Drying with two radial jets: development of radial jet reattachment drying arrays

Thomas C. Gruber Jr., Robert H. Page, Jamal Seyed-Yagoobi, and Sheri L. Albrecht

ABSTRACT: Impinging jets are used to enhance the drying of sheet materials. However, conventional jets may produce excessive force on an impingement surface. An alternative to conventional jets, the radial jet, was investigated. The radial jet is a new type of jet that produces a variable net force on the impingement surface. Two impinging radial jets were used for drying a cotton cloth with a dry basis moisture content (DBMC) of 1.5. This was accomplished with two –10° radial jet reattachment (RJR) nozzles, which produced a net negative force on the surface. The DBMC was measured as a function of time for various rectangular test areas. The drying rate was determined as a function of area. The radial jet results were compared to two conventional in-line jets. For some conditions, the radial jets provided a greater drying rate than in-line jets. Multiple RJR nozzles can be used to assist conventional drying processes.

KEYWORDS: Development, drying, force, impingement drying, jets, nozzles.

One application of radial jets is in paper manufacturing. Because paper drying consumes 1/3 of the energy in paper manufacturing, there is interest in drying methods that consume less energy *(1)*. Impinging jets of dry air positioned adjacent to the paper sheet may assist conventional drying. Jets are known to produce high transport from an impingement surface. However, only 10% of all types of paper drying utilize impinging jets. Pulp drying has the highest percentage use of impinging jets at 70% *(2)*. One of the disadvantages of drying with conventional jets is the aerodynamic force produced on the paper, because excessive jet velocities can damage paper. A radial jet, which is relatively new, avoids this problem through a design advantage that allows a negative, null, or positive net force on the paper. The radial jet was developed by Page *et al. (3)*. A cross section of the radial jet flow field impingement is shown in **Fig. 1.** The radial jet flow is characterized by a subatmospheric recirculation region under the nozzle and a turbulent reattachment ring on the impingement surface. The flow exit angle, as shown in Fig. 1, can be used to control the force on the impingement surface *(4)*. The force per jet on the surface can be estimated with:

$$Force = A\,\rho V^2 \sin\theta \qquad (1)$$

where

A = exit area of the jet

ρ = density of air

V = jet exit velocity

θ = jet exit angle.

A negative exit angle results in the flow exiting the nozzle away from the surface. This produces a net negative force on the surface.

Drying with a single radial jet was investigated by Habetz *et al. (5)*. Recently, four flow types were determined for two interacting, –10° radial jet nozzles by Gruber *(6)*, as shown in **Fig. 2**. It was found that one type of interaction (type 2) produced the best heat transfer from an impingement surface. The drying tests reported in this paper were

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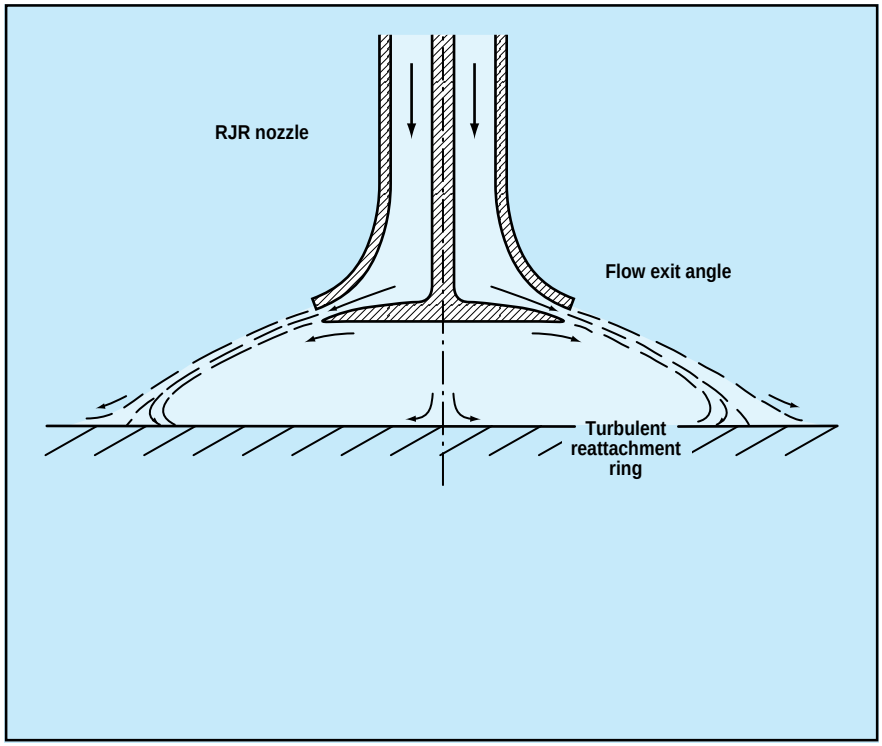
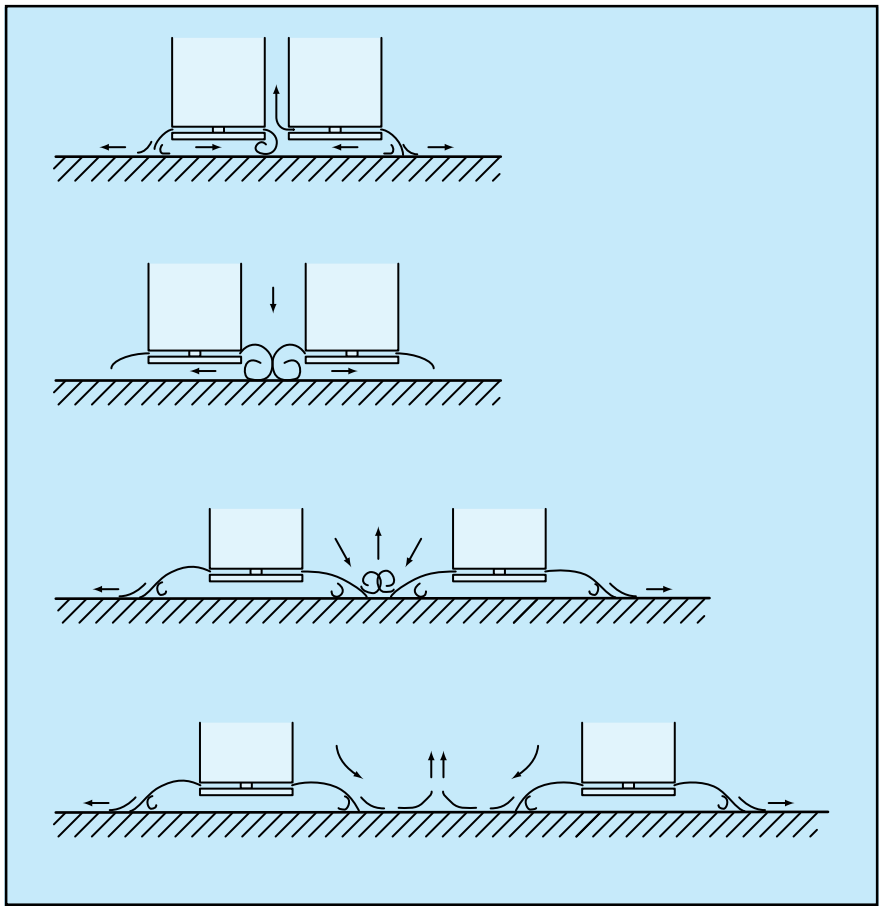
1. Radial jet flow impingement



2. Flow types for –10° radial jets in order from 1 (top) to 4 (bottom)



therefore conducted with a nozzle height (distance from center of exit to impingement surface) and crowding (distance between nozzle centerlines) that corresponded to flow type 2, of Fig. 2. These radial jet reattachment (RJR) results were compared with conventional in-line jets (ILJs).

Recently, an array of RJR nozzles was implemented for drying paper by Thiele *et al. (7)*. A row of –10° RJR nozzles was installed adjacent to a moving paper sheet between two drum dryers within the pocket. This array improved drying rate while reducing sheet flutter with the net negative force of the radial jets.

Experimental program

The Drying Jet Impingement Facility (DJIF) was used for automated measurement of the dry basis moisture content (*DBMC*) of the impingement test material. *DBMC* was defined as:

$$DBMC = (\text{water in test material, g})/(\text{dry basis weight, g/cm}^2)(\text{test material area, cm}^2) \quad (2)$$

The DJIF was used to obtain drying data to evaluate the –10° radial jets and compare them to two ILJs. All the nozzles had an exit area of 304 mm^2. A system developed by Gruber *(6)* was used to support the nozzles and distribute the air.

A compressed air system provided dry air with a dew point of –40°C for the RJR nozzles. The impingement surface material consisted of a 0.23-mm thick, 100% cotton cloth with a basis weight of 0.011 g/cm^2 and a porosity of 70%. The cloth was supported by a flat 550 mm by 275 mm by 16 mm thick Styrofoam sheet. A template was used to mark the 2 to 1 ratio rectangular test area of interest. Then, the impingement surface was moistened uniformly with water from a spray bottle until a *DBMC* of 1.5 was obtained. To ensure the same flow field for all tests, the impingement surface area was the same as the dimensions of the Styrofoam

sheet, but the moistened area was variable with this procedure. Prior to the test, the template was removed and the sample was placed on the balance under the pre- positioned nozzles. The digital balance was connected to a 386 computer. A computer program was used to obtain the mass of the test surface at 10-s drying intervals. Between each interval, a solenoid bypass valve was activated to interrupt flow to the nozzles for 8 s so that an accurate measurement was possible with the digital balance. Only the actual drying time was recorded since negligible drying occurred during weighing. The computer program was used to obtain data until *DBMC* of 0.05 was reached.

The data were used to calculate the predicted derivative of *DBMC* with respect to time. This was accomplished with third order polynomial curve fits of the *DBMC* data:

$$DBMC(t) = a+bt+ct^2+dt^3 \qquad (3)$$

where t is time.

A comparison of a polynomial such as Eq. 3 with experimental data showed excellent agreement and that a more complicated curve fit would not be required. The drying rates were used to calculate the drying rate ratio (*DRR*) between RJR and ILJ data:

$$DRR = \frac{\left[\frac{d(DBMC)}{dt}_{RJR}\right]}{\left[\frac{d(DBMC)}{dt}_{ILJ}\right]} \qquad (4)$$

DRR was then plotted versus *DBMC*.

Results and discussion

The results illustrate the potential of drying with multiple radial jets. Their feasibility is demonstrated by comparison with conventional in-line jets. The results are shown for a limited number of configurations due to the cost and time involved in such studies. However, this does not mean that the concept of drying with radial jets is not clearly demonstrated. For all tests, the jet exit velocity was 70 m/s and the exit air temperature was 22°C. The ambient air had a 40% RH and a temperature of 22°C. Initially, the drying material was also 22°C. For the –10° radial jet tests, the height and nozzle crowding were selected for flow type 2 interaction (Fig. 2). The same exit area, exit velocity, nozzle crowding, and nozzle height were used for any comparison between RJR and ILJ nozzles. The flow rate and nozzle height were the same for any two nozzles in a test.

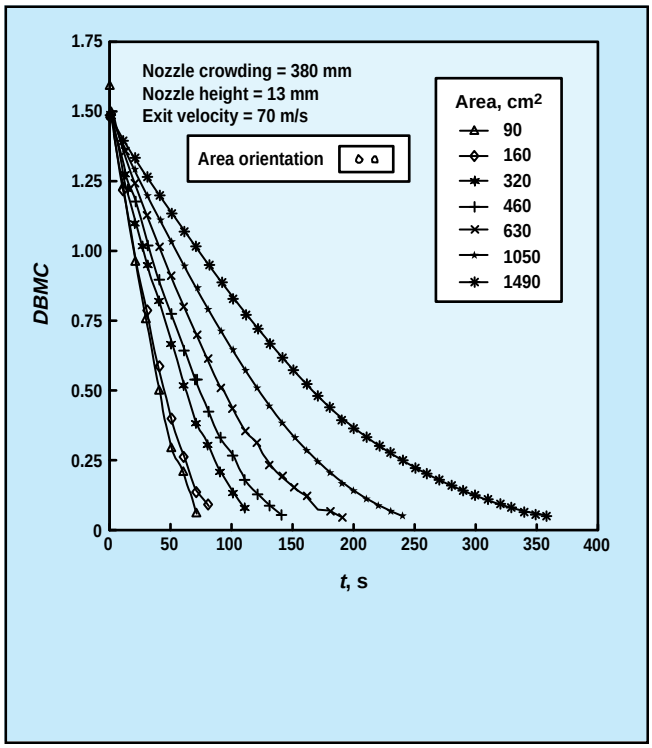
The dry basis moisture content (*DBMC*) as a function of drying time is shown in **Fig. 3** for the impinging –10° radial jets. The curves identify data for particular areas. As area increased, the drying time increased. The orientation of the area is shown in the figure, where the location of the nozzles relative to the impingement surface is indicated by the circles. The effect of the orientation was investigated and found to have almost no effect on the drying, as shown in **Fig. 4**. The jets produced high transport from the surface in the vicinity of the reattachment locations while the edges of the rectangular test area took longer to dry due to lower local velocities, which explains why the orientation had little effect on drying. An increase in nozzle height increased the drying time for the radial jets, as shown in **Fig. 5.** At a height of 25 mm, the velocities near the surface were less. Since there is a direct relationship between local velocity and surface transport, the drying time increased as local velocity decreased. The values of crowding and height are indicated in the figures and the results in **Figs. 5-9** have the same area orientation as shown in Fig. 3. A typical comparison between ILJs and RJRs is shown in Fig. 6. The drying was better for RJRs than for ILJs for values of *DBMC* less than 0.5. The RJRs had an advantage in providing high transport over a larger area through the reattachment ring. Therefore, once the area in the immediate vicinity of the nozzles was dry the RJRs were better able to dry the remainder of the surface. This condition probably occurred at a *DBMC* of less than 0.5.

The drying rate was predicted as a function of area, as shown in Fig. 7. Recall the drying rate was predicted by taking the derivative of the curve fit of the data. The drying rate increased for the two –10° RJR nozzles as area decreased and *DBMC* increased. The drying rate ratio (*DRR*) was predicted for several impingement areas as a function of *DBMC*, as shown in Fig. 8. The *DRR* has a value greater than 1 for values of *DBMC* less than 0.5 and for a nozzle height of 13 mm. An increase in impingement area increased the *DRR*. The radial jets produced faster drying than the in-line jets for an area of 1490 cm^2 only, as indicated by a *DRR* greater than 1 for the entire range of *DBMC*. This result indicates that the RJR nozzles provided higher transport over a larger area than the ILJ nozzles. The *DRR* was less than 1 for the height of 25 mm, since the velocities near the surface were less for RJR nozzles at this height. The results in Figs. 7 and 8 were predicted by taking derivatives of curve fits of data and by using Eq. 4, respectively.

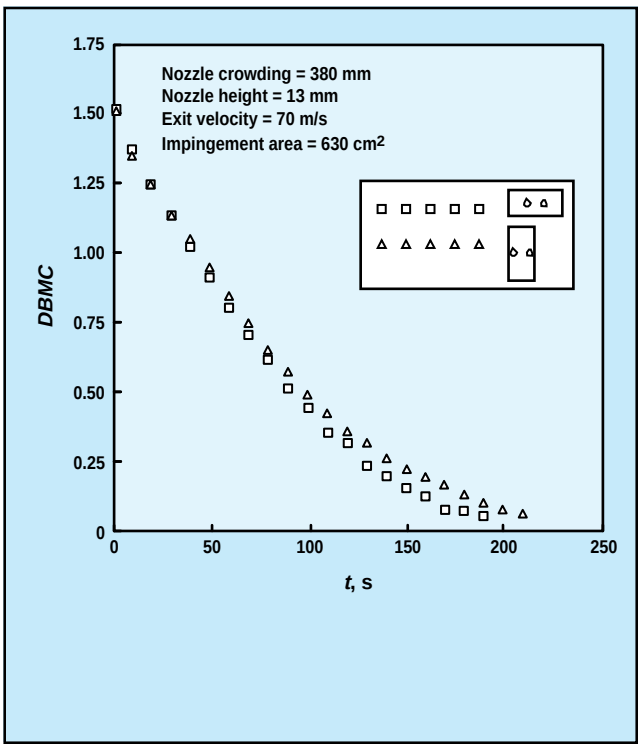
A typical repeatability of the data is shown in Fig. 9. The minimum uncertainty was ± 1% at a *DBMC* of 0.05 and the maximum uncertainty was ± 8% at a *DBMC* of 1.5. The jet exit velocity and temperature uncertainties were ± 5 m/s and ± 1°C, respectively.

The force on the impingement surface per nozzle was estimated with Eq. 1, where θ was –10° for the RJR nozzles and 90° for the ILJ nozzles. The result was multiplied by 2 since obviously there were two nozzles. The net force was –0.6 N and 3.5 N, for the two radial and two in-line jets, respectively. Higher drying rates are possible with RJRs without damaging the drying material since the

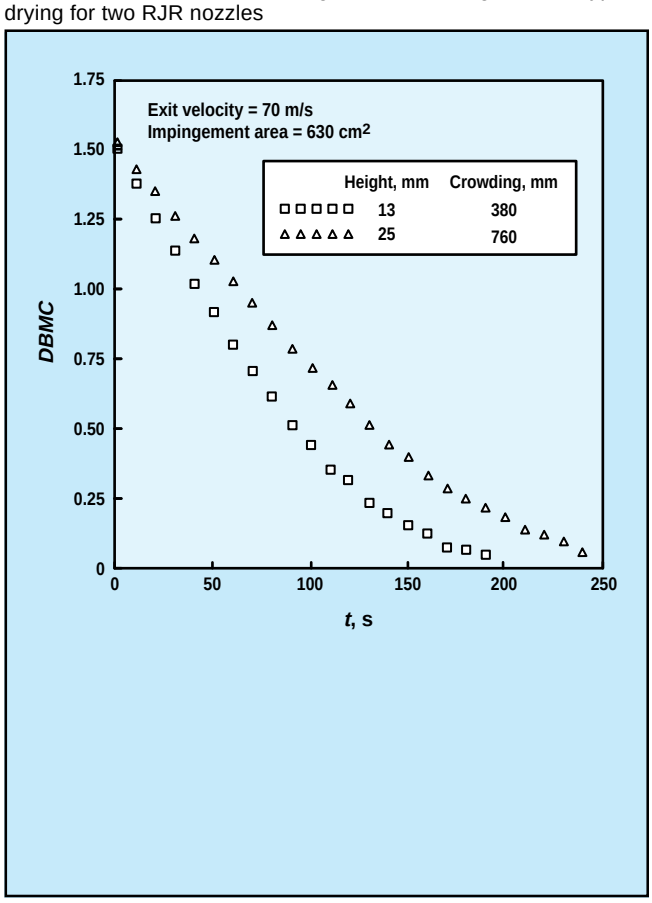
3. *DBMC* as a function of time and impingement area for two RJR nozzles



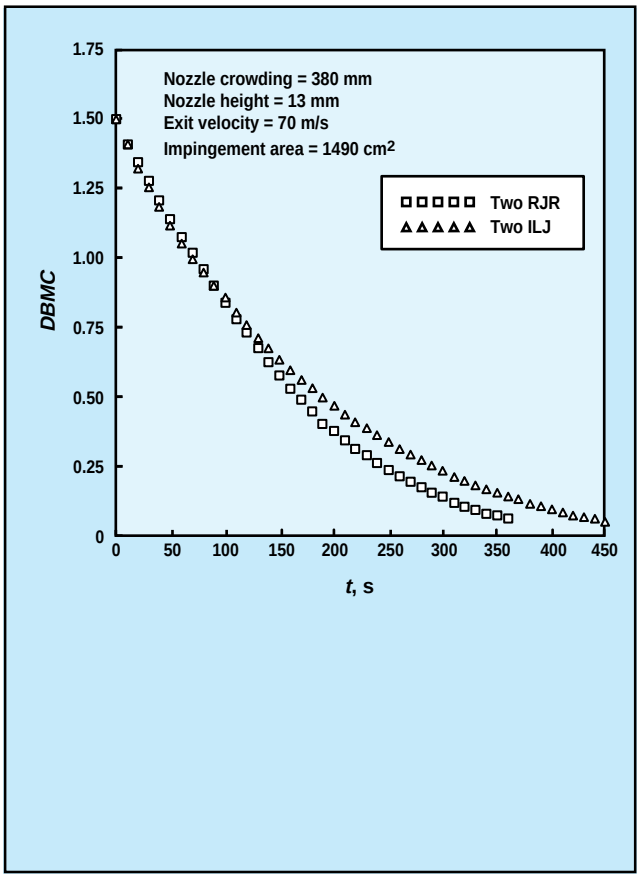
4. Effect of rectangular test area orientation for two RJR nozzles



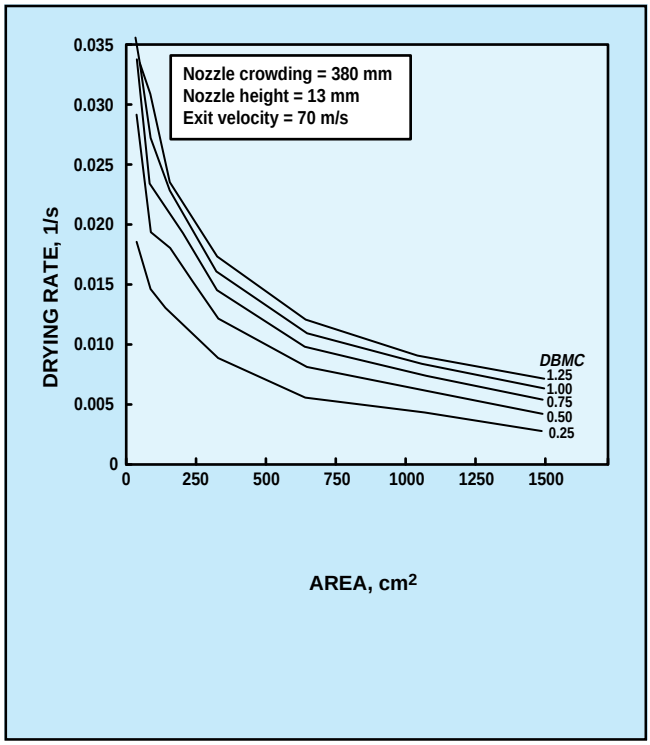
5. Effect of different nozzle height and crowding on flow type 2 drying for two RJR nozzles



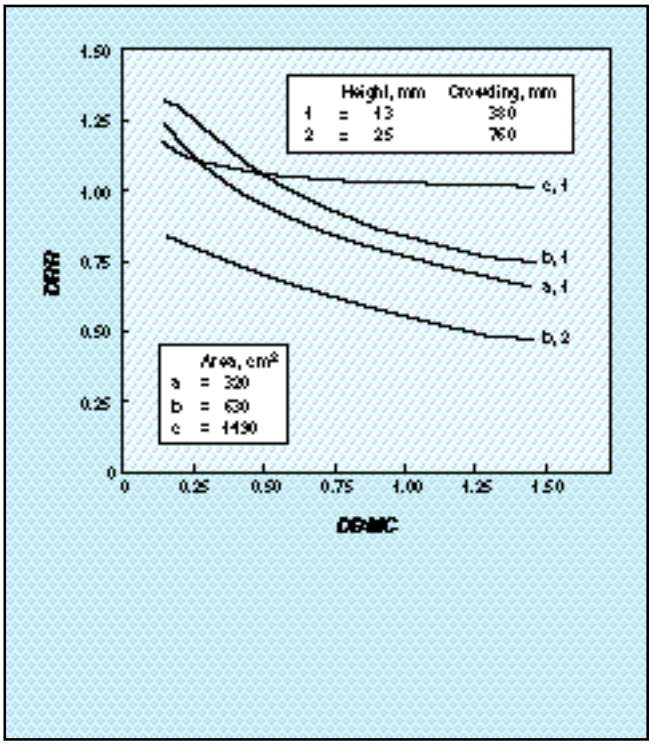
6. Comparison between two –10° RJR and two ILJ nozzles



7. Predicted drying rate as a function of area and *DBMC* for two RJR nozzles



8. Predicted *DRR* as a function of *DBMC* for two RJR nozzles compared with two ILJ nozzles



magnitude of the force for a given jet exit velocity is considerably less than for ILJs.

Conclusions and recommendations

The drying results show that –10° radial jets at a height of 13 mm and a crowding of 380 mm would be especially effective for drying materials with *DBMC*s of 0.5 or less. The RJR nozzles were shown to perform as effectively as conventional in-line jets without developing a positive force on the impingement surface for a range of *DBMC* of 0.05 to 1.5. The results indicated that pairs of –10° RJR nozzles could be used to construct an effective drying array.

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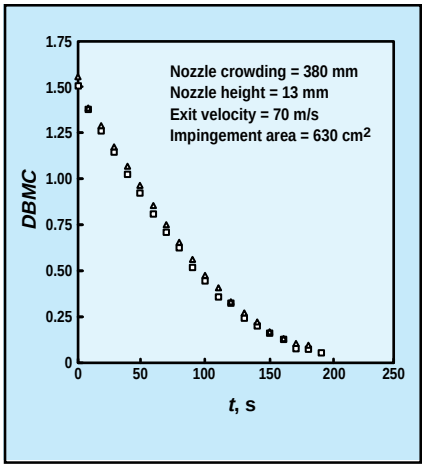
9. Repeatability drying results for two tests of two RJR nozzles