

Heat Transfer Performance with Dryer Bars

Gregory L. Wedel
President
Kadant Johnson Inc.

Gerald L. Timm
Vice President, Research & Development
Kadant Johnson Inc.

Technical White Paper Series

EXECUTIVE SUMMARY

Dryer bars are used in paper machine drying cylinders to increase the rate of heat transfer and uniformity of drying. A number of different configurations of dryer bars have been used for these purposes, but they have achieved mixed results.

Dryer bars can reduce the speed at which the condensate layer will move from the cascading stage to the rimming stage. This can provide a significant reduction in the power and torque required to drive the dryer cylinder. Dryer bars can also greatly increase the rate of heat transfer from conventional paper dryers. The increase can be as large as 50%, even when compared to the performance of dryers with modern, close clearance rotating syphons. The maximum increase, however, requires the bars to operate with the optimum condensate layer thickness.

When operating with the right configuration of bars and the corresponding optimum condensate depth, dryer bars can not only achieve a high rate of heat transfer, but also achieve a high degree of drying uniformity.

Simulation tests are required to identify the best syphon and bar configuration for the specified dryer operating conditions. This paper has outlined the results of one such study and includes an introduction to the technology of dryer bar design and presents the factors to be considered to achieve optimum performance.

CONTENTS

Condensate Behavior	3
Analysis of Dryer Bars	6
Practical Considerations	7
Drying Rate Improvements	8
Test Results for Joco 4000	9
Test Results for Joco 6000	12
Drying Uniformity	15
Drive Power and Torque	16
Summary	17
References	17

CONDENSATE BEHAVIOR

Condensate in a dryer cylinder can form a puddle in the bottom of the dryer, it can be tumbling inside the dryer, or it can form a thin layer around the inside surface of the dryer. The behavior of the condensate depends primarily on the speed of the dryer cylinder and on the amount of condensate that is inside the dryer.^{1,2}

Rimming condensate presents a resistance to the flow of heat from steam inside the dryer cylinder to the inside surface of the dryer cylinder.

At slow speeds, the condensate forms a pond at the bottom of the cylinder. As the dryer speed increases, this pond moves in the direction of dryer rotation and widens. As the speed is further increased, the trailing edge of the pond extends over the horizontal centerline and the condensate tumbles (“cascades”) back to the bottom of the dryer cylinder. The third stage of condensate behavior occurs as speed is increased still further, and the condensate forms a rimming layer on the inner surface of the dryer cylinder.

These three stages of condensate behavior are shown in Figure 1. The three stages are normally referred to as ponding, cascading, and rimming.

The speed at which the condensate will rim depends primarily on the diameter of the dryer cylinder and on the amount of condensate that is in the dryer. The graph in Figure 2 shows the rimming speed as a function of the residual condensate film thickness for a 1.5 meter diameter cylinder.

Rimming condensate presents a resistance to the flow of heat from steam inside the dryer cylinder to the inside surface of the dryer cylinder. The condensate heat transfer performance is often expressed as the condensate heat transfer coefficient, h_c . This is the reciprocal of the heat transfer resistance and it is used throughout this paper.



Figure 1: Condensate Behavior in a Dryer

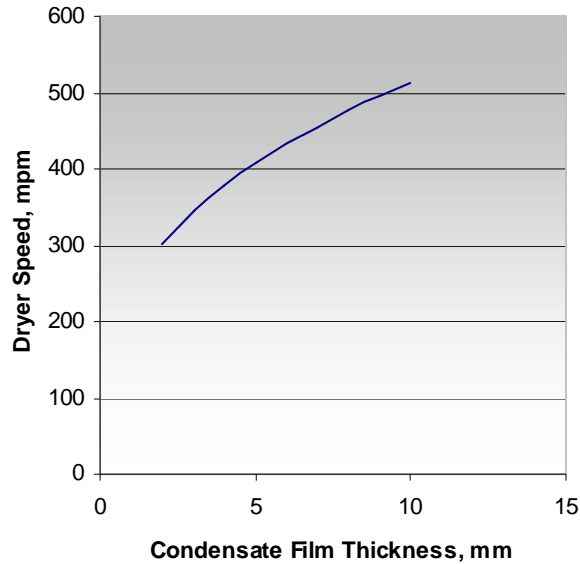


Figure 2: Effect of film thickness on the dryer rimming speed (1.5 m dryer diameter).

The condensate heat transfer film coefficient h_c relates the flow of heat per unit area Q'' through the condensate layer to the difference in temperature between the steam T_s and the inside surface of the dryer cylinder T_d , as shown in the following equation.

$$Q'' = h_c (T_s - T_d)$$

The condensate film coefficient (h_c) is shown in Figure 3 for a close-clearance rotating syphon for various dryer speeds. Note that the steam pressure and steam condensing rate were held constant for these tests.

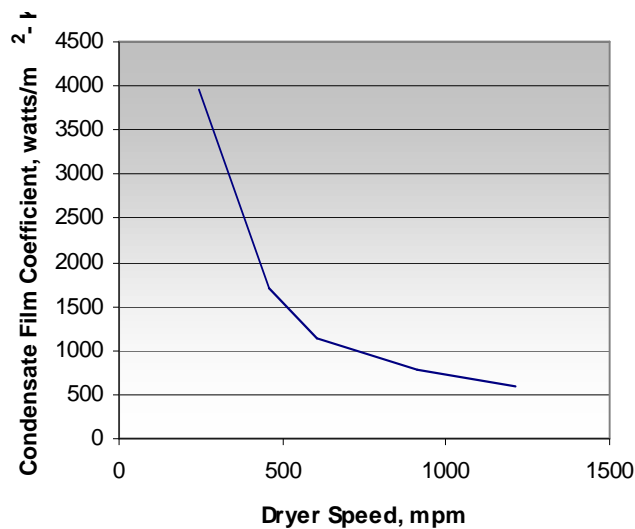


Figure 3: Effect of dryer speed on the condensate heat transfer coefficient.

Figure 3 shows that the condensate coefficient is quite high when the dryer is running at low speeds, even though the condensate layer is rimming. This is because, at low speeds, the rimming condensate film does not move at the same speed as the cylinder, nor is its velocity constant. As the cylinder surface rises, gravity decelerates the condensate film. As the cylinder surface descends, gravity accelerates the condensate film. An oscillation is created by this alternating acceleration and deceleration. This natural oscillation produces turbulence in the rimming layer, which reduces the heat transfer resistance (increases the condensate coefficient).

Axial bars can be placed in the dryer cylinder to create turbulence in the rimming condensate layer. If the spacing of the bars is chosen correctly, resonant waves are created in the condensate film.

The velocity of this oscillation depends on both the speed of the dryer and on the thickness of the condensate film. At high speeds, the oscillation of the condensate film (its turbulence) is greatly reduced. As a result, the condensate layer produces a very significant reduction in the transfer of heat from the dryer cylinder, particularly in high-speed operations with thick condensate films

Large-perimeter, close-clearance rotating syphons can reduce the depth of the rimming condensate layer, but they cannot increase its level of turbulence. As a result, there is a progressive loss in heat transfer as the dryer speed increases. This is particularly evident in dryers operating at high speed with high condensing loads (for example, wide dryers operating at high steam pressures). This loss in heat transfer is the direct result of a decrease in turbulence in the rimming condensate layer. At speeds over 600 mpm, the condensate heat transfer resistance can exceed the thermal resistance of the dryer shell.

Axial bars can be placed in the dryer cylinder to create turbulence in the rimming condensate layer. If the spacing of the bars is chosen correctly, resonant waves are created in the condensate film, between each pair of bars. This significantly increases the level of turbulence, even at high dryer speeds. This increase in turbulence reduces the resistance to heat transfer from the steam, through the condensate film, to the dryer shell.

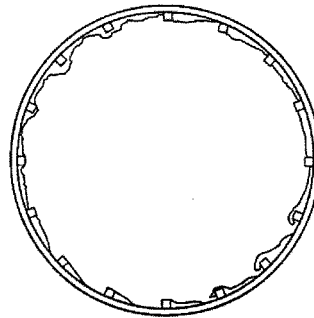


Figure 4: Schematic of Dryer Bar Operation

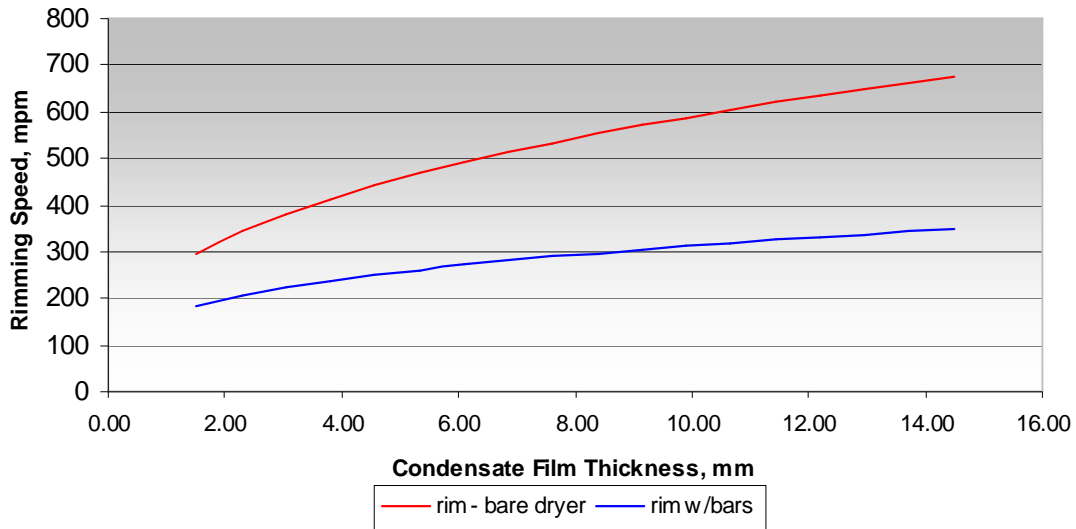


Figure 5: Rimming Speed with and without Dryer Bars

In addition to increasing the condensate turbulence, dryer bars also promote rimming at lower speeds. Figure 5 shows the rimming speed as a function of the amount of condensate in the dryer, both with and without bars in the dryer.

The reduction in the speed required for rimming to occur can be as large as 300-350 mpm. For dryers that are operating close to the rimming speed, the application of dryer bars will help to insure that rimming does occur. This will reduce the drive power for the dryer cylinder, improve the heat transfer uniformity, and reduce the amount of blow through steam required to evacuate the condensate from the dryer.

The most important aspect of dryer bars, however, remains the ability to increase the rate of heat transfer from dryers in which the condensate layer is rimming.

The following section outlines the technology associated with the application of dryer bars for this purpose.

ANALYSIS OF DRYER BARS

In open channel flow, the velocity of a wave is given by

$$v = \sqrt{g \delta}$$

where g is the acceleration of gravity and δ is the depth of the water in the channel.

In a rotating cylinder, the centripetal acceleration (f^2/r) replaces the gravitational acceleration g , yielding:

$$v = f \sqrt{\delta / r}$$

where f is the cylinder tangential velocity and r is the cylinder radius. The time, t , for one revolution of the cylinder is given by:

$$t = 2 \pi r / f$$

and the distance x covered during this revolution is:

$$x = vt = 2 \pi \sqrt{r \delta}$$

During one revolution, a wave will traverse the space between bars twice, so the required bar spacing S for resonance is given by the following equation:

$$S = x / 2 = \pi \sqrt{r \delta}$$

Appel and Hong⁴ first showed this equation for the theoretical spacing for resonance in the rimming condensate layer. This theoretical equation indicates that resonant motion can be achieved for any bar spacing, provided that the correct fluid thickness can be achieved inside the dryer.

PRACTICAL CONSIDERATIONS

The minimum practical condensate film thickness in a commercial paper dryer is about 2 mm. Thinner films cannot be easily achieved in wide paper machine dryers without multiple close-clearance syphons and syphon grooves. Using the above equations, the practical limit to the minimum spacing between bars is therefore around 120 mm.

Condensate film thickness in excess of 10 mm requires high torque to achieve the transition from the cascading stage to rimming^{3,6}. This torque requirement limits the maximum spacing between bars to around 290 mm.

The normal range of bar spacing is therefore 120 to 290 mm.

The optimum film thickness is shown in Figure 6 for two common dryer diameters, over the practical range of bar spacing.

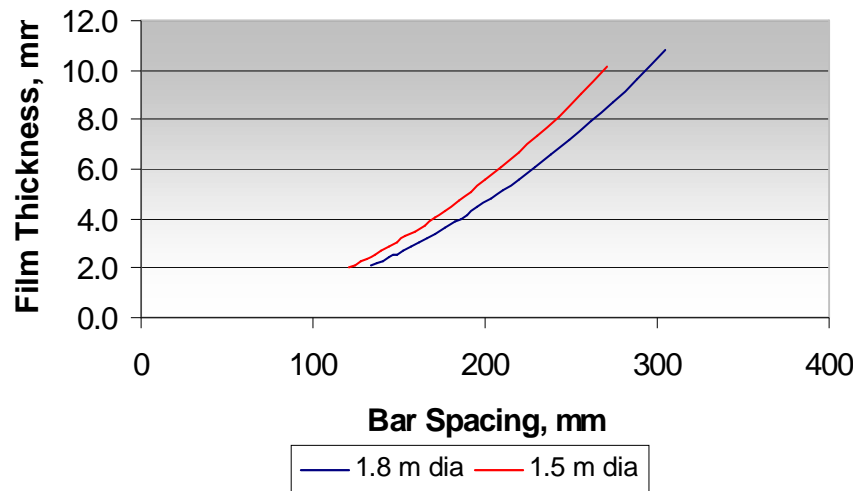


Figure 6: Theoretical Condensate Depth for Resonant Oscillation

DRYING RATE IMPROVEMENTS

Tests are also required to establish the appropriate syphon-to-shell clearance that will produce the correct condensate depth for the selected configuration.

The amount of improvement in drying capacity depends on the performance of the existing syphons as well as on the performance of the dryer bars. The improvement in drying rate when bars are added to a cylinder is shown in Figure 7 as an example. For this example, the dryer bars were assumed to achieve a film coefficient of 2000 watt/m²-K. The graph applies to dryers equipped with modern close-clearance rotating syphons, over a range of dryer widths, steam pressures, syphon positions in the dryer, and condensing loads.

As shown in this figure, the improvement in heat transfer can be quite large, particularly at the higher speeds. The improvement in heat transfer would be even larger when dryer bars are placed in dryers with older, large-clearance syphons and in dryers with stationary syphons.

While resonance of the condensate layer may be achieved with many different combinations of condensate film thickness and bar spacing, testing is required to establish which of these configurations results in the highest condensate coefficient.

Tests are also required to establish the appropriate syphon-to-shell clearance that will produce the correct condensate depth for the selected configuration. This is because the thickness of the residual condensate layer may be greater than or less than the clearance between the syphon and the shell. As the condensate wave washes against a bar, some of the condensate passes over the bar while the remainder is reflected. The amount of condensate that is retained between the bars depends on the bar configuration (number and height of the bars), on the operating conditions (speed and condensing rate), and on the syphon design. A proper bar configuration will retain the correct amount of residual condensate over a wide range of operating conditions, with a fixed syphon clearance.

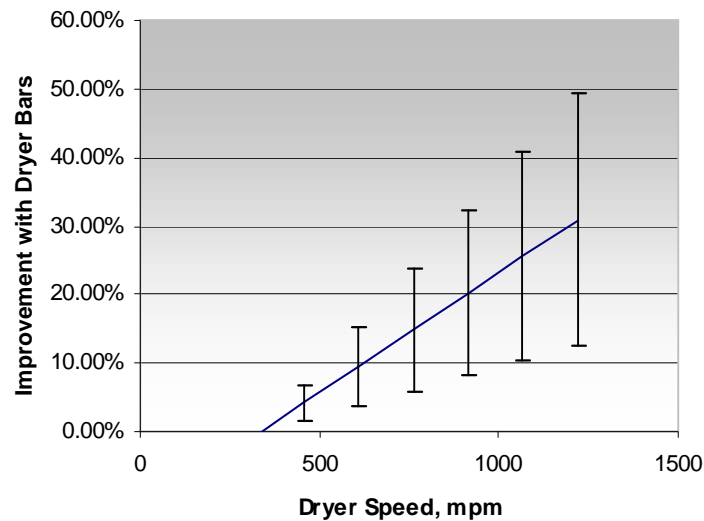


Figure 7: Theoretical Improvement in Drying Capacity with Dryer Bars

TEST RESULTS FOR JOCO 4000

Dryer bars can be produced in a number of different configurations. Dryer bar tests were conducted at the Kadant Johnson Research Center in Three Rivers, Michigan using its two test dryers, to evaluate a wide variety of bar configurations. One of these test dryers (the Joco 4000) has a 1.5 m diameter and a 6.4 m face width. The other dryer (the Joco 6000) has a 1.8 m diameter and a 8.4 m face width. In these tests, the dryer bar width, height, construction, and spacing were tested for various dryer speeds, condensing loads, condensing rates, steam pressures, and syphon configurations, in both of the test dryers.

This report covers the results of a series of tests for experimental configurations with (18) axial dryer bars in the Joco 4000 test dryer and (21) axial bars in the Joco 6000 test dryer. Both test dryers were equipped with stationary syphons located in 3 mm deep circumferential syphon grooves. The syphon clearance was measured from the bottom of the groove.

The cooling load was applied to each dryer by spraying water onto its surface and then doctoring off the excess water. The dryer surface temperature was measured using a traversing, contacting surface pyrometer. The heat transfer was determined by measuring the condensing load, the dryer steam pressure and temperature, and the dryer surface temperature. The heat transfer coefficient was determined over a range of syphon clearances and dryer speeds.

The results of the Joco 4000 tests are shown in Figure 8, with the dryer speed and syphon clearance on the two horizontal axes and the condensate heat transfer coefficient on the vertical axis.

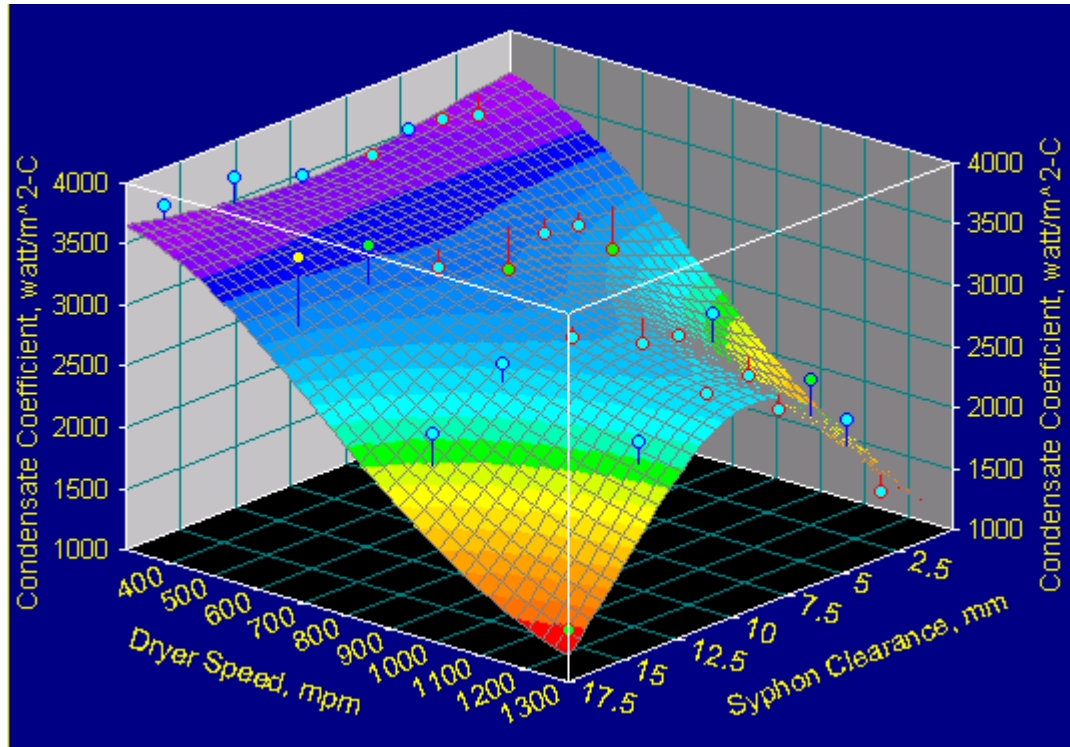


Figure 8: Condensate Coefficient—1.5 m Diameter Dryer

The graph depicts the following general trends:

- 1) As the dryer speed increases, the value of the condensate heat transfer coefficient (h_c) generally decreases. The amount of decrease is dependent on the syphon clearance.
- 2) In general, the highest heat transfer performance, and the least loss in heat transfer, occurs when the syphon clearance is set near the optimum values. A region exists for a range of syphon clearances for which the film coefficient is highest over the entire speed range. For this particular experimental configuration, the range is 5 to 11 mm.

Cross-sections can be taken from the above three-dimensional plot to show the effect of speed on the heat transfer coefficient, for two different syphon clearances. Two of these cross-sections are shown in Figure 9.

In the first cross-section, the syphon clearance was set at a fixed value of 1.5 mm from the bottom of the circumferential groove. This produced a high heat transfer rate at low speeds, but the heat transfer rate dropped off markedly as the speed was increased.

The second cross-section represents the heat transfer coefficient for a fixed syphon clearance of 9.5 mm. In this case, there is also a loss in heat transfer with speed, but the loss is much less than it was with the

smaller syphon clearance. This is because resonant waves were being developed in the rimming condensate layer, and this resonance was still quite strong, even at the higher machine speeds.

A cross-section was then taken from the three-dimensional plot, this time at a fixed machine speed of 1200 mpm. This cross-section shows that the heat transfer coefficient can be significantly increased, over a fairly wide range of syphon clearances (see Figure 10). At the ends of this graph, however, there is a significant fall-off in heat transfer.

That is, the syphon clearance can be either too large or too small to achieve the optimum (maximum) heat transfer coefficient.

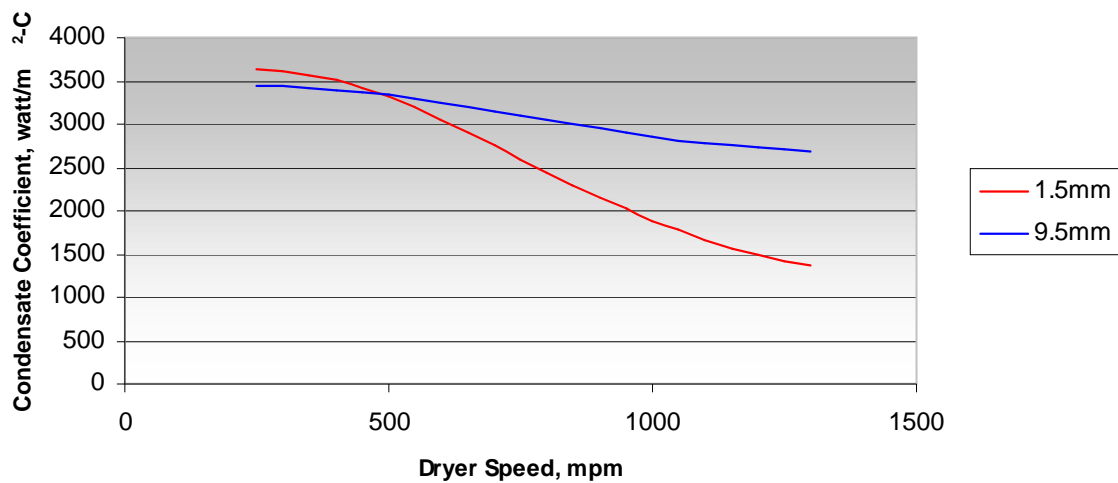


Figure 9: Effect of Dryer Speed on Condensate Coefficient—1.5 m Diameter Dryer

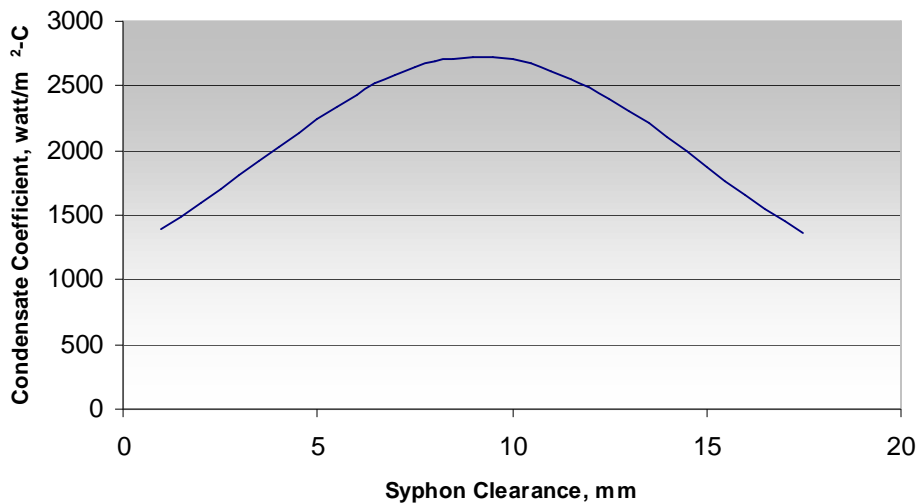


Figure 10: Effect of Syphon Clearance on Condensate Coefficient—1.5 m Diameter Dryer

TEST RESULTS FOR JOCO 6000

Operating at the optimum syphon clearance not only maximizes the capacity to transfer heat at a given speed, it also minimizes the loss of heat transfer with increasing speed.

In the next series of tests, an experimental configuration of (21) axial dryer bars were installed in the second of the two test dryers at the Kadant Johnson Research Center (the Joco 6000). The Joco 6000 dryer was also equipped with a stationary syphon located in a 3 mm deep circumferential syphon groove and the syphon clearance was once again measured from the bottom of the groove.

The heat transfer coefficients were evaluated in the same way as was done on the Joco 4000 dryer. The results are shown in Figure 11, with the dryer speed and syphon clearance on the two horizontal axes and the condensate heat transfer coefficient on the vertical axis.

Similar trends were observed in this series of tests with the 1.8 m diameter dryer as in the tests with the 1.5 m diameter dryer. The highest heat transfer performance, and the least loss in heat transfer, occurs when the syphon clearance is set near the optimum values. A region exists for a range of syphon clearances for which the film coefficient is highest over the entire speed range. For this particular experimental configuration, the range of syphon clearance over the syphon groove is 10-14 mm. The resulting condensate depth was significantly less.

Note that the theoretical optimum condensate thickness in the previous tests was 7.3 mm. The optimum condensate thickness for this second series of tests, according to the theory, is slightly less: 6.5 mm. In these tests, however, the optimum film coefficient was found to occur at a much larger syphon clearance (in this case, 10-14 mm) than was required in the Joco 4000 tests. This is because the syphon clearance was measured from the bottom of the circumferential groove. The residual condensate film thickness depends on the location of the syphon with respect to the dryer groove, as well as on the dryer diameter, condensing load, bar configuration, and syphon design. Tests are required to determine the proper syphon clearance for each set of dryer configuration and operating conditions.

Also note that the heat transfer values were much lower at the higher speeds in the 1.8 m diameter dryer than for the same bar configuration in the 1.5 m dryer. This is not a fundamental phenomenon. Rather, it is the result of some irregularity of the cylindrical surface of the 1.8 m diameter test dryer. This irregularity produced an inconsistent distance in these tests between the temperature sensor and the shell. The measured dryer surface temperature measurements were correspondingly less than the actual temperatures. This resulted in a reduction in the apparent heat transfer coefficients.

A series of cross-sections, shown in Figure 12, were also taken from this three-dimensional graph to show the effect of speed on the heat transfer coefficient, for three different syphon clearances.

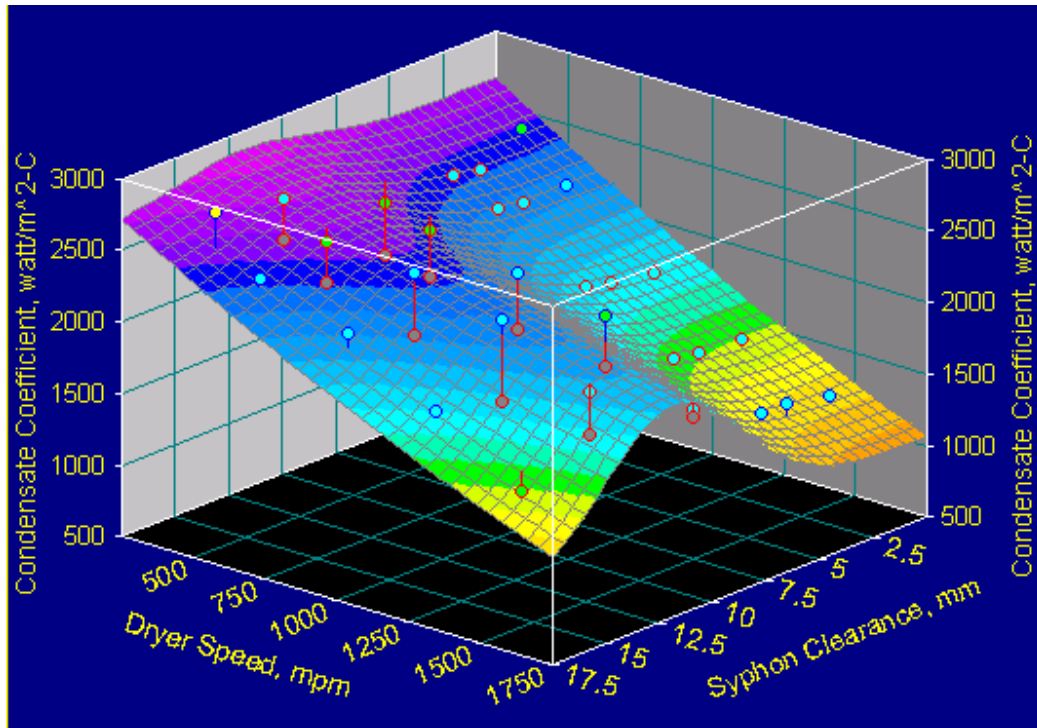


Figure 11: Condensate Coefficient—1.8 m Diameter Dryer

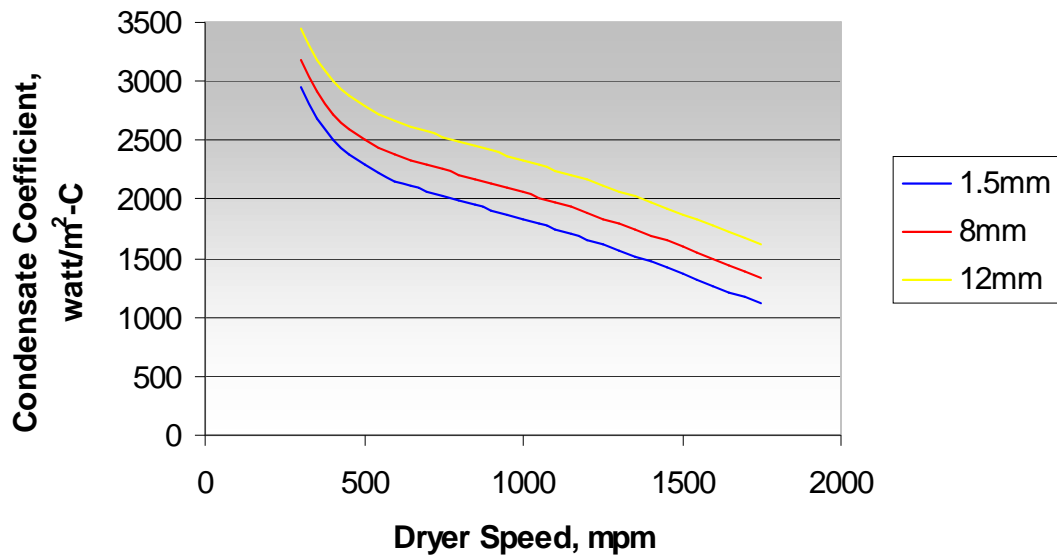


Figure 12: Effect of Dryer Speed on Condensate Coefficient—1.8 m Diameter Dryer

In the first cross-section, the syphon clearance was set at a fixed value of 1.5 mm from the bottom of the circumferential groove. This produced a high heat transfer rate at low speeds, but the heat transfer rate dropped off markedly as the speed was increased (see Figure 12).

The second cross-section represents the heat transfer coefficient for a fixed syphon clearance of 8 mm. In this case, there is also a loss in heat transfer with speed, but the loss is less than it was with the smaller syphon clearance. This is because the waves between the bars were closer to the optimum (resonant) condition.

In the third cross-section, the syphon clearance was 12 mm. In this case, the highest heat transfer of any of the three settings was achieved, over the entire range of dryer speeds. This indicates that the condensate film thickness was closer to the resonant condition.

Operating at the optimum syphon clearance not only maximizes the capacity to transfer heat at a given speed, it also minimizes the loss of heat transfer with increasing speed.

A cross-section was then taken from the same three-dimensional plot, this time at a fixed machine speed of 1500 mpm. This cross-section shows once again that the heat transfer coefficient can be significantly increased, over a fairly wide range of syphon clearances, if the syphon clearance setting is close to the optimum (see Figure 13). Significant losses in heat transfer occur if the syphon clearance is incorrect. That is, the syphon clearance can be either too large or too small to achieve the optimum (maximum) heat transfer coefficient.

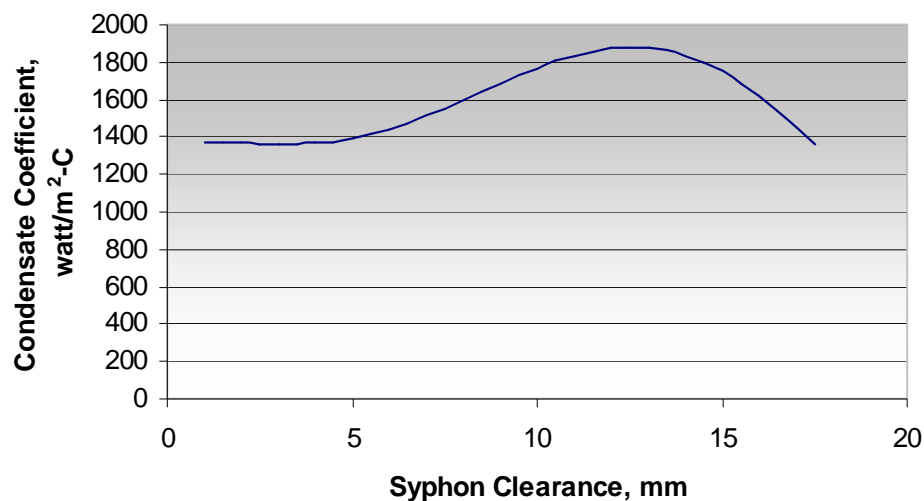


Figure 13: Effect of Syphon Clearance on Condensate Coefficient—1.8 m Diameter Dryer

DRYING UNIFORMITY

If a dryer does not have bars, any non-uniformity in the thickness of the condensate layer will directly result in a non-uniformity in the heat transfer. This is particularly evident in wide dryers with high condensing rates, where there is more non-uniformity in the thickness of the condensate layer and correspondingly in a cross-machine variation in the reel moisture profile.

If bars are placed in the dryer, the condensate heat transfer coefficient is much less sensitive to variations on the condensate depth. Dryer bars can produce a high degree of uniformity in drying, particularly if the condensate layer is close to the optimum value. This is because slight variations in condensate layer thickness no longer produce significant variations in the condensate heat transfer coefficient.

Figure 14 shows the dryer surface temperature, as measured on the Joco 4000, using the scanning surface pyrometer. In this figure, the temperature variation (minimum to maximum) was over 7 °C when the dryer did not have bars and less than 2 °C when bars were installed.

If, on the other hand, the condensate layer is not close to the optimum, there can be non-uniformities in the heat transfer coefficient, even though the dryers are operating with bars.

When operating with the right configuration of bars and the corresponding optimum condensate depth, dryer bars can not only achieve a high rate of heat transfer, but also achieve a high degree of drying uniformity.

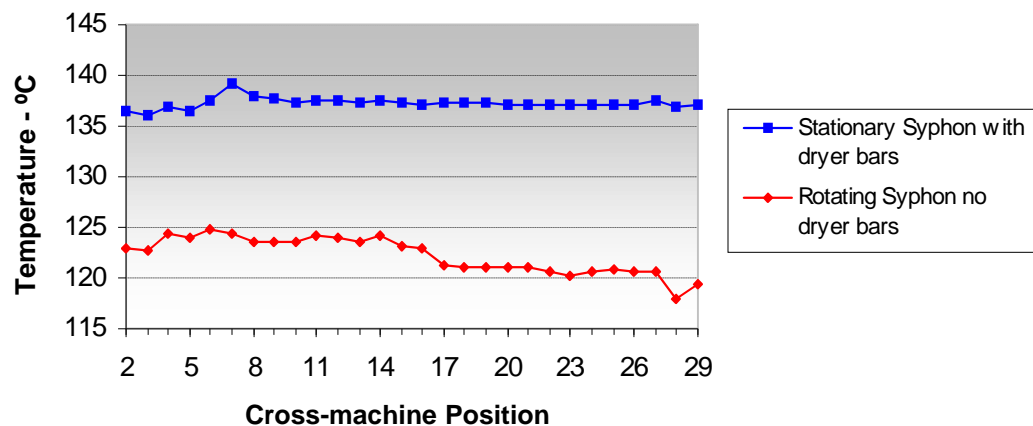


Figure 14: Temperature Profile Comparison

DRIVE POWER AND TORQUE

The power and torque required to drive the dryer cylinders depend on the dryer speed, amount of condensate in the dryer, and the type of dryer bars that are inside the dryer. ^{5,6}

The drive power and torque were determined for each of the tests outlined above. The dryer doctors were unloaded during the measurement of drive power in order to better isolate the effect of the condensate on the drive load. The results from the tests on the Joco 4000 are shown in Figure 15.

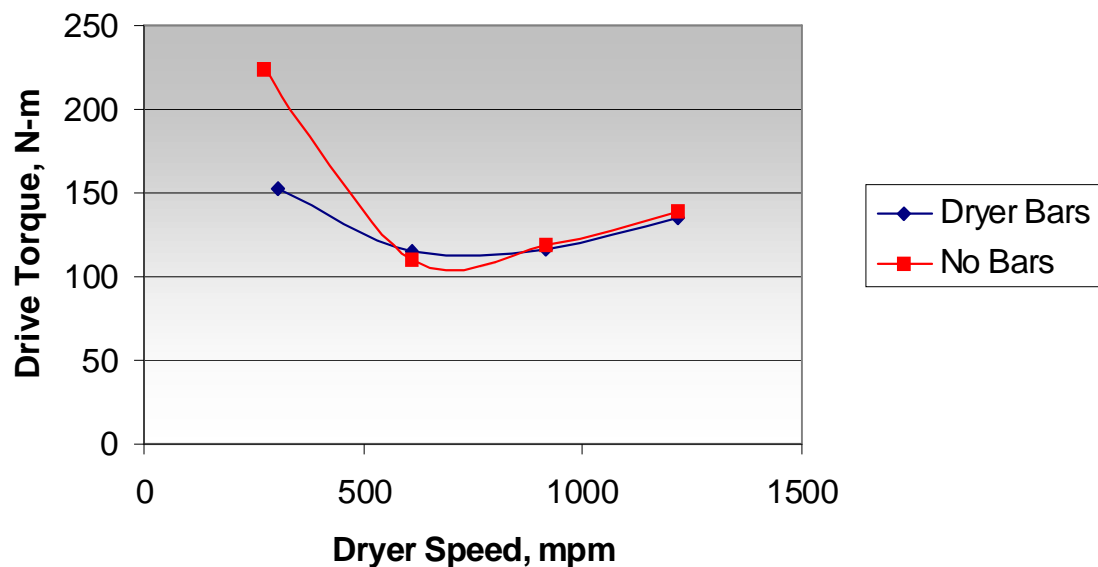


Figure 15: Effect of Dryer Bars on Drive Torque (1.5 m diameter dryer)

SUMMARY

Dryer bars can reduce the speed at which the condensate layer will move from the cascading stage to the rimming stage. This can provide a significant reduction in the power and torque required to drive the dryer cylinder.

Dryer bars can also greatly increase the rate of heat transfer from conventional paper dryers. The increase can be as large as 50%, even when compared to the performance of dryers with modern, close clearance rotating syphons. The maximum increase, however, requires the bars to operate with the optimum condensate layer thickness.

Dryer bars can also improve the uniformity of heat transfer. When operating with the optimum condensate depth, the cross-machine temperature profile can be level within 2 °C.

The optimum condensate layer thickness depends on the dryer bar configuration and on the dryer operating conditions. Specifically, for a given syphon clearance, the resulting condensate depth depends on the width, height, spacing geometry, and number of dryer bars. It also depends on the dryer speed, steam pressure, condensing load, dryer diameter, and groove configuration.

Simulation tests are required to identify the best syphon and bar configuration for the specified dryer operating conditions. This paper has outlined the results of one such study.

REFERENCES

1. White, R.E. and Higgins, T.W., "Effect of the Fluid Properties on Condensate Behavior," *TAPPI Journal*, 41(2): 71-76 (1958).
2. Calkins, D.L., "A Comparison of Rotary & Stationary Siphon Performance in Paper Dryers," The Johnson Corporation 1973.
3. Concannon, M.D., "Condensate Effects on Torque and Horsepower in Paper Dryers," *TAPPI Journal*, 63(9): 69-72 (1980).
4. Appel, D.W., and Hong, S.H., "Optimizing Heat Transfer using Bars in Dryers," *Paper Technology and Industry*, 16(4): 264 (1975).
5. Derrick, R. P., "Drive Power Requirements for Pulp and Paper Machine Dryer Sections," 1978 Engineering Conference Proceedings, Book II, TAPPI Press, Atlanta, p. 381.
6. Wedel, G.L. and Timm, G. L., "Drive Power and Torque in Paper Machine Dryers," TAPPI Engineering Conference Proceedings, September, 2001.

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.

- Steam and Condensate Systems
- Dryer Section Surveys
- Dryer Management System® control software
- Stationary Syphons
- Rotating Syphons
- Rotary Joints
- Turbulator® Bars
- Thermocompressors
- Desuperheaters
- Direct Injection Water Heaters
- Vortec™ Vacuum Generators
- Sight Flow Indicators
- Flexible Metal Hoses
- Installations Services

KĀDANT
AN ACCENT ON INNOVATION