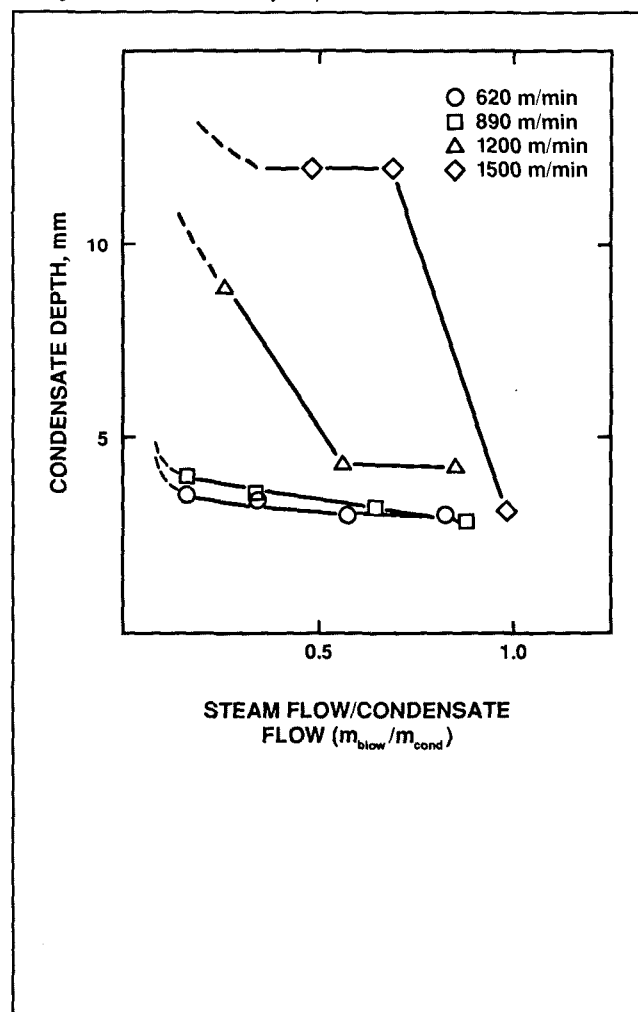
Design and installation

The probe is a 1.5-mm stainless-steel pin that sits in a small Teflon holder at the bottom of the groove in a ribbed Yankee dryer. The top portion of the pin is anchored in a Teflon plate, which holds the probe in the center of the groove. The Teflon holder and plate electrically isolate the probe from the cylinder. The model in Fig. 1 shows how the probe would be installed in a typical Yankee groove. The probe was capable of measuring condensate layers with depths of 2-25 mm. The lower limit was set by the height of the small Teflon holder in the bottom of the groove. The upper limit corresponded to a groove filled with condensate.

A single electrode was used to measure the conductivity between itself and the grounded Yankee shell. Normal conductivity probes work with a given cell constant, and the readings are proportional to the change in solution conductivity. In this case, the conductivity for the condensate is constant or changes only moderately, while the cell constant changes with differing condensate depth. Accurate and representative samples of condensate conductivity were obtained by connecting a condensate cooler to the condensate tank, where blow-through steam is separated. This allowed collection of separate condensate samples for each run.

Each groove is equipped with three siphons equally

3. Condensate depth at probe 1 in Yankee dryer as a function of blow-through steam flow at four dryer speeds



spaced around the cylinder circumference. Three probes were installed in the same groove equally spaced between two siphons, as seen in **Fig. 2**. Teflon-insulated cables were used to withstand the temperatures in the cylinder, and the signals were transmitted to the control room over a slip-ring device with silver contacts. The conductivity meter used was a Philips PW 9527 model. To avoid disturbances from ac motors running in the tissue machine, the frequency of the conductivity measurements was normally set to 4000 Hz.

Calibration

The probe was calibrated in a model Yankee groove with dimensions identical to those in a full-size cylinder but only 50 mm long. The model facilitated investigation of probe response for different condensate levels and conductivities. The response at different condensate levels was highly linear. A slight deviation from linearity was observed only when the groove was almost full of condensate.

The probe response was directly proportional to the solution conductivity. However, the response could be expected to depend on the type of ions present in the condensate. The conductivity of the condensate varied between 1.54 $\mu\text{S}/\text{cm}$ and 2.21 $\mu\text{S}/\text{cm}$, and good correlation was obtained between this conductivity and the probe response. The difference in condensate properties could thus be determined as a one-point calibration for each condensate sample.

The conductivity is strongly dependent on the temperature of the solution, with an increase in temperature resulting in an increase in conductivity. The following linear equation has been proposed to compensate for deviations in temperature:

$$\mu_x = \mu_r [1 + \alpha/100(T_x - T_r)] \quad (1)$$

where

μ_x = conductivity at sample temperature T_x

μ_r = conductivity at reference temperature T_r

α = factor correlating temperature dependency

For normal aqueous solutions, the value of α is around 2, which means that a temperature change of 10°C results in a 20% change in conductivity. The equation was tested with tabulated conductivity data for various salts at different temperatures. With α determined from the data, it was possible to reproduce the temperature dependency within 3% for temperatures up to 200°C. This was considered satisfactory for this simple one-parameter correlation.

For each condensate sample, α was determined by slowly heating the condensate from 20°C up to 90°C and measuring the conductivity. Although the value for α was determined only in the 20–90°C range, it was assumed to be applicable for the entire temperature range 20–175°C. In order to reduce uncertainties from this assumption, most of the runs were performed at the same steam temperature, thus reducing the possible relative errors between different runs.

The change in conductivity with temperature of the metal path between the probe and the ground was accounted for by filling the cylinder groove with conden-

sate and correlating the probe response to condensate conductivity and cylinder temperature.

Results

Condensate levels

The runs were performed at four different Yankee speeds: 620, 890, 1200, and 1500 m/min. For each speed, the amount of blow-through steam was varied in three to four steps from a high to a very low value corresponding to blow-through steam velocities in the siphon riser tubes between 10 m/s and 70 m/s. The lowest machine speed of 620 m/min was selected on the basis that the speed was above rimming speed for this ribbed Yankee cylinder. This was confirmed by the probes, which were easily able to detect the presence of a condensate puddle.

The stepwise reduction of blow-through steam caused the condensate level to increase, thus reducing the heat flow from the interior of the dryer to its surface. This reduction in heat flow was compensated for by increasing the air temperature in the Yankee hood, thus maintaining a constant moisture content in the tissue paper. All other variables were kept constant to facilitate comparisons between runs.

Figure 3 shows condensate depth within the Yankee dryer as a function of steam flow/condensate flow ($m_{\text{blow}}/m_{\text{cond}}$) at the four dryer speeds. The stepwise decrease of blow-through steam resulted in only small increases in condensate depth at dryer speeds of 620 m/min and 890 m/min (3.0 mm to 3.5 mm and 2.8 mm to 4.0 mm, respectively). Condensate depth increased dramatically only at very low velocities in the siphon tube, at which point it was no longer possible to drain the cylinder. At speeds of 1200 and 1500 m/min, the condensate depth at the high blow-through steam flows was between 3 mm and 4.2 mm, which is about the same level as was recorded for the low dryer speeds. The results for the full range of dryer speeds (620–1500 m/min) indicate that if the blow-through steam flow is sufficiently high, the condensate depth attains a minimum value that is dependent on the distance between the siphon tube and the groove. However, reducing the amount of blow-through steam at high dryer speeds results in a rapid increase in condensate depth, as seen in **Fig. 3**. This indicates that condensate drainage from a high-speed dryer is extremely sensitive to the amount of blow-through steam used.

The critical steam flow, m_{cr} , for each of the four dryer speeds was calculated from **Fig. 3** and is shown in **Fig. 4** as a function of the centrifugal force (centrifugal acceleration/gravitation). Critical steam flow, defined in **Eq. 2**, is the lowest ratio of blow-through steam flow and condensate flow needed to maintain the condensate depth at a minimum value.

$$m_{\text{cr}} = m_{\text{blow}}/m_{\text{cond}} \quad (2)$$

where

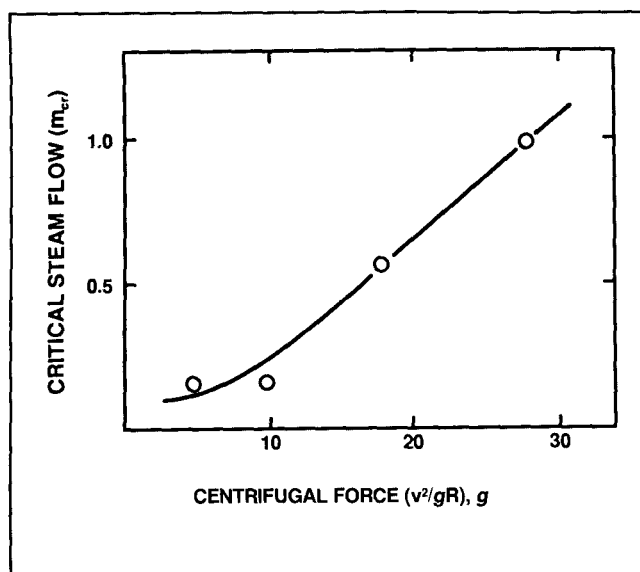
m_{cr} = critical steam flow

m_{blow} = steam flow needed to maintain minimum depth

m_{cond} = condensate flow

A reasonable correlation is obtained for centrifugal force (v^2/gR) (where v = cylinder speed, m/s; R = cylinder radius

4. Critical blow-through steam flow as a function of centrifugal force



m ; and g = acceleration of gravity, 9.81 m/s^2) above $10 g$, indicating that the centrifugal forces for the evacuation of condensate dominate in this region.

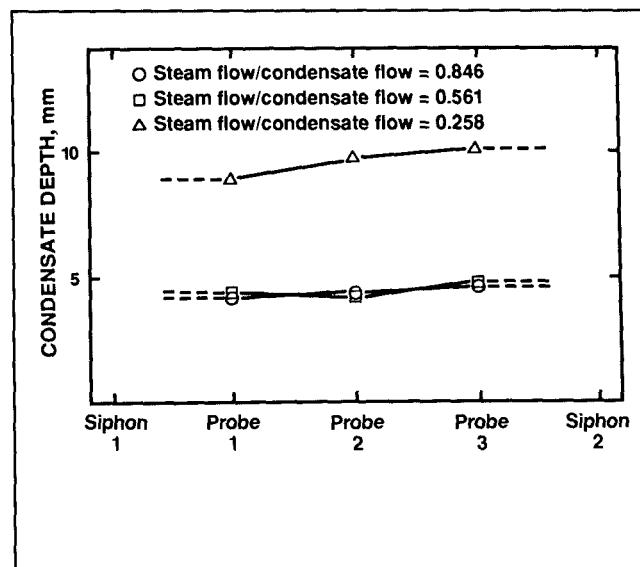
Condensate flow in a groove

Figure 5 shows the condensate depth at the three probes (between two siphon tubes) for three levels of steam flow and a dryer speed of 1200 m/min . Within the experimental error, the three probes indicated the same condensate depth for a given speed between 620 m/min and 1500 m/min . The results show that only small differences in depth are needed to maintain the flow of condensate in the groove to the siphon and that the differences in condensate depth occur close to the siphon tube. Figure 6 depicts the predicted behavior of the condensate at depths below and above the siphon-to-groove distance.

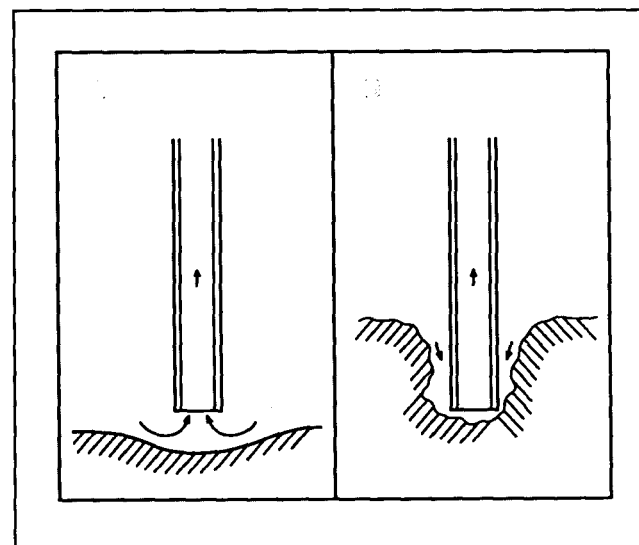
The pressure difference needed for the flow of condensate in the groove between two siphons was estimated by calculating the corresponding laminar pressure drop in a tube. This would represent an upper limit for the pressure drop in the groove. The assumptions were as follows: Between two siphons, the condensate is presumed to be divided into two halves. The condensate between siphon 1 and probe 2 flows to siphon 1, while the condensate between siphon 2 and probe 2 flows to siphon 2 (see Fig. 5). The flow of condensate increases linearly from probe 2 to the siphons. However, the arithmetic average velocity, $\bar{v}$, was used in the calculations, and maximum velocity, v_{max} , was calculated from the total amount of condensing steam.

$$\bar{v} = v_{max}/2 \quad (3)$$

The diameter of the tube was selected as the width of the groove. Physical data for the condensate were calculated at the steam saturation temperature. With these assumptions, the pressure drop, Δp_{tube} , is 0.81 Pa . With a centrifugal force of $10 g$, the corresponding height difference for flow between probe 2 and the siphons is only 0.009 mm . The experimental result, with very small

5. Condensate depth detected by the three probes at three levels of steam flow and a dryer speed of 1200 m/min 

6. Condensate flow at siphon inlet: (A) when condensate depth is less than that of siphon-to-shell clearance and (B) when condensate depth is greater than that of siphon-to-shell clearance.



differences between the siphons, is thus confirmed using this estimation and is in good agreement with results presented by Appel and Hong for flow over nonribbed surfaces toward rows of siphons (4).

Blow-through steam is directed from the center of the cylinder to the siphon tubes and reaches velocities up to 80 m/s in the siphons. Close to the siphons, most of the vapor can be assumed to be directed to the grooves, and vapor velocities at distances of a few siphon diameters were estimated to be on the order of 10 m/s . For two-phase flow in horizontal tubes with high relative velocities, it is possible to establish different flow regimes, such as slug and wavy. The large relative velocities cause instabilities of the liquid surface, create surface waves, and possibly induce slugs to be transported by the vapor flow. It seems

reasonable that this phenomenon is applicable also for condensate flow close to the siphons.

One further mechanism of condensate flow is caused by gravity. At low cylinder speeds, where the centrifugal force is less than 10 *g*, pulsation and movement of condensate caused by acceleration and retardation by gravity during the rotation of the cylinder will be important. This was confirmed by measurements recorded by the probes.

Conclusion

A probe was developed to measure the depth of condensate within a drying cylinder. The device, which can be applied in either smooth or ribbed cylinders, measures the conductivity of the condensate and is capable of estimating depths between 2 mm and 25 mm. Probe response is proportional to the depth of condensate at a given conductivity. The solution conductivity is strongly dependent on the solution temperature. Corrections for the temperature dependency are made with the aid of a simple one-parameter linear equation. The temperature coefficient used in this equation has so far been determined only up to 90°C, while temperatures inside the Yankee cylinder range up to 175°C. Further knowledge about the temperature dependency in the range 90–175°C is desirable. This will require conductivity measurements under pressure with conductivity cells that can withstand elevated temperatures.

Measurement of condensate depth in a full-size, ribbed Yankee cylinder showed that condensate depth is strongly dependent on cylinder speed and flow of blow-through steam. There was no significant difference in measured depth at three different positions between two siphons. Thus any change in the depth of the condensate within the groove must occur close to the siphons.

At machine speeds above 1500 m/min—where centrifugal force increases rapidly—the control of condensate drainage is extremely important. Under these conditions, the ability to monitor condensate depth and blow-through steam is useful in optimizing the dryer's heat flow. □

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