Options for controlling convective coating dryers

Kenneth G. Hagen and James R. Bowden

Coating quality and dryer efficiency can be improved by using exhaust flow as a process control parameter.

Modern coated paper drying systems have routinely employed convective-air dryers for the past three decades. Although it is widely held that the machine-direction drying strategy can have a significant impact on binder migration and mottle, control of convective dryers has remained simplistic. Opportunities to provide the coater operator with better and more convenient control of the whole drying process have been largely neglected.

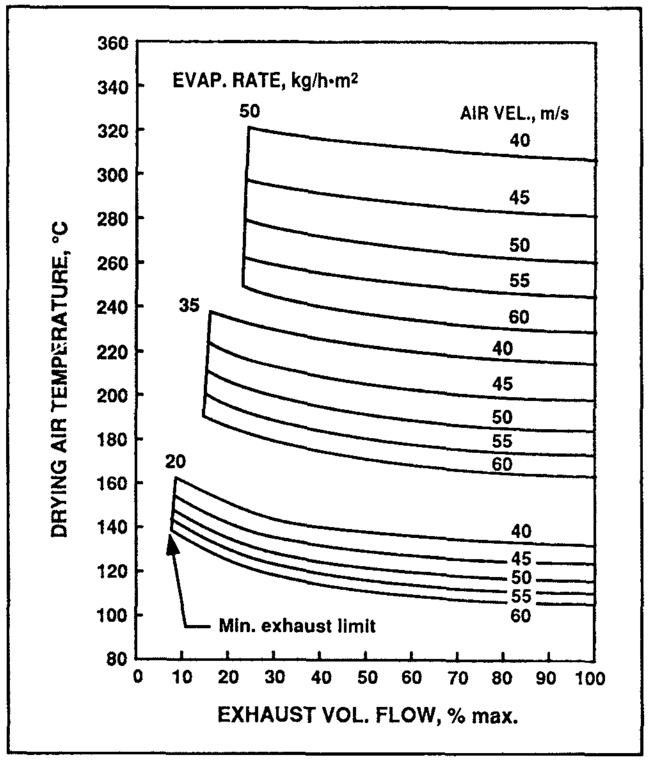
Flotation has emerged as the preferred form of convective-air drying for most coated paper grades and will constitute the focus of this paper; however, the findings are also applicable and appropriate for the various forms of conveyorized and air-cap convective dryer types.

In a typical floater dryer, heated air is delivered to supply ducts within the dryer, above and below the web, by a fan. A number of headers then conduct the air to the nozzles which apply it to the web at high velocity. The air picks up moisture from the web and passes between the nozzles into the plenum chamber represented by the dryer enclosure. From here it is collected, partially recycled, reheated, and then returned to the dryer.

Slots are provided at each end of the dryer enclosure through which the web enters and leaves. The staggered arrangement of the nozzles above and below the web has been found necessary for good flotation. Modern nozzles usually create a pressure pad which induces a sinusoidal-like shape to the web as it passes through the dryer. This provides a measure of cross-machine rigidity which flattens mild ripples and enables the web to resist edge curl.

For coated paper applications, the dryer has an external air system. After leaving the dryer, return air is collected from the upper and lower dryer halves. A portion is extracted by the exhaust fan, the remainder is recirculated back to the heat source where it is directly heated by a fuel burner or indirectly by steam coils. Drying rate is controlled by means of the air temperature or the air velocity delivered to the web by the nozzles, or both. Heat addition is automatically controlled to hold drying air temperature at a selectable setpoint, and a damper in the air supply duct either before or after the supply fan is used for velocity control.

1. Compatible dryer operating conditions

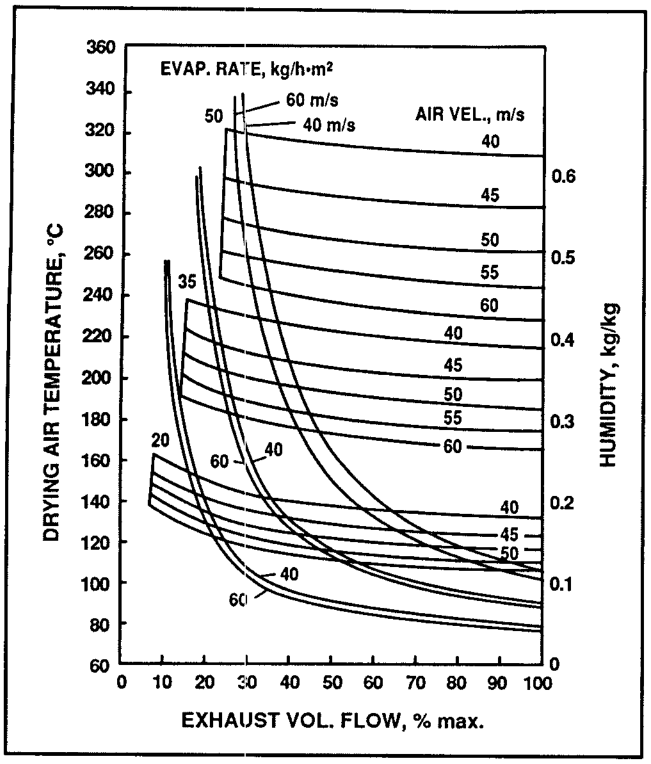


Recirculation is used for fuel economy; it also affects the humidity within the dryer and, therefore, the temperature of the web while it is being dried. The amount of recirculation may be controlled by adjusting the exhaust damper, but it is also affected by changes in the supply velocity. Changes in the exhaust damper setting may cause air to enter or leave the dryer web entry and exit slots unless corresponding adjustments are also made in the position of the makeup air damper. Where hot air puffing from a dryer is easily recognizable and generally avoided, infiltration is more subtle and its negative effects largely unknown.

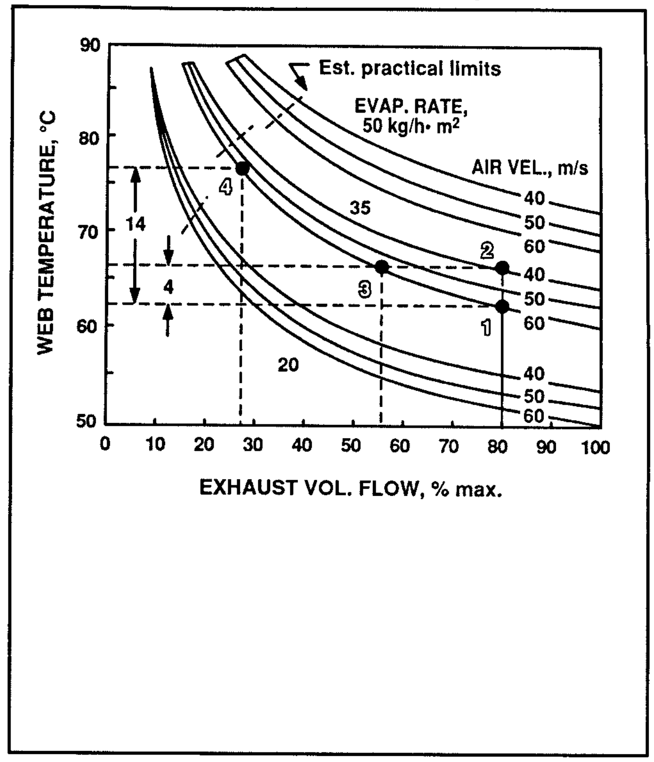
Because of these circumstances, proper use of these two dampers tends to be confusing and poorly understood. To

Hagen is vice president, technical, and Bowden is a controls engineer at Thermo Electron Web Systems, Inc., P.O. Box 269, Auburn, MA 01501.

2. Dryer internal humidity behavior



3. Influence on web temperature of dryer operating conditions



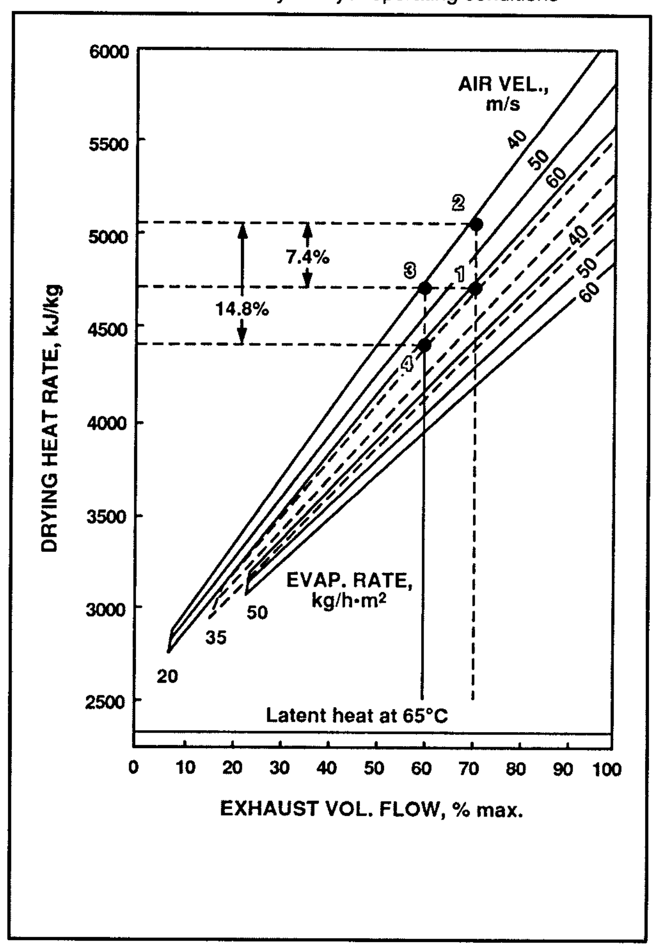
compound the difficulty, both exhaust and makeup air dampers are usually remote and manually operated with no easily interpreted data available to the machine operator to guide his or her adjustment. As a result, dryers often operate at low efficiency; capacity is compromised, and opportunities to improve the process conditions for the benefit of coating quality are missed. This paper analyzes the performance of typical flotation dryers parametrically and describes a control scheme which permits the performance envelope to be easily accessed without incurring dryer end slot flow.

Dryer parametric operating conditions

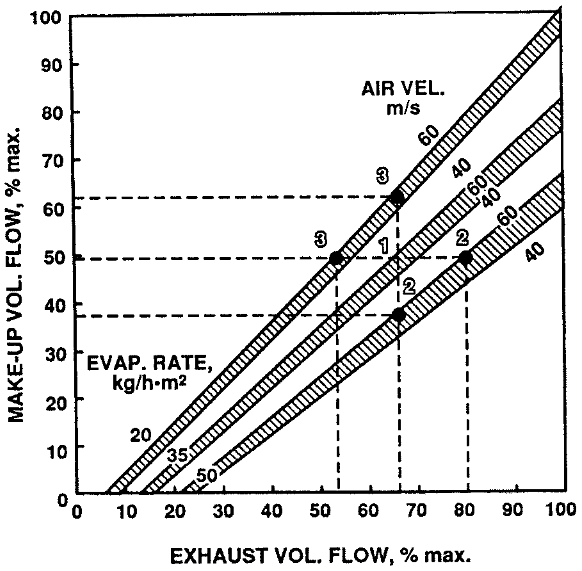
Many operational parameters enter into the analysis of a convective dryer; however, they are linked by well known equations, and the heat transfer attributes of modern dryers are based on reliable experimental data. Thus, with the aid of computers, parametric performance data can be generated with comparative ease. The results of such analysis give reliable insight into the expected behavior of these machines.

There are three phases of operation in the normal drying system: warm-up, constant rate drying, and falling rate drying. Since the concepts developed in this paper apply equally well to all three regimes, data is shown for the constant rate phase because it is simpler to present parametrically. **Figure 1** shows the interrelationship between drying air temperature, exhaust flow, air velocity, and drying rate. Exhaust flow is presented as a percentage of maximum; the maximum, in this case, is chosen to provide an exhaust rate equal to 25% of the supply flow at the maximum (design) velocity of 60 m/s. Each

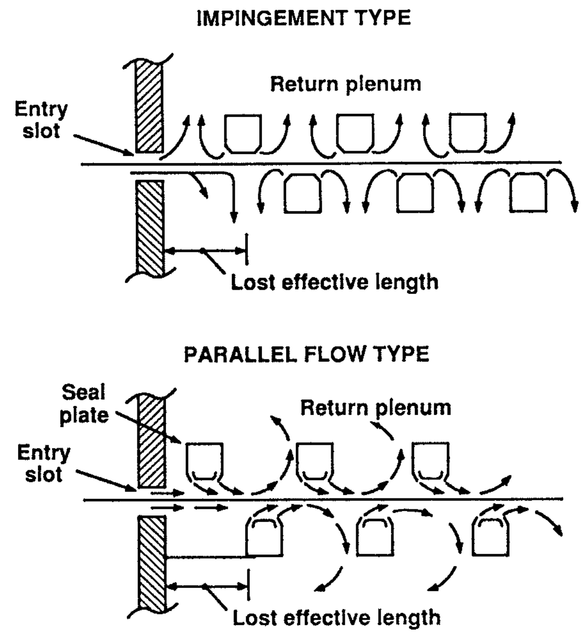
4. Influence on fuel economy of dryer operating conditions



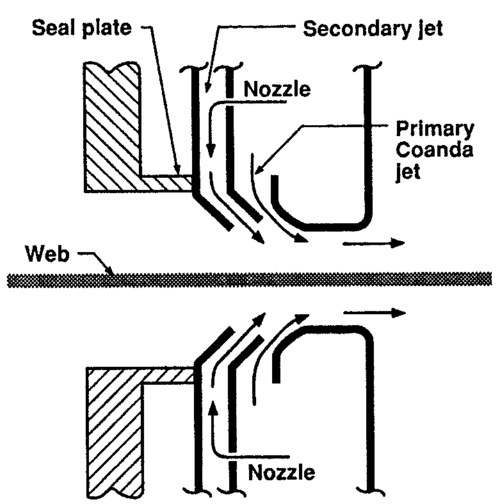
5. Exhaust and makeup air flow relationships



6. Dryer end-slot region



7. Sealing nozzles



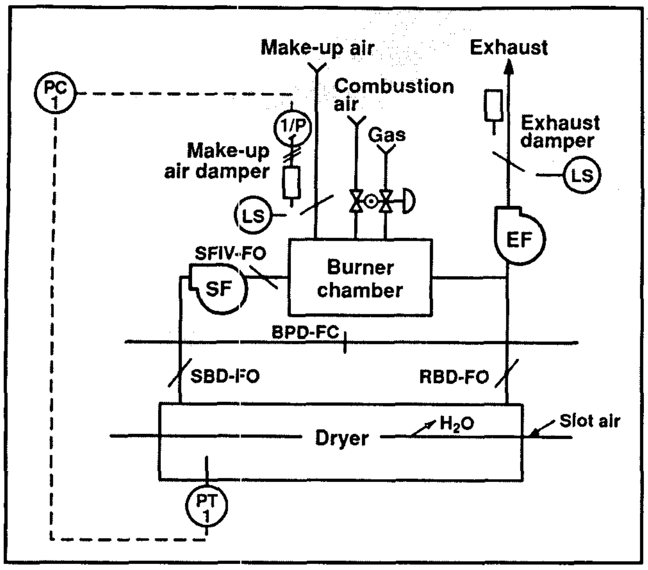
group of curves is for a single drying rate.

As velocity is decreased, temperature must increase to maintain the drying rate. The cut-off line for each set of curves represents a theoretical minimum exhaust when it exactly equals the sum of the combustion products and the water evaporated from the web, assuming 10% excess combustion air. For an indirectly heated dryer (as by steam), these cut-off lines would move to the left. Exhaust volume can be decreased considerably for a very small compensating increase in air temperature to maintain the drying rate. This required temperature rise becomes quite significant only at the lower drying rate and when the exhaust volume is below 30%. Thus, for much of the range, drying rate is mainly established by a combination of supply temperature and velocity. Exhaust flow can be adjusted almost independently of drying rate.

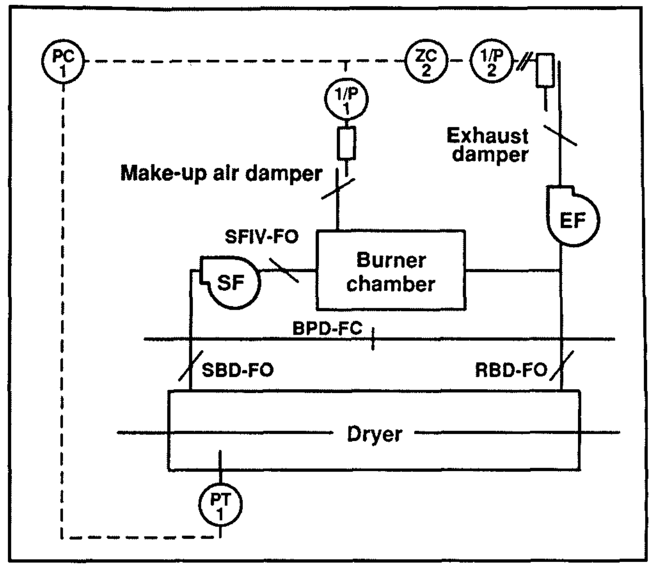
One major consequence of reducing the exhaust rate is illustrated in **Fig. 2**, which overlays the corresponding dryer internal humidity onto the parametric data of Fig. 1. Air velocity is seen to have a minor effect on humidity. As the velocity is decreased, there is a small increase in humidity. This is associated with the density change of the air as the temperature is increased to maintain the drying rate. The main impact of the humidity inside the dryer is its effect on web temperature (**Fig. 3**).

Reportedly, higher drying rates can be tolerated, from the viewpoint of binder migration, using a combination of high air temperature and low velocity rather than the reverse (*1–4*). Higher web temperature will generally result from such a combination. It has been postulated (*5, 6*) that there is a theoretical basis to support the value of raised web temperatures in combating binder migration for both soluble and particulate binders. Figure 3 plots

8. Plenum pressure control



9. Fuel usage control



web temperature against exhaust rate for the three drying rates and the range of air velocities shown previously. These curves show that reduced air velocity does increase web temperature but only by a small amount.

Point 1 in the figure represents an operating condition of 60 m/s air velocity at 168°C (from Fig. 1) for a drying rate of 35 kg/h•m² at an 80% exhaust rate. Decreasing the velocity to 40 m/s (Point 2) would require an air temperature increase to 218°C and would increase the temperature of the web by 4°C. Changing the exhaust setting from 80% to 56% without changing the air velocity (Point 3) would have the same effect on web temperature. A further decrease in the exhaust setting to 27% would increase the web temperature an additional 10°C (Point 4). Changing both parameters would be even better, but there are counter arguments about reducing air velocities.

As mentioned earlier, recirculation is employed to save fuel. **Figure 4** may be used to evaluate this feature. In this case, fuel economy is defined in terms of a heat rate—the amount of heat required to evaporate a given amount of water. The latent heat at 65°C is shown at the bottom of the graph as a reference. It represents a minimum requirement. Again sets of curves are shown for the previous ranges of air velocities and drying rates. To minimize confusion, the middle group is shown with dotted lines. Point 1 designates an operating point at 60 m/s air velocity and 70% exhaust volume. Dropping the velocity to 40 m/s while raising the temperature enough to maintain the same drying rate results in an increase in energy consumption of 7.4% (Point 2). To avoid this, the exhaust rate must also be changed from 70% to 60% (Point 3). However, had the velocity been left at 60 m/s at this reduced exhaust rate (Point 4), an energy savings would have been realized.

Exhaust rate is a potent parameter for favorably altering drying conditions; also, changing the air velocity is not generally advantageous. In fact, from the viewpoint of runnability, for the newer floater dryers, maintaining a reasonable velocity level is positive because it enhances the pressure pad and the corresponding S-wave. To implement exhaust flow as an operating parameter for convective dryers, there are additional factors which must be addressed.

Dryer system mass balance

When a floater dryer is commissioned, its exhaust and makeup air dampers are adjusted to establish a suitable negative pressure within the dryer enclosure. This is done, among other reasons, to ensure that the dryer doesn't puff hot air into the working environment. Six flows are involved in dryer balancing:

- M_E = exhaust
- M_F = fuel (usually gas)
- M_{CA} = combustion air
- M_W = water evaporation from the web
- M_{MU} = makeup air
- M_I = infiltration or exfiltration (slot flow).

They are related by the following mass balance equation:

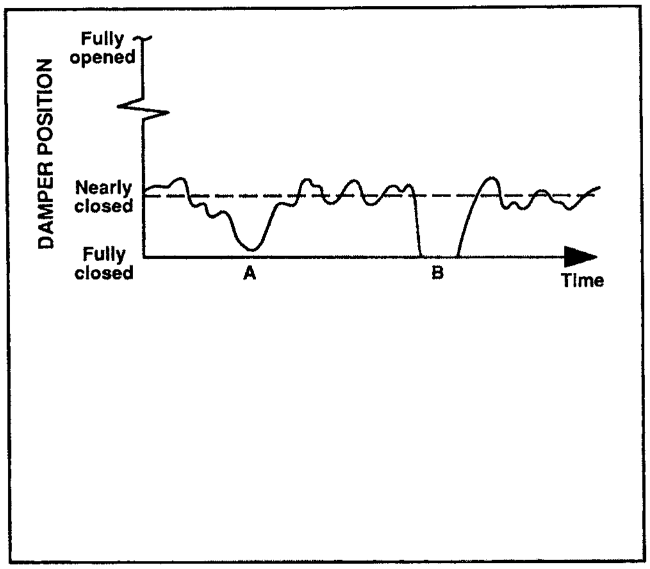
$$M_E = M_F + M_{CA} + M_W + M_{MU} + M_I \qquad (1)$$

The last term is a consequence of imperfect balancing. When positive, it is infiltration; when negative, it is exfiltration.

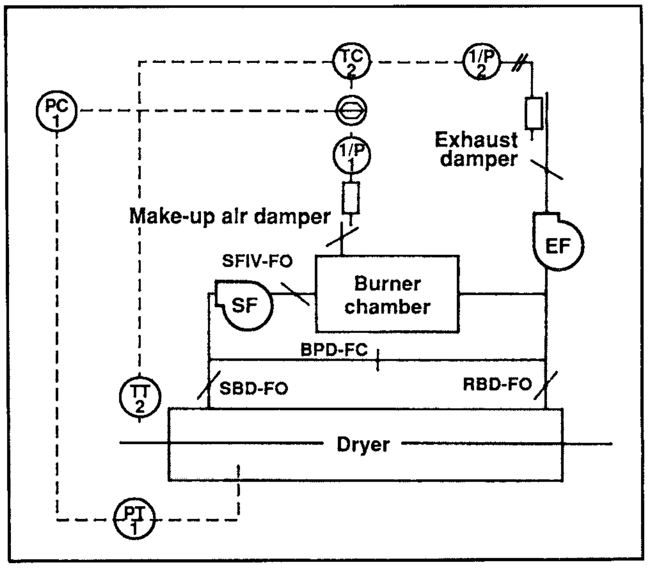
Exhaust and makeup air dampers must work in unison if the balance of the dryer is to be maintained for all operating conditions. For example, increasing the drying rate implies an increase in the fuel, combustion air, and evaporation flows. Thus, for a given exhaust flow, the makeup air must be reduced as the drying rate is increased. It is also clear that using the exhaust damper as a primary process control requires that the makeup air damper be correspondingly adjusted if infiltration or exfiltration are to be avoided.

The interactions between these two dampers are illustrated in **Fig. 5.** Here we assume that the makeup air damper is sized, when fully open, to provide a balanced

10. Makeup air damper modulations



11. Web temperature control



dryer at the air velocity of 60 m/s and drying rate of 20 kg/h·m². At any given exhaust setting, reducing velocity or increasing the drying rate, or both, requires a reduction in the makeup air setting to avoid any slot flow. Point 1 represents an example setpoint with the makeup air at 50%, the exhaust at 66%, the drying rate at 35 kg/h·m², and the velocity at 60 m/s. Starting from this condition, and intending to avoid slot flow, required combinations of exhaust and makeup settings to accompany changes in drying rate are shown.

Points 2 show a drying rate increase. If the makeup air setting doesn't change, exhaust must be increased to 80% or puffing will occur. Alternatively, if the exhaust remains at 66%, the makeup must be reduced to 38% or puffing will occur. The second choice is best; the first results in a cooler web and poor efficiency.

Points 3 exemplify a decrease in drying rate. In this case, failure to make the appropriate damper adjustments results in infiltration, and the preferred choice is to reduce the exhaust. Of course, in general, closing the exhaust favors higher efficiency and a hotter web, but there are limits.

Once the makeup air damper is fully closed, sufficient exhaust is required to extract the combustion products and the evaporated water. The minimum settings for the exhaust are seen to increase as the drying rate increases. In practice, exhaust settings can never be made as low as these. Most ducting systems have some leakage through explosion door seals, mechanical joints, etc., and dampers are not usually leak-tight when closed. Present balancing practice is usually aimed at avoiding puffing, and dryer designs tend to incur a certain amount of end-slot infiltration because no provisions are incorporated to avoid it and operators prefer infiltration to puffing. Clearly there is a definite dryer performance incentive to utilize and maintain good quality, leak-tight ducting and to keep the mass balance neutral as the operating conditions change.

Infiltration

End-slot infiltration is not generally regarded as an operational defect. In some ways, it is a convenient self-controlling source of makeup air and is used as such. Many older machines have no provision for makeup air, and some operators run the dryers with makeup air dampers closed. Infiltration is not desirable and can have a serious negative impact on drying capacity and coating quality, particularly with short dryers. For vertical or highly tilted dryer orientation, end-slot flow can be induced by a chimney effect wherein infiltration occurs at the bottom and puffing at the top, with serious negative impact on the working environment and a waste of energy. To control a dryer for optimum performance, end-slot flow needs to be understood and properly managed.

Figure 6 illustrates the end-slot region for both impingement and parallel-flow types of flotation nozzles, with the usual staggered nozzle placement. The main influences on air flow through the entry slots are negative pressure in the plenum and dimensions of the opening through which the infiltration actually enters the dryer, which is different for the two cases.

The impingement type requires a negative pressure to pull spent air from the region of the web up into the return plenum. Without this condition, hot air from the end nozzles would flow out of the dryer end slot. This negative pressure also pulls in cool ambient air through this entry slot as shown by the arrows in Fig. 6. Such infiltrated air does no drying. The combined effect above and below the web is a loss in effective dryer length.

In the parallel-flow type of dryer, the hot air from the end nozzle is always directed inward and away from the end slot. Since no air is required to flow into the return plenum between the end nozzles and the dryer end wall, seal plates can be added to prevent ambient air from entering the dryer in this region. With a negative pressure in the return plenum, ambient air can still be drawn into the dryer, but it must pass through the small passages between the web and nozzles. In so doing, it degrades the performance of the end nozzles by cooling the drying air as it passes through, resulting in the illustrated loss of effective length. For all combinations of operating conditions, there is a theoretical value of plenum pressure for which no air will infiltrate.

The space between the end-nozzle face and web can vary because of random lateral movement of the web under the combined actions of nozzle air velocity, web tension, and external disturbances. Since the ideal flow passage width is about 5 mm and the random web movement at this entry region can be on the order of 0-4 mm, the proportional effect on available flow area can be quite large. This makes the practical control of infiltrated air difficult.

For both types of dryers, infiltration can cause a loss in effective drying capacity. It also represents uncontrolled makeup air, which results in increased fuel usage and decreased humidity with a corresponding reduction in web temperature during drying.

Infiltration management system

To prevent or minimize infiltration and exfiltration, a system is needed to tightly control and minimize the size of the entry apertures at the dryer ends and to maintain the negative pressure within the return plenum at a suitable value under all operating conditions. Furthermore, this infiltration management system (IMS) should not employ the exhaust damper, it must take into account the safety issue raised by regulatory agency requirements, and it should be automatic.

A special sealing nozzle can be incorporated for both types of dryers (**Fig. 7**). Because the nozzles are of the parallel-flow type, they can be mounted opposite each other and maintain the stability of the web as it runs between them. These nozzles are positioned close to the dryer end wall and fitted with seal plates. Their secondary jets provide hot dryer air for the small aspiration flow induced by the primary Coanda jets. These sealing nozzles are fully active and yield maximum effective dryer length. The seal plates prevent entry of cold air into the return plenum between the end nozzles and the dryer wall. With this configuration, a plenum pressure can be found to minimize infiltration and exfiltration in both the impingement and parallel-flow type dryers.

With the stabilized entry geometry afforded by the sealing nozzles, pressure control is the remaining issue. This is accomplished as shown in **Fig. 8**. The mass balance given by Eq. 1 indicates that an automated system could control the makeup air flow, within limits, so that infiltration would always be zero. To accomplish this, pressure can be measured with a very accurate differential pressure transmitter, and the makeup air damper can be adjusted to maintain the plenum setpoint pressure and prevent infiltration. Such a system has proven its effectiveness on a production machine for over a year.

This approach frees the exhaust damper to be used as a primary control device for energy efficiency or coating quality-related variables.

Dryers that use gas as the fuel source must meet the requirements of the regulatory agencies such as Factory Mutual, Industrial Risk Insurers, and the National Fire Protection Association to ensure safety of personnel and equipment. An automated infiltration management system must therefore provide a full four-volume purge before lighting a gas burner. This means that the exhaust and makeup air dampers, which modulate under operating conditions, must be moved to their full open position during a purge to minimize purge time. The full open position must also be confirmed with limit switches.

Dryer control options with the IMS

Incorporation of an IMS into a dryer makes possible a range of new control options involving the exhaust damper. Two rudimentary examples are described here.

The mass balance given by Eq. 1 shows that, as the exhaust flow decreases, the makeup air flow must also decrease to prevent slot air flow. However, the flow of makeup air can be zero (i.e., the damper completely closed) before the exhaust flow is zero. The fully closed and opened positions of the makeup air damper define the operating limits of the infiltration management system. The exhaust damper can be adjusted only within these limits to minimize fuel usage or to control web temperature.

The maximum amount of hot air should be recirculated through the burner chamber and dryer, and the minimum amount of ambient makeup air should be introduced into the burner chamber to minimize fuel usage. This dictates the exhaust damper should be adjusted toward closed until the makeup air damper is "almost" closed. **Figure 9** illustrates a control scheme to accomplish this. The position of the makeup air damper, which is modulating to control the plenum pressure, is the process variable of a proportional-integral-derivative (PID) controller, which modulates the exhaust damper. The setpoint for the exhaust damper control is determined empirically based on maintaining the makeup air damper in a "nearly" closed position. That is, the makeup air damper is modulating in response to process changes about a position which is "nearly" closed (**Fig. 10**).

The modulating swings close the damper occasionally, as illustrated in Fig. 10 at Point A. At Point B, the makeup air damper is fully closed and the operating limit has been exceeded. To correct this, the exhaust damper will be moved toward open by its controller, which will reduce the pressure in the dryer causing the makeup air damper to open.

The control of web temperature is a factor in reducing binder migration in coatings. **Figure 11** shows a scheme for accomplishing a range of web temperature variation. A noncontact infrared sensor measures the web temperature exiting the dryer. This process variable is the input to a PID controller which modules the exhaust damper to maintain a setpoint web temperature. Changing the exhaust rate changes the humidity inside the dryer and therefore the web temperature. The plenum pressure is still controlled using the makeup air damper as described previously.

Without introducing other complexities beyond the scope of this paper, there may be limits on web temperature setpoint selection, determined by the drying air temperature and the IMS operating limits, which bound the range of temperature control that can be accomplished with this simple control concept. For example, if the IMS causes the makeup air damper to reach its "nearly closed" position prior to attainment of the web temperature setpoint, an automatic bias changes the setpoint to the value corresponding to this IMS limit. This becomes the maximum value obtainable for the current process conditions. Even with this limitation, it is evident from Fig. 3 that a significant range of temperature control can be accessed with this exhaust modulation concept.

Conclusions

Drying rate for convective dryers is mainly determined by air velocity and temperature. Exhaust volume flow has a minor effect until it gets below about 10% of the recirculating air flow. Thus, exhaust volume can be adjusted over a wide range, almost independently of drying rate.

Air infiltration into such dryers can impair drying capacity, increase fuel consumption, and cause low web temperatures during drying. Pressure balancing should not only prevent puffing but should also minimize infiltration.

Effective pressure balancing can be accomplished with an infiltration management system comprised of special nozzles at the entering and exiting ends of the dryer, to tightly control the dimensions of the web apertures and to restrict lateral web movements, plus a pressure-sensing automatic makeup air control. It is not necessary to use exhaust flow for this purpose.

Reduction of exhaust flow is far more effective in raising web temperature (with its benefits to binder migration control) than is restricting drying air flow. Further, dryer efficiency is dramatically improved by reducing exhaust flow but impaired by reducing drying air flow. Thus, exhaust flow should be used as a process control parameter. This is made possible by the implementation of an infiltration management system.□

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