EXECUTIVE SUMMARY

A basic parameter in the design of a paper machine dryer drive system, whether it has an open gear, enclosed gear, or felt drive, is the drive power requirement. Previous work on the drive power for paper machine dryers covered a 1.5 meter diameter cylinder. This paper presents the results for both 1.5 and 1.83 meter diameter cylinders with and without dryer bars.

Torque, as well as power, is an important aspect in designing and operating a modern dryer section drive. The torque and power required to drive a dryer increase significantly as the amount of condensate in the dryer increases. The torque is greatly reduced when the condensate passes into the rimming condition. Dryer bars significantly reduce the speed at which the condensate rims and decrease the power and the torque required to make this transition.

These results are presented along with information on the observed behavior of the condensate inside the dryer under a wide range of operating conditions. This information will help in predicting the drive power and drive torque that is required in the commercial operation of paper machine dryers.

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INTRODUCTION

The power required to drive a dryer section of a conventional paper machine must overcome the following:

- Mechanical inertia, particularly of dryer and felt rolls
- Aerodynamic drag, particularly associated with dryer fabrics and rolls
- Fabric flexing, which depends on fabric design and tension and roll diameters
- Rotary joint friction, which depends on dryer speed, joint design, number of joints, and steam pressure
- Web tension, particularly following or preceding draw locations
- Dryer doctor friction, which depends on speed, dryer surface condition, blade load, and blade material
- Threading rope drag, particularly if the ropes are stretched in draws
- Blow box and ventilator seals, particularly those that contact the dryer fabrics
- Ventilation roll seals, which depend on the seal material, seal load, and dryer speed
- Dryer drive gears and gear boxes (spur, helical, lubricated or dry)
- Dryer and felt roll bearings, greased or continuous lubrication
- Fabric guide rolls, particularly when there is fabric distortion
- Dryer syphons, both rotating and stationary types
- Condensate behavior, which depends on the dryer speed, the amount of condensate in the dryer, the speed history, and the use of dryer bars

The drive power associated with the above items marked with an asterisk typically increases directly with dryer speed. For the others, the drive power increases with the square of the dryer speed. As a result, the drive power for a conventional dryer section increases with some power of speed that is greater than 1 but less than 2.

This paper is focused on testing to quantify the dryer drive power associated with the condensate behavior.

Condensate in a dryer cylinder has three stages of behavior that depend on speed. At slow speeds, condensate forms a puddle at the bottom of the cylinder. In this stage, the power consumption is low. As the speed increases, the puddle moves in the direction of rotation and widens. As the speed is further increased, the second stage occurs as the trailing edge of the puddle extends over the horizontal centerline of the cylinder and condensate cascades back to the bottom of the cylinder. The height to which the condensate rises before it cascades increases with the cylinder speed, as does the flow rate of the condensate that cascades.
The combination of the increasing elevation and increasing flow causes a quadratic increase in the power required as speed increases. The final stage occurs as speed is increased further, and the condensate forms a rimming layer on the inner surface of the cylinder. Power consumption in this stage is much lower. These three stages of condensate behavior are shown in Figure 1.

As speed is decreased, the rimming condensate film will collapse and the condensate will return to a cascade and eventually back to a puddle. The speed at which the condensate rim collapses is less than the speed at which the rim was established.

**DRYER DRIVE POWER TESTS**

The dryer drive power and torque were determined using the Kadant Johnson Joco 4000 and Joco 6000 pilot dryers at the W. R. Monroe Research Center in Three Rivers, Michigan. The Joco 4000 and Joco 6000 dryers are commercial paper machine dryers, with nominal diameters of 1.5 m (60") and 1.8 m (72"), respectively. They each have commercial face widths: 6.35 m (250") and 8.81 m (347") and are capable of operating at speeds up to 1520 mpm (5000 fpm) and 2000 mpm (6560 fpm), respectively. Both dyers have condensate grooves near the heads allowing for testing of both rotating and stationary siphons, located in and outside siphon grooves. For these tests, the grooves were filled with steel rings to simulate cylinders without siphon grooves. Testing with the grooves unfilled was reported in a previous paper (5).

For each test condition, a measured amount of water was placed in the dryer and the dryer speed was slowly increased to a maximum and then slowly decreased back to a stop, measuring the drive torque continuously. Tests were conducted with and without dryer bars in the dryers. The very slow acceleration and deceleration rates eliminated the dryer inertial load and helped to give more definition to the resulting drive load curves.
The data presented here covers the power and torque requirements for a wide range of dryer speeds, with the water going from puddling, through cascading, to rimming conditions. The speeds at which the condensate rims and collapses from the rim were determined for each of the various amounts of condensate in the dryer.

**DRYER DRIVE POWER**

In the first series of tests, the dryers were operated without dryer bars. The amount of condensate (water) in the dryers was varied from an equivalent rim depth of 1.6 mm (0.063") to 12.7 mm (0.5"). In the second series of tests, dryer bars were installed in the cylinders. The dryer bars used for these tests were Kadant Johnson Turbulator® Tube™ bars. These bars are 15 mm in height and 25 mm in width. They are equally spaced around the inside surface of the dryer, to generate resonant oscillation of the condensate layer. This oscillation increases the rate and cross-machine uniformity of heat transfer.

The drive power is shown in Figure 2 for each of five different amounts of condensate in the 1.5 m diameter dryer and in Figure 3 for the 1.8 m diameter dryer. The drive power is listed in kW per meter of dryer face width. The condensate amounts are listed as the “equivalent” rimming film thickness, that is, the thickness calculated as if the condensate were distributed in an even film on the dryer inside surface.

As the dryer speed increases, the condensate moves from puddling, to cascading, then to rimming. The drive power increases quadratically until the condensate begins to rim. At that point, the drive power decreases substantially. Figures 2 and 3 show four important points. The power required to pass through cascading into rimming increases as the amount of condensate in the dryer increases. Secondly, the speed at which the peak power consumption occurs increases as the amount of condensate in the dryer increases. Thirdly, when the condensate is rimming, the power required to drive the dryer is not significantly influenced by the amount of condensate, even when the rimming depth is as large as 12.7 mm. Note that for a given condensate thickness, condensate in the 1.8 meter diameter cylinder rims at a higher speed and requires more power than condensate in the 1.5 meter diameter cylinder.

Figures 4 and 5 show similar data for the dryers with dryer bars. These figures show that, for a dryer with bars, the power required to pass through the cascading condition into the rimming condition also increases as the amount of condensate in the dryer increases and that the speed at which the peak power occurs increases as the amount of condensate in the dryer increases. The power required to drive a dryer with dryer bars and rimming condensate is not significantly influenced by the amount of condensate in the dryer.
A comparison of Figure 2 to Figure 4, and Figure 3 to Figure 5, shows that condensate in a dryer with dryer bars will rim at a much lower speed than condensate in a dryer without dryer bars. Furthermore, the drive power at which this transition occurs is much less in a dryer with dryer bars than in a dryer without dryer bars.
Figures 6 and 7 show the drive torque (in N-m per meter of dryer width) for the 1.5 m and 1.8 m diameter dryers, respectively, without bars in the dryers. These figures show that the drive torque required to pass through the cascading condensate condition into the rimming condensate condition increases as the amount of condensate in the dryer increases, and the speed at which the peak torque occurs increases as the amount of condensate in the dryer increases. Once the condensate is rimming, the drive torque increases only slightly with speed.

Figure 6. Dryer Drive Torque versus Dryer Speed
1.5 meter diameter dryer, without dryer bars

Figure 7. Dryer Drive Torque versus Dryer Speed
1.8 meter diameter dryer, without dryer bars
Figures 8 and 9 show similar torque data for the dryers with dryer bars. For a dryer with dryer bars, the drive torque required to pass through the cascading condensate condition into the rimming condensate condition increases as the amount of condensate in the dryer increases. Furthermore, the speed at which the peak torque occurs increases as the amount of condensate in the dryer increases. With the dryer bars in the dryer, the drive torque is only slightly affected by the amount of condensate in the dryer, once the condensate is rimming.

**Figure 8. Dryer Drive Torque versus Dryer Speed**  
1.5 meter diameter dryer, with dryer bars

**Figure 9. Dryer Drive Torque versus Dryer Speed**  
1.8 meter diameter dryer, with dryer bars
Collapsing speed is defined as the highest recorded speed at which the increase in the dryer drive power and torque was complete. 

Data from the previous figures is presented in cross-plots for rimming speed, collapsing speed, and peak torque. In these cross-plots, rimming speed is defined as the lowest recorded speed (during the increasing speed test) at which the reduction in the dryer drive power and torque was complete. Collapsing speed is defined as the highest recorded speed (during the decreasing speed test) at which the increase in the dryer drive power and torque was complete. In between the rimming speed and the collapsing speed, the condensate may be either rimming or cascading, depending on the speed history of the dryer cylinder, as shown in Figures 10 and 11.

Figure 10. Dryer Drive Power versus Dryer Speed
1.5 meter diameter dryer, 12.7 mm rim layer, without dryer bars

Figure 11. Dryer Drive Power versus Dryer Speed
1.5 meter diameter dryer, 12.7 mm rim layer, with dryer bars
For cylinders without bars, the difference between the rimming and collapsing speeds increases with increasing condensate film thickness. The speed at which the maximum torque was observed is about 90-95% of the rimming speed. The torque load rapidly decreases at speeds between 90% and 100% of the rimming speed. Figures 12 and 13 show the cross plots for the 1.5 and 1.8 meter cylinders respectively.
With bars, the difference between rimming and cascading speeds decreases with increasing condensate film thickness.

Figures 14 and 15 show the cross plots of rimming and cascading speeds for cylinders with dryer bars. These speeds are lower than the speeds for dryers without bars. The difference between rimming and cascading speeds decreases with increasing condensate film thickness. Further, the rimming speed for a cylinder with bars is much lower than for a cylinder without bars. The peak torque load with bars occurs at about 50% to 80% of the rimming speed, depending on condensate film thickness.
Figures 16 and 17 compare the rimming and collapsing speeds for the 1.5 and 1.8 meter diameter cylinders with and without bars. Again, both rimming and collapsing speeds are significantly reduced with bars.

Figure 18 shows that the peak drive power is approximately 50% lower in dryers with dryer bars than in dryers without dryer bars. This can be very important, particularly in dryers with low drive capacity. The reduction in drive power is most significant with large rimming depths (a large amount of residual condensate).
Figure 18. Peak Power versus Film Thickness
Dryers with and without dryer bars

Figure 19 shows that the peak torque is also less with dryer bars than in a cylinder without dryer bars, provided both of the dryers have the same amount of condensate.
ANALYTICAL MODELS

In 1958, White and Higgins (2) published a correlation for rimming speed based on dimensional analysis and data from a 0.305 meter diameter cylinder without bars. The rimming speeds observed in the 1.5 meter diameter and 1.8 meter diameter cylinder testing were somewhat higher than predicted from their analysis. This is primarily because White and Higgins defined “rimming speed” as the point of peak power and torque, rather than the point at which the transition to rimming was complete.

Following White and Higgins, a correlation was applied to the above data resulting in the following equation; for a dryer without bars:

\[ V = 12.4 \left( \frac{\delta}{\nu} \right)^{0.5} \left( \frac{R}{\delta} \right)^{0.18} \left( \frac{g \delta}{\nu^2} \right)^{0.013} \]  

(1)

where \( R \) is the dryer inside radius, \( \delta \) is the rimming film thickness, \( \nu \) is the kinematic viscosity, \( g \) is the gravitational acceleration, and \( V \) is the rimming speed of the inner surface. The exponent on the dimensionless group with the fluid properties could not be established from these tests, since the fluid properties did not vary. The exponent established by White and Higgins (2) was used instead.

A similar correlation can be applied to the collapsing speed:

\[ C = 2.0 \left( \frac{\delta}{\nu} \right)^{0.5} \left( \frac{R}{\delta} \right)^{0.452} \left( \frac{g \delta}{\nu^2} \right)^{0.013} \]  

(2)

where \( C \) is the speed at which the condensate rim collapses back into a cascade.

For a cylinder equipped with dryer bars, the equations are:

\[ V = 2.9 \left( \frac{\delta}{\nu} \right)^{0.5} \left( \frac{R}{\delta} \right)^{0.362} \left( \frac{g \delta}{\nu^2} \right)^{0.013} \]  

(3)

and

\[ C = 7.1 \left( \frac{\delta}{\nu} \right)^{0.5} \left( \frac{R}{\delta} \right)^{0.107} \left( \frac{g \delta}{\nu^2} \right)^{0.013} \]  

(4)

Note that all of the testing was performed at a constant water temperature (21°C) and therefore the second dimensionless group only varied with the film thickness.
The data shown in Figures 12 through 17 include these correlation curves for rimming and collapsing speed.

Just prior to rimming, condensate in the cylinder is, in effect, lifted from the bottom of the dryer up to the top of the dryer where it cascades. If the entire volume of condensate is lifted to the horizontal centerline of the cylinder axis each revolution, the power required can be estimated by the following equation:

\[ P_p = 4 \gamma \delta R V_p \]  \hspace{1cm} (5)

where \( \gamma \) is the weight density, \( \delta \) is the film thickness, \( V_p \) is the dryer speed at peak power, \( R \) is the cylinder radius, and \( P_p \) is the peak drive power expressed per unit of dryer face width.

Condensate behavior in the dryer deviates from this simple model in three ways: First, some of the condensate is lifted above the horizontal centerline. Second, there is some portion of the condensate film which does not cascade, but remains in a rim at higher speeds. And third, some of the condensate does not fall all the way back to the bottom of the cylinder, but impacts the opposite side above the cylinder floor. The above equation, however, can be combined with Equation (1) for rimming speed to provide the format for developing a correlation for the peak power. The resulting equation for a dryer without dryer bars is given below.

\[ P_p = \gamma \delta R (\delta g)^{0.5} (R/\delta)^{0.41} (\delta^3 g/\nu^2)^{0.013} / 1098 \]  \hspace{1cm} (6)

From Figures 2 and 3, it is clear that the drive power for dryers without bars is proportional to the square of the dryer speed, for dryers that are operating below the condensate rimming speed. The drive power can therefore be estimated at any speed up to rimming by the following equation:

\[ P = P_p (S/V_p) \]  \hspace{1cm} (7)

where \( S \) is less than or equal to the rimming speed \( V_p \).
At speeds above rimming, the power for a cylinder without bars can be seen from Figures 2 and 3 to also be proportional to the square of the dryer speed. The drive power for a dryer with rimming condensate can therefore be estimated by the following correlation equation:

$$P = (0.4 \times 10^{-6}) S^2$$  \hspace{1cm} (8)

where the drive power is expressed in kW per meter of face width and $S$ is the dryer speed expressed in m/min.

This estimate for drive power is comparable to a Normal Running Load (NRL) factor, in that it excludes dryer and felt roll inertia, web tension, and dryer doctor drive loads. It does, however, also exclude the drive load associated with felt rolls, dryer fabrics, rotary steam joints, threading ropes, and gearboxes.

Figures 20 and 21 show a comparison between the calculated values of drive power and drive torque and the measured values for a 1.8 meter diameter cylinder without bars and with a 6.4 mm condensate film.

![Figure 20. Comparison of calculated power and observed data](image)

1.8 meter diameter dryer, 6.4 mm rim layer, no dryer bars
For a cylinder equipped with dryer bars, the peak power can also be correlated using the format of Equation (3) combined with Equation (5). The resulting correlation equation for a dryer with dryer bars is given below:

\[ P_p = \gamma \delta R (\delta g)^{0.5} (R / \delta)^{0.463} (\delta g / v^2)^{0.013} / 2780 \]  \hspace{1cm} (9)

When the dryer has bars, the drive power for dryers operating below the rimming speed can also be approximated as proportional to the square of the dryer speed, as seen in Figures 4 and 5. The drive power can therefore be estimated at speeds up to rimming by Equation (7):

\[ P = P_p (S / V_p) \]  \hspace{1cm} (10)

where \( S \) is less than or equal to the rimming speed \( V_p \).

At speeds above rimming, the power for a cylinder with dryer bars can be estimated by the following equation:

\[ P = (0.5 \times 10^{-3}) S \]  \hspace{1cm} (11)

where the drive power is expressed in kW per meter of face width and \( S \) is the dryer speed expressed in m/min. Note that the drive power for a dryer with bars is linearly related to speed, whereas the drive power for a dryer without bars was related to the square of the dryer speed.
Figures 22 and 23 show a comparison of the calculated and measured values of power and torque using the above equations for a dryer with bars.

![Figure 22. Comparison of calculated power and observed data 1.5 meter diameter dryer, 9.5 mm rim layer, with dryer bars](image)

Torque for a cylinder without bars at speeds above rimming increases with speed while the torque for a cylinder with bars is nearly constant.

![Figure 23. Comparison of calculated torque and observed data 1.5 meter diameter dryer, 9.5 mm rim layer, with dryer bars](image)
SUMMARY

This paper highlights the difference in the condensate rimming speed for paper dryers operating with and without Turbulator bars. The paper also quantifies the difference between 1.5-meter and 1.8-meter diameter dryers. The paper provides equations for estimating the rimming speeds and collapsing speeds, using the same dimensionless groups, and the associated drive power and torque.

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REFERENCES

Kadant Johnson is a global leader in the design, manufacture, and service of dryer drainage systems, rotary joints, syphon systems, and related equipment for the dryer section of the paper machine. For more information about Kadant Johnson products and services, email info@kadant.com or visit www.kadant.com.

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