METERING SIZE PRESS DRYING

By:
James M. Rennes, P.E.
Global Technologies, LLC
Green Bay, WI 54304
USA

ABSTRACT

Today's papermakers face an ever-increasing requirement for the production of sophisticated paper products with a variety of functional surface coatings. The move towards these higher value added products and the recent trend towards "on-machine" coating operations has in turn brought with it a requirement for advanced drying configurations and contactless web handling systems. Typically, this requires the addition of supplemental non-contact drying and non-contact web handling equipment.

Advances in drying and web handling have also brought forth a myriad of new machine configuration possibilities not thought possible with older generation equipment. These possibilities are still emerging and some new layouts have emerged as a direct result of the new technology.

This paper will provide an overview of the current state of the art drying and web handling strategies being employed on metering size press applications. Topics will include the discussion of gas IR, air flotation drying and hybrid systems which turn and dry the web all in one enclosure arrangement. Other topics will include the application of air turns and web stabilizers in the overall scheme. Each of the drying and web handling systems will be described in terms of the operating principles, process advantages and quality enhancement features.

Having a thorough understanding of the drying process, application requirements, drying hardware and some of the quality defects the drying process can induce will be beneficial in selecting the right dryer/web handling combination.

Key words: gas IR drying, air flotation drying, steam cylinder drying, air turns, web stabilizers, combination systems, integrated air turn drying systems, drying configurations

INTRODUCTION

The recent advances in metering size press (MSP) technology have resulted in a way for mills to improve paper quality with minimum investment costs. To provide the quality required, coated paper manufacturers have had to undertake a comprehensive review of existing "on-machine" sizing/coating facilities and corresponding drying and web handling systems.

It is well known that coating quality is directly affected by the structure and composition of the base sheet, the coating formulation, the method of application, and the details of the drying process. Additionally it is common knowledge that an improper drying strategy can very quickly ruin a potentially good surface coating even though the coating technology is correct. To avoid this potential problem, it is important to have a clear understanding of the drying and web handling technology available and how to apply these systems in typical MSP applications.

Today's MSP applications will typically have a combined drying arrangement to take advantage of the benefits each system has to offer. The following is a list of the web handling and drying systems typically employed in drying coated paper in MSP applications:

- Air Turns (non-heated and heated)
- Web Stabilizers
- Gas IR Systems
- Air Flotation Dryers (Conventional and High Performance)
- Combination Gas IR / Air Flotation Drying (Hybrid Systems)
- Integrated drying systems which turn and dry the coated web

It is important to realize that when the respective drying and web handling equipment are brought together in the tight space configurations prevalent in existing machine configurations, new and innovative layouts need to be considered.

Drying Paper Coatings

One of the first requirements for drying coated paper is to dry the newly applied coating without the wet surface having an opportunity to be picked off or displaced by physical contact with a roll surface. Secondly, the drying must be done in such a manner so that coating quality problems are not developed (binder migration) during the drying process. Surface deposits of binder can influence the printing process by affecting ink receptivity causing print mottle.

The most critical period during the drying process starts when the coating is applied and ends when the coating reaches the gel or immobilization point. Typically this is defined as the point in the drying process where the coating binder movement drops off to a harmless level regardless of the drying rate applied. This occurs when the binder becomes physically trapped between the particles of pigment and becomes immobilized or consolidated. Actual applications have shown that coating immobilization is not a discrete event but occurs over a range of average solids contents.

Prior to the entry of the first dryer, the entire surface of the coated paper web is wet and available for evaporation. The drying process will initially remove water from the free liquid on the coating surface and as long as the surface water remains continuous, all the evaporation will occur from that area. Once this surface layer has evaporated, the air/liquid interfaces will move down in the coating pores with surface tension forces drawing water by capillary flow from the spaces between the pigment particles in the coating to replace that removed by evaporation. As more water is removed, consolidation or gelling of the coating solids will occur at the surface of the coating towards the base sheet. As the drying process continues the water from within the coating layer will no longer replenish the surface which results in the showing of dry coating pores. At this point, the coating solids down through the coating will be consolidated and the coating binder wherever it may be, will be locked in place.

Figure 1 illustrates the drying process. The drying process is opposite of the dewatering process since it moves binder towards the base sheet. Manipulating the drying process will allow the organized movement of moisture to the coating surface in a fashion which insures coating quality.

Optimizing coating quality requires a delicate drying balance. Drying rates, coating application temperature, base sheet temperatures and distance to the drying system all must be managed to ensure the optimum sheet quality. Drying the coating too aggressively can lead to potentially harmful binder migration. Drying too slowly can lead to potentially harmful dewatering with corresponding fiber swelling. Therefore, it is important that care be taken so as to apply each type of drying properly and in the proper sequence at the necessary intensity.

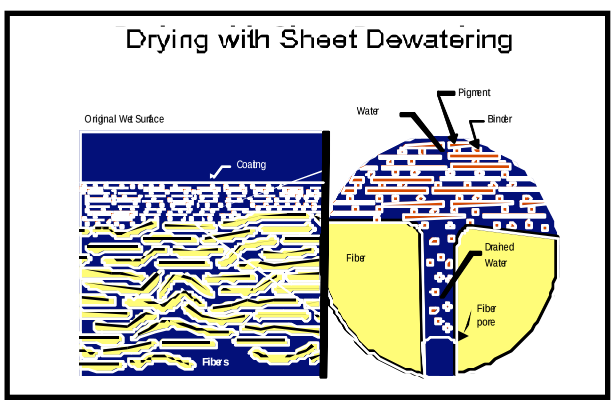


Fig. 1

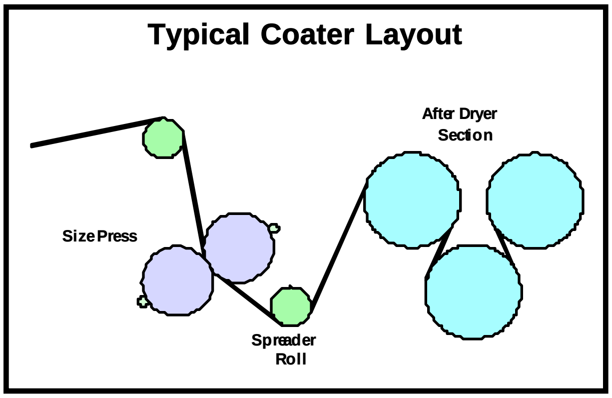


Fig. 2

Solving the Non-Contact Turning Problems – Air Turns

Figure 2 is an illustration of a typical size press arrangement using conventional chill or spreader rolls to turn the sized web into the steam cylinder section. Surface sizing rewets the sheet causing fiber swelling and corresponding sheet expansion leading to troublesome wrinkles. The most commonly used device to compensate for sheet expansion is the curved spreader (bowed) roll.

Contact turning spreader rolls have been known to cause picking problems and was in some respects a limiting factor in the development of new coating techniques employed in MSP technology.

The development and application of metering size press technology allowed mills to begin applying higher solids coatings at higher speeds. Consequently problems were encountered with wet coating "picking" on the turning roll(s) and the lack of drying capabilities to "set" the coating prior to the introduction to the steam cylinders.

To address the quality problems being experienced required the development of non-contact turning in conjunction with determining how additional drying could be incorporated into the already tight space following the MSP. The tight configurations of "on-machine" arrangements provided machine builders some difficult problems to solve.

Air turns were initially developed in the '70's and helped solve a wide range of problems of contactless web handling after coating and size press applications. In essence this product is a circular air flotation web handling system designed to allow a change of web direction without any surface contact. A typical air turn arrangement is shown in Figure 3.

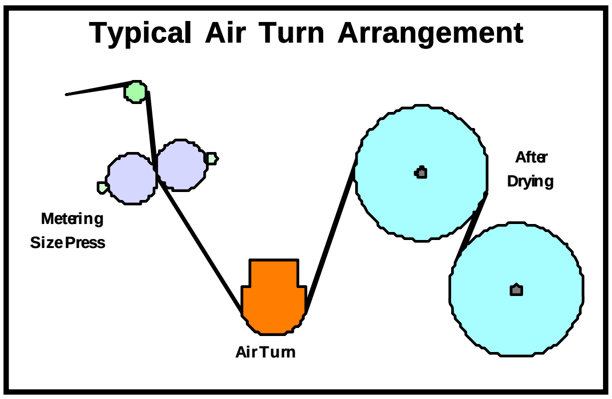


Fig. 3

Modern day air turns employ the proven performance of twin slot pressure pad flotation air bars which have seen extensive use in flotation drying systems in "off machine" coating operations. The air bars provide a stable cushion of air extending across the full width of the unit. These cushions provide full support to the sheet such that the flotation height is the same in the center of the sheet as it is at the edge of the sheet irrespective of the width of the sheet.

In operation, these air bars generate supporting air cushion between the surface of the air bar and the coated web being processed as shown in Figure 4.

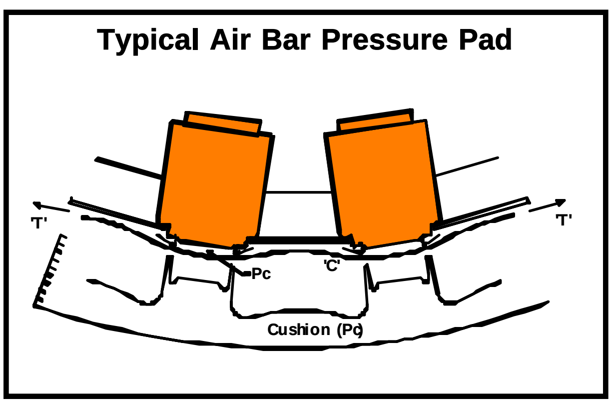


Fig. 4

The very best designs utilize regions of high and low pressure to bring about a perfectly symmetrical profile which in turn results in high clearance and firm web stability. Performance is directly related to the special aerodynamic effects brought about as the air exits from the slot outlets. The forces generated in the air flotation cushion need to be high in magnitude since these are used to effectively offset the force generated by the tension in the web. The modern air turn system embodies these features and benefits by using these same air bars arranged in a curve path as depicted in Figure 5.

The flow channel areas provided between the air bars control the escape of air from the air cushion at the end of the air bars which provides additional support and minimizes the fan power required to operate the system. The flow of air throughout the area between air bar channels also imparts a smoothing effect to the sheet reducing wrinkles and creases.

Modern air turn systems are designed to accommodate the following operating requirements typically found in MSP applications:

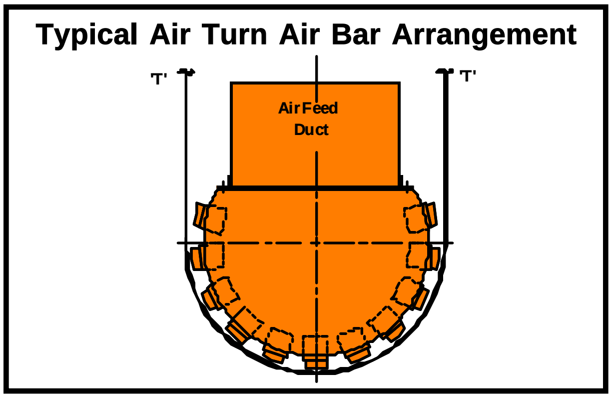


Fig. 5

- Non-Contact Web Handling
  The distance between the coated sheet and the surface of the air turn should be at least _ inch (6 mm) to insure trouble free operation without the possibility of contact and contamination of the coated surface during operation.

- High and Low Tension Capabilities
  With the operating tension ranges of various MSP systems varying, the air turn needs to be capable of handling tension ranges of _ to 2.5 pli (10-50 kg/m) while maintaining the clearance mentioned above.

- Web Turning Angles
  Due to many configurations available today, air turns need to accommodate wrap angles of 20 to 180 degrees.

- Air Turn Width and Diameter Flexibility
  Today's MSP applications require flexibility in design to accommodate wide web widths, i.e. 350 inches (8.9 meters). Air turn radiuses typically range from 21.65 to 31.5 inches (550 to 800 mm).

- Wrinkle Free Operation
  By supporting the traveling web on a stable air cushion, the natural dimensional changes in the web can take place without creases being formed into the web.

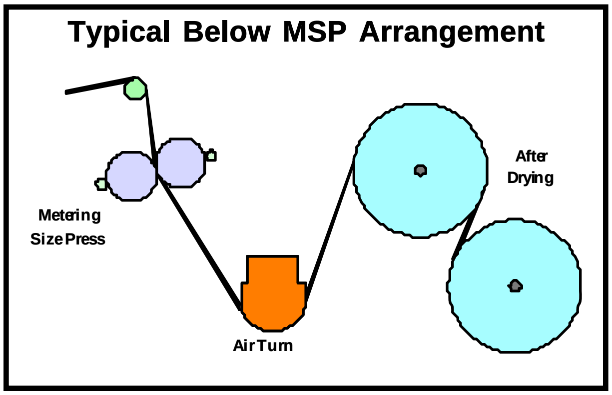


Fig. 6

Air Turn Configurations

When used in conjunction with the latest MSP designs, the air turn provides increased product quality and runability of this new generation of equipment. Depending on the design attributes, MSP configurations can result in either a vertical or inclined orientations.

In an inclined arrangement the air turn is placed below the MSP as shown in Figure 6. In this configuration the coating or size can be applied to both sides of the sheet and turned in a non-contact fashion towards the after dryer section. Vertical configurations have the air turn unit placed above the MSP and require the non-contact turning of the web as shown in Figure 7. The successful development of this form of coating arrangement has largely depended upon the availability of a suitable air turn system.

Heated Air Turns

As has been mentioned, the primary development of the air turn was to overcome handling problems. It was not envisioned that air turns would have any effect on drying performance following the sizing or coating operation. However, mill supervisors, where air turns are in operation, notice that extra machine speed could be achieved following the introduction of the air turn unit.

This can be attributed to the impingement effect from the pressure pad nozzles which provide forced ventilation on the web sheet traveling over the air turn. The air turn, having ventilated the surface of the sheet, insures that the air boundary layer on the surface of the coated sheet is removed.

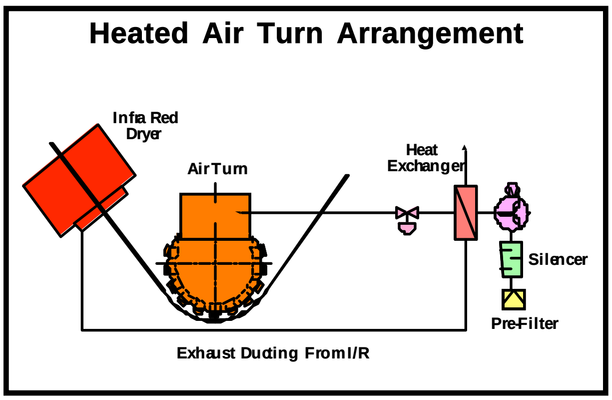


Fig. 8

Typical Air Turn Drying Potential

SHEET TEMP	EV RATE	DRYING RATE
100°F (38°C)	1.0-2.5 lbs/hr-ft² (4.8-12.2 kg/hr-m²)	1.7-8.3 lbs/hr-ftw (2.5-18.4 kg/hr-mw)
170°F (77°C)	10-18 lbs/hr-ft² (48.8-87.9 kg/hr-m²)	16-60 lbs/hr-ftw (23.8-89.3 kg/hr-mw)

Fig. 9

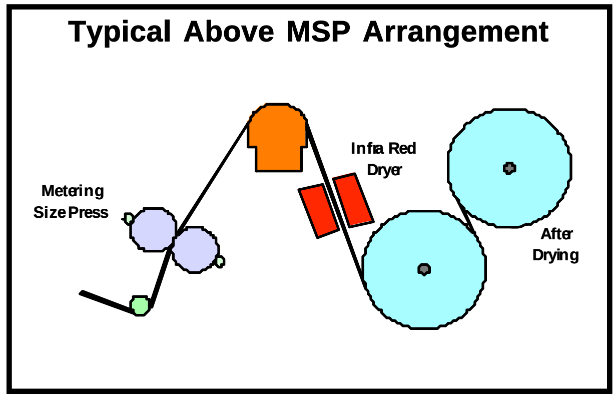


Fig. 7

It is possible to use heated air turn supply air for the purpose of conditioning and/or drying the web as it passes around the air turn. In this arrangement, air turn supply air is normally drawn in from the machine room through a prefilter unit and then passed through an air to air heat exchanger before being delivered to the air turn unit (Fig. 8). If a gas IR system is used, the exhaust air can be used as a source of energy.

On leaving the air turn, the air is simply discharged back into the machine room at the temperature which it leaves the air turn. The primary reason for using heated air is to provide supplemental energy to the sheet which is being cooled from the evaporation of moisture from the surface of the sheet. Depending on circumstances, a heated air turn will result in a slight improvement in the drying rate [0.5 to 1.0 lb/hr/ft^2 (2.4 to 4.9 kg/hr/m^2)] from an unheated system. Actual practice will show that the overall coated sheet temperature entering the air turn, coupled with the angle of wrap, is of much greater importance to improving the drying performance capabilities of air turn systems.

Depending on the temperature of the sheet and the drying application, an air turn can develop single-sided drying rates over the surface of the air turn as shown in Figure 9. Limited drying can, therefore, be achieved even when ambient air is applied and no form of IR heating is utilized prior to the air turn. In this situation the temperature of the coated sheet is between 140 and 170°F (60 and 77°C) due to the on-machine nature of the application. The primary drawback to this arrangement is that the drying is single-sided and constrained due to the short effective drying length of a typical air turn.

Gas IR

Gas IR has been used to supplement the drying of coated webs for many years, most notably at the start of the drying process, as shown in Figure 10.

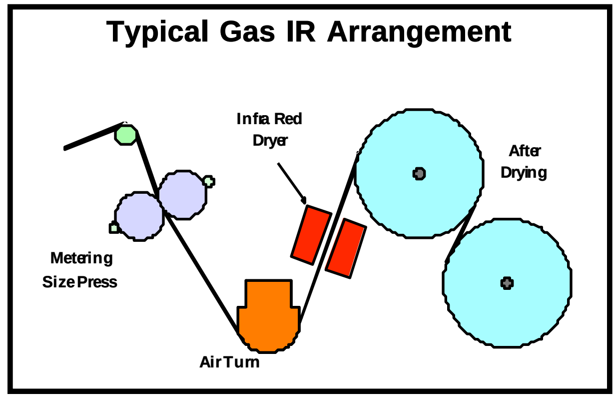


Fig. 10

Early mill reports observed that the drying rate could be increased to a higher level with gas IR than other types of drying before there was binder migration to the surface of the coating. Consequently, the use of gas IR which is compact and easily installed in the area around the MSP brought initial benefits by being able to put a lot of energy into the sheet to immobilize the coating quickly in a very compact space. To do this requires that gas IR sensibly heat the coated sheet to a level of 170 to 180°F (77 to 82°C) while facilitating the evaporation of coating moisture to the immobilization point or beyond.

Considerable discussion has continued on what is the precise point at which the freeze or immobilization of coating occurs. It is not the intent of this review to address this difficult area but merely to point out that immobilization will occur over a range of solids content depending on the chemistry being utilized in each individual coating.

There are a number of opinions on how much gas IR drying one should use in a MSP application. It is generally agreed that the heat transfer in the early stages of drying can effectively be done with gas IR. However, the ideal percentage of the drying load that each of the drying components must contribute is not easily defined and will usually vary with coating formulation and grade.

The wide acceptance of the use of infrared energy for drying has led manufacturers to improve the systems rendering IR drying as a safe and effective way of drying. The key advantages in gas IR technology concern space requirements, fire safety issues and sheet handling characteristics.

Some manufacturers have taken their design enhancements a step further and are addressing the increased system reliability and runability requirements associated with the demanding MSP application. Examples of this include increased IR power densities, increases hood ignition repeatability, fail-safe fire suppression and special air web handling.

The principle behind the operation of IR system comes from the fact that any object or material that is warmer than its environment will radiate infrared energy. IR radiation results from the atomic excitation of the material. This IR energy will travel in the form of electromagnetic waves at the speed of light until it strikes another material such as coated paper where it can be absorbed or reflected or retransmitted. Electromagnetic waves occur over a wide range of wavelengths with useful wavelengths for drying coated paper in the area of 1-3 µm.

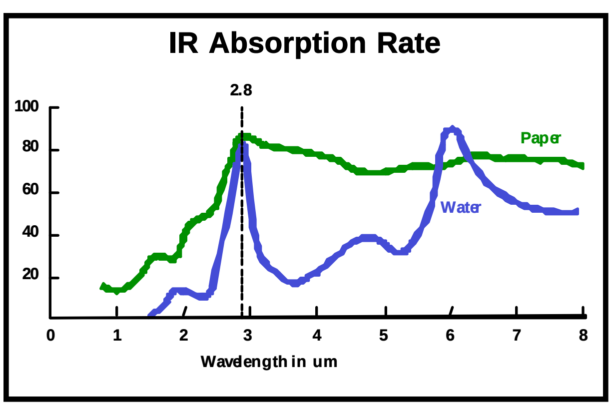


Fig. 11

An important factor which also needs to be considered is the effect on emitted energy wavelength on the heat transfer efficiency. Infrared dryers have a characteristic emission spectrum which is a function of their operating temperature. Optimum wavelengths for absorption of IR energy into the coating moisture are around 2.8 µm as shown in Figure 11.

Longer wavelengths are more strongly absorbed into the water: shorter wavelengths penetrate deeper into the sheet. The absorbtivity of IR energy is also dependent on the thickness of the material and the

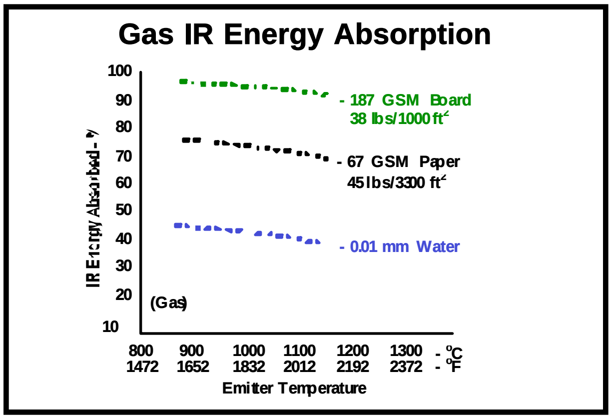


Fig. 12

wavelength of the radiant energy. The effects of this are illustrated in Figure 12. As the base material increases in weight, more of the transmitted radiant energy is absorbed while the 10-micron film of water is relatively transparent.

Energy efficiency of gas IR systems should not be confused with the efficiency in conversion of input energy to infrared energy. For drying equipment comparisons, the energy efficiency should be a measure of the energy deposited into the sheet in comparison to the energy actually consumed.

Gas infrared systems are more widely used for drying coated paper due to their lower cost and the better match of the wavelength of the energy emitted on heat transfer efficiency. The most common type of gas IR used is the surface combustion burner. These systems use a metal or porous refractory from which gas is burned creating a radiant surface. Every infrared system consists of a group of individual modules referred to as emitters. Emitters are heated to a temperature of approximately 2000°F (1093°C) by the combustion of natural gas.

When used as a means of drying coated paper, gas IR systems are normally arranged in rows. Complementing the emitter arrangement is an air flow system which functions to remove exhaust gases and remove evaporated water. The purpose of this air flow is to breakup the laminar layer of saturated air and vapor on the surface of the sheet which decreases the surface vapor pressure and hindering water removal. Additionally the air flow keeps the moving coated web from touching the surface of the emitter and functions to cool the unit on shutdown.

A schematic cross section of a gas fired IR dryer consisting of several rows of emitters is shown in Figure 13.

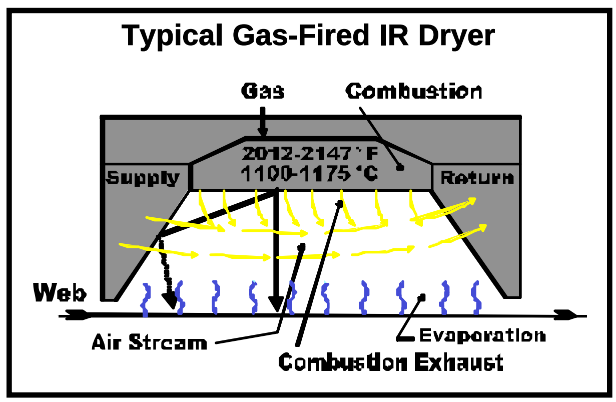


Fig. 13

The drying capability of gas IR is a function of a number of variables and will vary depending on the specific manufacture of gas IR dryer and the application (i.e. coating or starch). Figure 14 illustrates the drying potential of gas IR following an air turn in a MSP application.

Infrared drying systems, due to their high-energy capabilities, have seen extensive use in coated paper applications over the years. IR systems are typically used in conjunction with other forms of drying, particularly at the start of the drying process. Gas IR has been proven to be quite effective in supplying the sensible heat required in the drying process but is limited in its ability to provide mass transfer or water removal due to the lack of a sufficient air flow in most arrangements.

Gas IR Drying Potential
8 Rows (4 Top / 4 Bottom)

EV Rate	**Drying Rate**
25-40 lbs/hr-ft^2 (122-195 kg/hr-m^2)	100-150 lbs/hr-ftw (149-223 kg/hr-mw)

Fig. 14

The application of gas IR systems following air turns initially allowed papermakers to successfully dry webs coated on both sides in the limited space between the MSP and the steam drying cylinders. This solution worked reasonably well on slower speed machines but on faster machines problems again surfaced with excessive picking occurring on the first after-drying cylinders. Additionally, when too much IR was installed, a number of products developed quality problems such as orange peeling and cratering caused by the very high energy transfer resulting in the surface of the coating to rise to high temperature levels.

Some machine builders overcame the problems by removing some cylinders and giving the sheet a longer, free unsupported run. The primary reason for this was to provide a means for the hot sheet leaving the gas IR to be exposed to an environment whereby excess moisture at the surface will evaporate onto the surrounding air stream. A better solution is to install some form of air drying after the gas IR.

Adding Air Drying

While it is widely known that gas IR does an excellent job of applying sensible heat to the coated web, evaporation can be limited depending on the air flow across the coating surface. Additionally the air flow in gas IR systems do not lend to the stabilization of the sheet as it passes from unsupported draw between the MSP and the steam cylinders.

Typical MSP/Air Turn/IR Arrangement with Stabilizer Bars

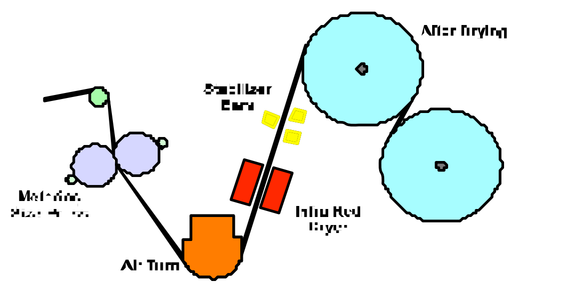


Fig. 15

One simple solution to this problem is to use the pressure pad air bar technology previously discussed. This would take the form of three air flotation nozzles configured as shown in Figure 15. This configuration would not only provide ventilation of the coated sheet leaving the gas IR but would also serve to stabilize the traveling sheet between the MSP and the steam cylinders. Air for the stabilizer could easily be ducted from the air turn supply fan resulting in an economical and compact arrangement.

Due to the overall length [typically 3.3 ft (1 m)], the drying capabilities of this arrangement are somewhat limited in terms of the ability to remove large volumes of moisture. However, the actual drying rates are high per unit area due to the high incoming temperature of the coated sheet leaving the gas IR unit (Fig. 16).

This arrangement has been proven to be a very economical method of providing post IR ventilation air due to the compactness/simplicity of the system and the fact that the supply air can be conveniently drawn from the air turn supply fan.

Web Stabilizer Drying Potential (3 Air Bar Arrangement)

EV Rate	Drying Rate
10-20 lbs/hr-ft^2 (48.8-97.6 kg/hr-m^2)	17-34 lbs/hr-ftw (25.3-50.6 kg/hr-mw)

Fig. 16

Flotation Dryers

For more demanding applications, the natural progression would be to employ an air flotation dryer following the gas IR system to provide further drying than what could be accomplished by only a three air bar stabilizer. An example of this arrangement is shown in Figure 17. This arrangement offers the advantages of increased drying and energy efficiency due to the recirculation nature of an enclosed flotation dryer.

Typical Arrangement with Flotation Dryer

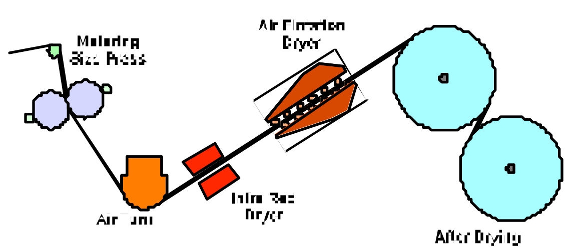


Fig. 17

The conventional air flotation dryer has been in operation for a number of years and widely used and accepted in the papermaking industry, both on-machine and off-machine.

The operation of a flotation dryer is quite simple. A heating and air supply system delivers heated air to the nozzle supply headers located above and below the web, as shown in Figure 18. The function of the header arrangement is to deliver the heated air to the nozzles or air bars. Arranged in a staggered configuration, the nozzles create a pressure pad which induces a sinusoidal shape to the web as it passes through the dryer. Return air is collected and either exhausted or reheated by a gas burner or indirectly by steam coil and returned to the dryer.

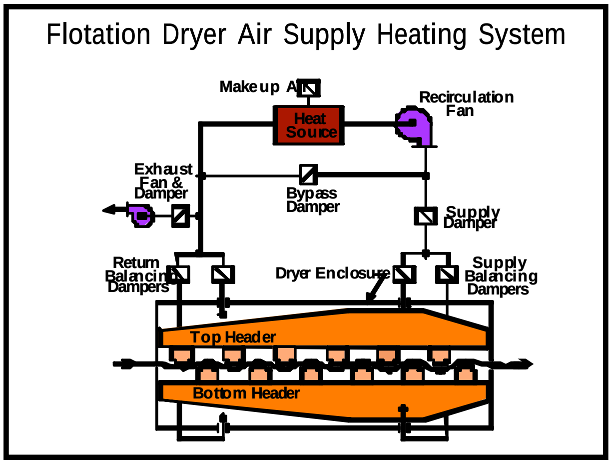


Fig. 18

Air bar designs have evolved over the years and have resulted in a number of designs. For coated paper, the predominate design today is a two slot pressure pad air bar. The design of this air bar consists of two slots separated by a flat support area between slots. Airs exiting the slots converge toward the center of the support area between the slots. This creates a pressure pad along the top of the air bar as shown in Figure 19.

The primary criteria for designing a good nozzle system lies in having the arrangement provide superior web handling and drying characteristics. The nozzle system needs to maintain adequate clearance between the web and the nozzle to prevent touching while the web is traveling through the dryer. The cushion pressure supporting the moving web needs to be stable to prevent the sheet from fluttering. Also important is the nozzle jet stability to prevent jet flip flop caused by machine speed.

Operating nozzle velocities range from low [5,000 fpm (25 m/sec)] to medium [10,000 fpm (50 m/sec)] to high [14,000 fpm (70 m/sec)].

Flotation air dryer enclosures vary in size depending on the width of the sheet, but usually do not vary in zone length beyond 20 feet (6 m). This is due to the physical size and handling of the attendant air handling equipment and the enclosure. Materials of construction are typically a combination of mild steel, aluminized steel and stainless steel.

Construction types can vary from panelized to all welded "tub in a tub" design with 3 to 4 inches (75 to 100 mm) of internal insulation. Access to the internal air bars is via a retraction arrangement. Common retraction systems are the clam shell pivoting design from the drive side or screw jacks on each of the enclosure corners which lifts the entire top half of the enclosure. Retraction heights are typically 16 to 20 inches (400 to 500 mm).

Flotation dryers normally use a draw-through air supply system where the heating medium is located on the suction side of the fan. This configuration will always deliver a constant air velocity, regardless of varying air density, which will result in a constant nozzle velocity.

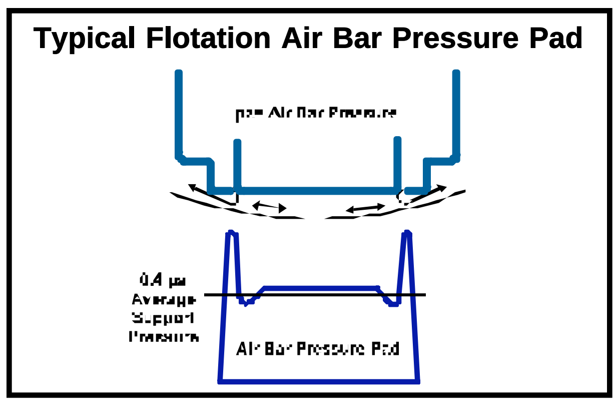


Fig. 19

Air systems can be designed to have heating supplied by either saturated steam or natural gas. Operating temperatures can range from 350 to 600^{o}F (176 to 315^{o}C). The air system is usually located on the back side of the dryer enclosure and connected through interconnecting ductwork.

The performance of an air flotation dryer is dependent not only on the air bar design, but also on the return air system. After leaving the nozzle area, return air is collected and either exhausted or recirculated back to the heat source fan arrangement. The exhaust air is extracted from the recirculating air prior to the heating plenum. Dryer exhaust volumes are sized to keep the enclosure internal pressure slightly negative and operating at a humidity level of less than 0.1 pound of vapor per pounds of dry air. Makeup air is supplied from a relatively stable temperature and moisture environment.

Control of the air temperature can either be by the use of a standard temperature controller or a PLC system. Nozzle velocity is controlled by the use of either manual or automatic actuated dampers. Exhaust air control is typically manually controlled and set to maintain a minimum exhaust pressure in the enclosure.

Air Flotation Dryer Potential (12 ft Dryer Following Gas IR)

EV Rate	Drying Rate
6-12 lbs/hr-ft^2 (29.3-58.6 kg/hr-m^2)	72-144 lbs/hr-ftw (107-214 kg/hr-mw)

Fig. 20

Drying rates for flotation dryers are controlled by adjusting air temperature and air velocity as delivered to the web. Figure 20 can be used as a general guide to the drying potential capabilities of a typical flotation dryer in paper coating applications following gas IR systems.

Combined Systems: Gas IR & Air

Seeing the advantages of having gas IR closely coupled with convective air flotation drying, has led several manufacturers to offer a combination system. In this arrangement which is conveniently packaged in a single enclosure, gas IR is used to provide sensible heat and the drying of the coating to the immobilization point. An air drying section uses the energy from the gas IR exhaust as make-up air to the preceding air flotation section resulting in improved energy efficiencies. The compact design, energy efficiency and web stability of combined systems provides many advantages in MSP applications. Figure 21 illustrates an integrated gas IR dryer and convection air flotation dryer after a MSP application. The amount of gas IR and convective air can be tailored to meet the application requirements.

New Generation Air Flotation Drying

For some paper mills it is not either convenient or suitable to use gas IR for MSP applications. This presents a difficult problem since space is at a premium in MSP applications and typically there is little room to increase the length of convective flotation drying. This situation has led to the development of a high performance drying system which combines the heat transfer capabilities of a gas IR system with the web handling and mass transfer capabilities of a conventional flotation dryer (Fig. 22).

Typical Gas IR Dryer and Convection Air Flotation Dryer

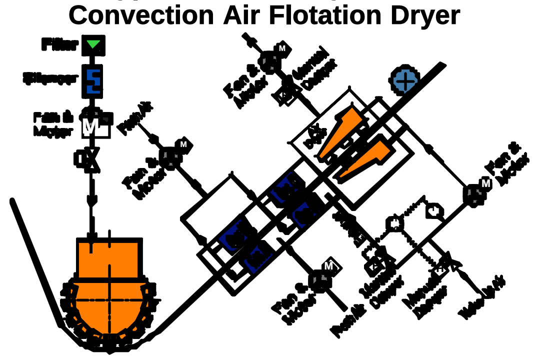


Fig. 21

Based on a conventional air flotation dryer but incorporating several patented modifications, this new flotation drying system will fit into the normally "tight" areas available yet deliver an enormous energy punch like gas IR resulting in large amounts of mass transfer.

Typical High Performance Drying System

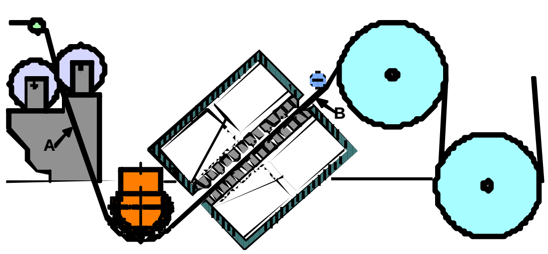


Fig. 22

By utilization of high temperatures in the range of 750 to 850°F (500 to 450°C) combined with nozzle velocities up to 13,750 fpm (70 m/sec) this arrangement can provide an interesting alternative to gas IR. The typical dryer length is between 3.3 and 6.5 feet (1 and 3 m) for the normal range of sizing/coating applications.

This new dryer system features an integration of proven air bar technologies to develop an evaporation rate equivalent to or exceeding that of a gas IR system. The effective nozzle system for the patented design calls for the insertion of intermediate air bars to be placed between the conventional air flotation air bars as depicted in Figure 23.

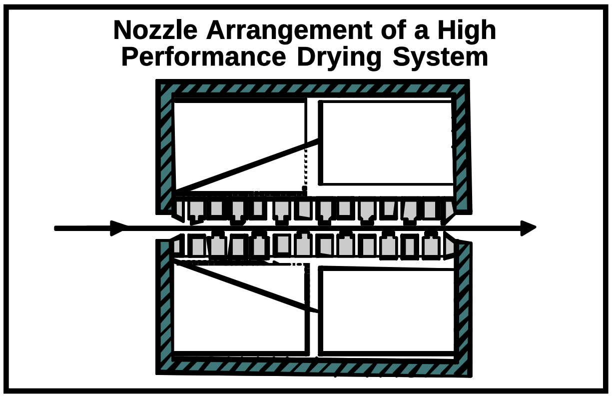


Fig. 23

Like the conventional flotation dryer, familiar air float nozzles are situated above and below the web path in conventional fashion but are supplemented by an equal number of non-air float, high impingement nozzles each arranged with a series of holes designed to maximize heat transfer.

A largely conventional heating system is used to power the dryer with all the usual features including air filtration, fresh air fan, gas burner or other heat source, recirculation fan, exhaust fan, and hot bypass to enable the entire system to continue running when the dryer is opened.

When compared with a conventional air flotation drying system of similar overall dimensions, we can see that by increasing the two important aspects of heat and mass transfer, together with an increase in impinging air velocity, it results in performance as shown in Figure 24.

The combination of an air turn and a high performance flotation dryer will provide an advantage of positive web handling while offering superior heat and mass transfer.

High Performance Air Flotation Drying Potential (6.5 ft Length)

EV Rate	Drying Rate
25-40 lbs/hr-ft^2 (122-195 kg/hr-m^2)	162-260 lbs/hr-ftw (241-387 kg/hr-mw)

Fig. 24

Integrated Dryer System

Traditional drying systems generally have a number of challenges to contend with and this is especially true in rebuild situations prevalent today. Some of the challenges faced by machine builders in developing a sound drying strategy are listed below:

- Space requirements to locate all the equipment
- Air turn is used only to turn the sheet into the dryer offering little drying potential
- Lack of web stabilization in the gas Infra-red section
- Having separate suppliers of the Infra-red and air dryer technology.

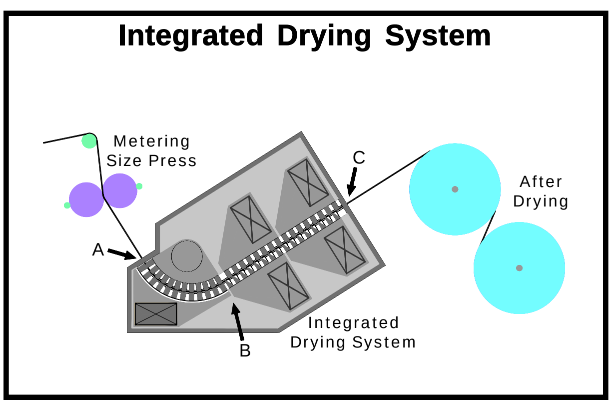


Fig. 25

The successful introduction of air turn technology naturally generated an interest in whether a true air flotation dryer could be developed which offers both non-contact turning and drying all in one enclosure. Having everything bundled together would provide a number of tangible benefits not currently available with current traditional drying strategies. This has resulted in a integrated air float system being developed recently.

The integrated air float arrangement differs in operation from the more traditional air turn air dryer unit in that the system is designed to operate as a flotation dryer from web entry to web exit as shown in Figure 25. A major milestone in this system was the development of a "drying" air turn system which provided non-contact flotation around the circular arc with hot air impinging on both sides of the sheet which is sandwiched between the upper and lower sections. The "turning" portion of the system is angular just as you would find with an air turn, except it is a full function air flotation dryer designed to deliver heated air, via an air bar system, above and below the web. Spent air is collected and returned to the heating plenum in the same manner as a more traditional air flotation drying system.

Often times the "turning" section functions as an independent zone in a multiple zone arrangement. Depending on the application requirements, the integrated system can comprise a combination drying, cooling and web handling zones, all of which are integrated into one continuous housing for compactness and thermal efficiency.

The drying arrangements that can be integrated include:

- Heated recirculating air turns
- Gas fired infra-red systems
- Electric infra-red systems
- Conventional air flotation dryers
- High Performance air flotation dryers
- Air flotation cooling

While it has previously been stated that high performance drying and gas IR drying offer alternative systems, it has long been considered that the ideal drying system for MSP applications would be the combination of the two systems. Using gas IR to provide sensible heat and immobilize the coating to prevent binder migration, together with the excellent mass transfer effect of the high performance air drying system described above is an ideal combination.

Depending on the particular application, gas or electric infra-red can be incorporated as one or more of the zones to provide sensible heat and additional drying. Using the infra-red exhaust as makeup air to the proceeding air flotation sections provides additional energy savings. Systems employing infra-red systems must be carefully designed to separate the infra-red section from air streams in the air flotation sections. Employing a combination arrangement allows a system to be tailored to the specific application requirements. Coupling infra-red with air flotation systems provides a means to provide excellent heat and mass transfer while providing superior sheet handling and stability characteristics. The flexibility of the new configurations allows the addition of an air flotation cooling section at the end of the drying arrangement if cooling is required web prior to entry into the next coater station.

Figure 26 shows a typical air circuit layout of a integrated air turn air dryer system. Gas heated systems operating at 750°F (4000°C) and above can achieve evaporation rates in excess of 35 lbs/hr/ft^2 (170 kg/hr/m^2) in the constant rate drying phase. A typical layout consists of an external heating circuit positioned on the drive side of the paper machine.

On conventional dryer arrangements an air turn is used to turn the web into the drying section with very little coating drying being done in the process. Employing a fully functional turning air float dryer results in a major benefit due to the reduced sheet run length since the entire non-contact web pass is employed for drying.

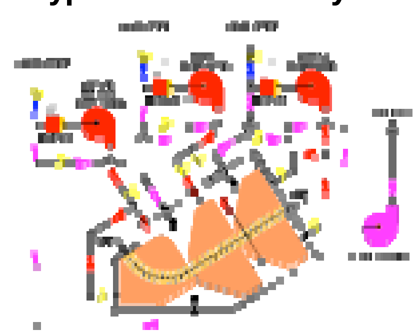

Typical Air Circuit Layout

Fig. 26

The impingement air provides two functions, that of supporting the web as well as bringing about high heat and mass transfer rates. The air delivered to each zone is passed through a heating device to raise the temperature to that required at the point of impingement, the air acts upon the surface of the web providing latent heat required for vaporization. The heat transfer brings with it the mass transfer of water from the sheet to the air stream.

The vapor-enriched air then passes from the surface of into the space between the supporting air bars positioned at the web line of the air flotation drying system. The air then returns to the fan where it is raised in pressure and passed through the heating device, restoring the energy transferred to the sheet. As the moisture-laden air returns to the recirculating fan, a small quantity is drawn off and exhausted to atmosphere in sufficient quantity to maintain the desired humidity in the drying system. Fresh air is introduced into the circuit to make up for that amount which is exhausted and the recirculating system is therefore balanced and brought into equilibrium. All of this takes place in the external recirculating circuit with no additional air required to be taken in or removed from the dryer itself.

In designing for an optimum operating humidity, the maximum amount of recycled air can be employed making the integrated air turn air flotation drying system very economical and efficient in terms of energy usage. Remotely controlled dampers that can be altered by the operator at the control panel regulate the quantity of air passing into each zone. This enables the operator to tailor the available drying rate of each section as required for optimum product quality and runablility. The system layout is therefore, a very compact design and all the air movement surrounding the sheet is processed consistent with the inherent recirculation system, resulting in no extraneous loss or intake of air from the enclosure.

Integrated Drying Potential

EV RATE	**DRYING RATE**
25-40 lbs/hr-ft^2	**162-260 lbs/hr-ftw**
(122-195 kg/hr-m^2)	**(241-387 kg/hr-mw)**

Fig. 27

The drying capacity of integrated air turn air flotation system is directly related to length of each zone [typically 5 to 6 ft (1.5 to 1.8 m) and the wrap angle of the sheet traveling around the air turn dryer. A five foot (1.5 m) radius air turn and a wrap angle of 60 to 90 degrees translate into an effective length of 5.2 to 7.8 feet (1.6 to 2.4 m). Depending on the temperature of the incoming coated sheet and the method of supplying heated air to the system will determine the drying capability of the air flotation system as shown in Figure 27

The air flotation mode of operation results in the drying process being carried out without contacting the air bar surface and as such, instances of sheet picking or contamination are totally eliminated. The air impingement system is designed to bring about higher drying rates than can be achieved with conventional drying arrangements, while at the same time being highly efficient since it utilizes high percentages of recycled air to keep energy usage and heat losses to a minimum.

The introduction of the integrated air turn air flotation drying system brings forth a new approach to drying which offers some special features that are beneficial when drying pigmented coated paper:

- Compact Arrangement, 25%-35% less machine length required
- Infra-red can be integrated as one of the drying zones
- Web turning done in a high performance air turn-air dryer system.
- Complete web stabilization throughout the entire drying arrangement
- Independent drying zones all with coordinated operating controls
- High heat and mass transfer rates
- One supplier advantage
- Less capital cost then individual systems

Steam Cylinder Dryers

Steam cylinder dryers have been around for many years and have been the workhorse of the paper industry in the production of coated paper and paperboard. The primary reasons for this is due to the many advantages that steam cylinder dryers offer in the production process:

- Positive web support during drying eliminating long draws and reducing tension requirements.
- Coated sheet is dried on a flat surface reducing paper stress, cockle and curl.
- Contact or drying by conduction is a very effective way of transferring the heat required for drying.
- Conversion of steam latent heat to drying energy is reasonably efficient resulting in an economical drying method.
- Ease of threading and broke handling.

Drying coated paper with hot cylinders is accomplished by conduction heat transfer from the steam source to the surface of the paper. Since all paper mills have a supply of steam available this is the most widely used and efficient heat source. Figure 28 depicts a typical cross section of a steam cylinder.

A steam cylinder operates by introducing saturated steam through rotary unions. As the steam condenses inside the dryer shell energy is transferred from the steam (heat of vaporization) to the web by conduction through the condensate layer, the dryer shell and to the coated paper. The drying rate is primarily dependent on the rate at which energy from the condensing steam can be transferred to the sheet and the drying phase of the process.

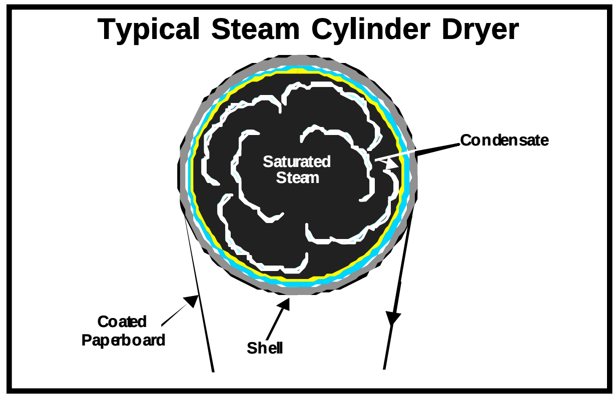


Fig. 28

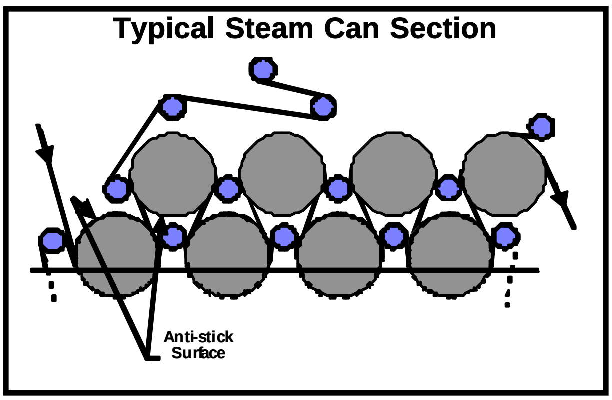


Fig. 29

While the inherent advantages of steam can drying are obvious for the production of uncoated papers, their use on coated paper requires that the coated side of the sheet be sufficiently dry to prevent sticking or picking of the coating on the hot dryer surface. Consequently, most coated grades require some type of non-contact drying prior to the steam cylinders.

It is advisable to have a non-stick surface on the first two cylinders in contact with the coated side (Fig. 29). Additionally, except for the first two, cylinders should be felted to maximize sheet contact and to ensure uniform heat transfer across the sheet. The felted cylinders also increase sheet contact friction to eliminate web slippage and improve web tension stability through the section.

Steam cylinders are frequently used for the final zone of coating drying after the possibility of coating picking has past. This point is normally reached when the sheet moisture is less than 13% by the preceding drying components.

Steam cylinders characteristically have a low drying rate and are unlikely to cause quality problems. Figure 30 is a chart which can be used to estimate a steam cylinder's drying rate as function of steam pressure.

Using steam cylinders at the end of the drying arrangement has been cited as a means to render the sheet moisture profile uniform. This result may occur but is not associated with any special attributes of the drying cylinders. The reasons for the uniformity improvement lies in the fact that steam cans are used in the falling rate drying phase which means the drying rate varies directly with the moisture content of the sheet. This means that in the falling rate phase, wetter places on the sheet will dry faster than drier places which will move a profile towards uniformity.

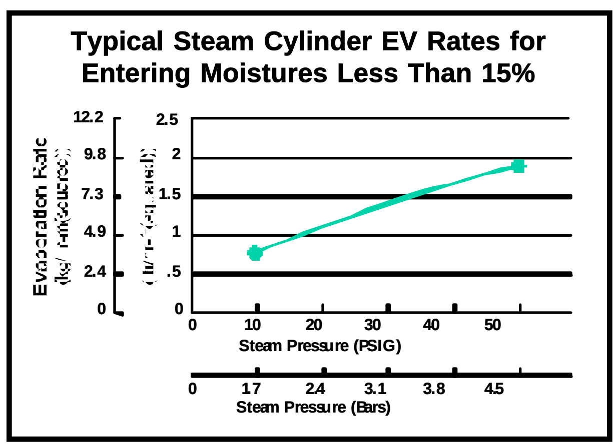


Fig. 30

Application of MSP Drying Systems

Drying arrangements for coated paper generally include a combination of the drying systems as discussed in the previous sections. The primary task is to determine the optimum combination required to properly dry the applied sizing/coating.

Just how much drying should each arrangement provide has been the subject of numerous papers and discussions. The primary focus of much of the research has centered on how to predict the optimum drying rates and how the drying configuration can either enhance or degrade the coating appearance. The conclusions drawn from this work is that there are no hard and fast rules to determine the drying contribution of each component and much depends on the coating formulation and running conditions.

Coating drying will typically use the three known methods of heat transfer, convection (air dryers), radiation (IR), and conduction (steam cylinder dryers). The optimum use of these drying systems can result in a high quality finished sheet, improper use will most likely provide disappointing results. For example, the improper application of gas IR resulting in very high operating temperatures could overheat the coated surface by not having proper air circulation resulting in not providing the required evaporative cooling. With air dryers it is possible for the drying level to exceed an acceptable rate causing binder migration in the coating. Steam cylinder dryers can be subject to pick off if the coating is not adequately dried before contact with the cylinder's surface. Consequently, it is very important that each type of drying is properly applied so the drying is done in the proper sequence at the proper rate.

A primary requirement for drying coated paper is to dry the newly applied coating without the wet coating surface having the opportunity to be picked off by physical contact with another surface. Secondly, the drying needs to be completed in a manner that the coating binder is not redistributed during the drying process.

The drying process is often described in three phases which are described below:

- Phase 1. Sensible heat load, where the sheet temperatures increase and drying begins.
- Phase 2. Steady state evaporation, where energy is consumed for free water evaporation while the sheet temperature remains relatively constant.
- Phase 3. Falling rate, where the sheet temperature increases as 'free" water becomes scarce and the evaporation rate begins to fall.

It is generally agreed that heat transfer or sensible heating in the early stages (phase 1) of drying can effectively be done with gas IR due to the penetrating heat characteristics of this form of heat transfer. Another alternative for consideration is the new high performance flotation dryers on integrated dryer systems described previously.

For this type of drying to be effective in high solids coating applications, the total heat transfer should be sufficient to not only provide all the sensible preheating, but also raise the coating solids to a level in which immobilization of the solids occurs. Each application needs to be addressed separately due to the numerous variables in determining the coating binders immobilization point. In sizing applications, this is not an issue. It is also worth noting that there are applications in the field where all the drying is completed by gas IR. Additionally, it is possible if space is available to do most of the drying via convective air flotation drying and conduction steam cylinder drying. However, when air flotation dryers are used for preheating and steady state drying, the drying process must be carefully monitored so as not to exceed a dryer rate so as not to cause binder migration.

Applying the above drying phase theory with the drying systems currently available typically result in the use of gas IR, followed by some type of air flotation dryer followed by finishing cylinder dryers. A schematic of this drying arrangement is illustrated in Figure 31.

Air turns offer a practical way to turn a coated web in a non-contact fashion. Gas IR drying has an advantage of compactness and high energy output, which allows this system to be located close to the coating head so as to initiate drying immediately upon exiting the coating head. Flotation dryers offer the advantages of non-contact drying and drying rate control until the coating solids are immobilized to allow contact with web support rolls or cylinder dryers. Steam cylinder dryers offer the advantages of contact drying for improved sheet appearance and are used for sheet and tension control.

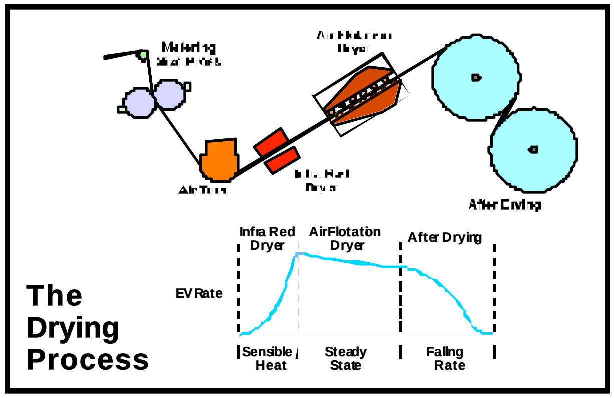


Fig. 31

The most productive way to put the shown information into practice is to look at an example which is characteristic of a MSP sizing and pigmentation application and review the performance of the various drying alternatives discussed.

To begin, we need to define an example MSP application which is expected to apply size and pigmentation coating as shown in Figure 32:

Typical "On Machine" MSP Application

Description	Coating	Size
Basic wt @2% MOI	34 lbs/3000ft² (553 gsm)	34 lbs/3000ft² (553 gsm)
Total Coat Weight	10 lbs/3000ft² (163 gsm)	1.36lbs/3000 ft² (221 gsm)
Sides Coated	2	2
Coating Solids (%)	55	10
Operating Speed	3000fpm (915 mpm)	3000fpm (915 mpm)
Web Temperature	140° F (60° C)	140° F (60° C)
Web Width	240inches(6100mm)	240inches(6,100mm)

Fig. 32

Potential Drying Alternatives

Case	Description
1	12 ft (3.6 m) Air Flotation
2	6.5 ft (2 m) High Performance Air Flotation
3	8 Rows Gas IR
4	8 Rows Gas IR & 3 Air Bar Stabilizer
5	8 Rows Gas IR & 12 ft (3.65 m) Air Flotation
6	8 Rows Gas IR & 6.5 ft (2 m) High Performance Air Flotation
7	Integrated Drying System 4 ft Turn & 10 ft Air Flotation

Fig. 33

Using the above coating and sizing information as a basis, the various drying equipment presented in the previous discussions can be compared by looking at the following seven different drying arrangements (Fig. 33).

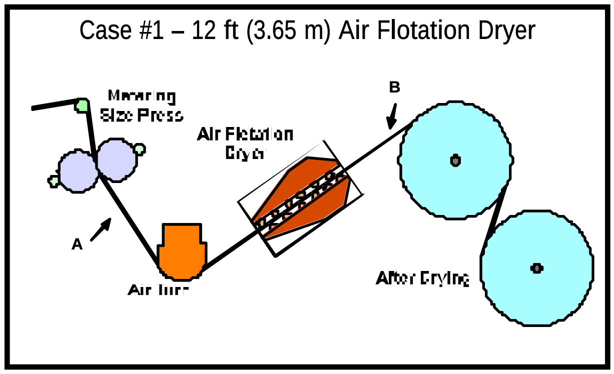
For the sizing application, the total water to be removed from the applied coating is 666.2 lbs/hr-ft (991.3 kg/hr-m) and is considerable larger than the coating application at 393.3 lbs/hr-ft (585.2 kg/hr-m). In terms of overall sheet moisture, the sized sheet leaves the MSP at 27.1%, with the coated sheet leaving at 16.9%. For the various alternatives, we will neglect the drying contribution of the air turn.

Case #1 looks at using a conventional 12 foot (3.65 m) effective length gas fired, flotation dryer. The average dryer evaporation rate has been constrained to less than 7 lbs/hr-ft^2 (33.7 kg/hr-m^2) in the coating application which has consequently limited the dryer's potential. Obviously the dryer could be made longer, however we must remember that most MSP applications are very tight for space. This case will also require additional drying to meet the drying requirements for the sizing operation. This case exemplifies why conventional air flotation dryers are not often the sole source of MSP drying in "on-machine" applications. The 12 foot (3.65m) air flotation dryer will provide 21% of the moisture removal for coating applications and 12% for sizing arrangements.

Case #1

All Conventional Air Flotation – 12 foot (3.65 m) (gas fired)

		A	B
Sheet Moisture	Ctg	16.9%	14.8%
	Sizing	27.1%	25%
Ev Rate (Ave.)	Ctg	6.8 lbs/hr-ft^2	*(33.2 kg/hr-m^2)*
	Sizing	11.9 b/hr-ft^2	*(58.1 kg/hr-m^2)*
Drying Rate	Ctg	81.6 lbs/hr-ft	*(121.4 kg/hr-m)*
	Sizing	142 lbs/hr-ft	*(212.5 kg/hr-m)*
Water Removed	Ctg	21% of the Drying Required	
	Sizing	12% of the Drying Required	

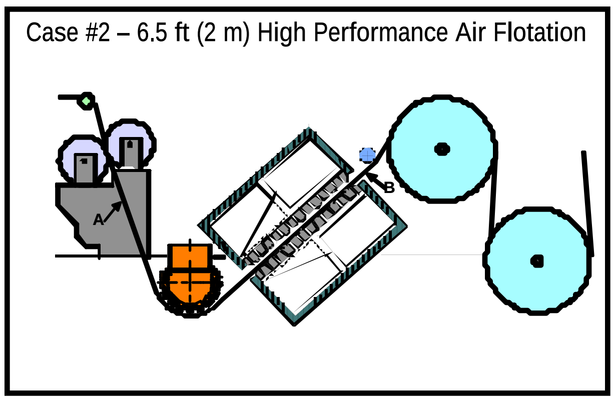


Case #2 looks at the new high performance flotation dryer's capabilities. Operating at elevated temperatures and velocities, a short 6.5 foot (2 m) dryer will result in exiting sheet moisture of 12.3% for coating and 21% for sizing applications. Having an average evaporation rate of between 25-34 lbs/hr-ft^2 (124-165 kg/hr-m^2) results in a drying rate of over 160 lbs/hr-ft (247 kg/hr-m). This arrangement will provide 42% of the moisture removal for coating applications and 33% for the sizing operation.

Case #2

High Performance Air Flotation 6.5 foot (2 m)

		A	B
Sheet Moisture	Ctg	16.9%	12.3%
	Sizing	27.1%	21%
Ev Rate (Ave.)	Ctg	25.4 lbs/hr-ft^2	*(124 kg/hr-m^2)*
	Sizing	33.72 lbs/hr-ft^2	*(164.6 kg/hr-m^2)*
Drying Rate	Ctg	166.6 lbs/hr-ft	*(247.9 kg/hr-m)*
	Sizing	221.2 lbs/hr-ft	*(329.1 kg/hr-m)*
Water Removed	Ctg	42% of the Drying Required	
	Sizing	33% of the Drying Required	

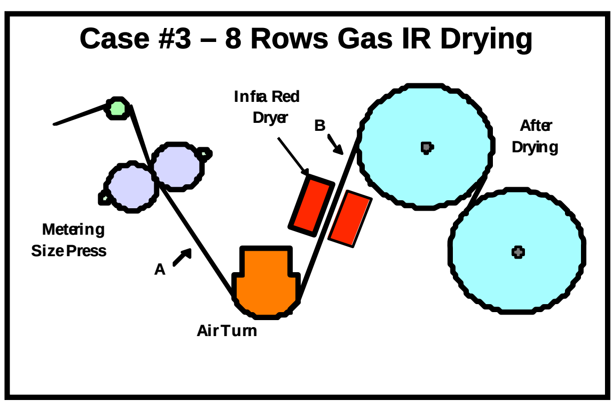


Case #3 considers the capabilities of an 8 row (4 rows/side) gas IR system. Note the performance of this arrangement results in an exiting sheet moisture of 13.3% for the coating application and 22.8% or the sizing arrangement. Drying rates are 120.8 to 145.5 lbs/hr-ft (179.7-216.6 kg/hr-m) respectively. This system will provide 31% of the coating and 22% of the sizing drying requirements.

Case #3

Gas IR --- 8 rows

		A	B
Sheet Moisture	Ctg	16.9%	13.3%
	Sizing	27.1%	22.8%
Ev Rate (Ave.)	Ctg	30.2 lbs/hr-ft^2	*(147.5 kg/hr-m^2)*
	Sizing	36.4 lbs/hr-ft^2	*(177.7 kg/hr-m^2)*
Drying Rate	Ctg	120.8 lbs/hr-ft	*(179.7 kg/hr-m)*
	Sizing	145.6 lbs/hr-ft	*(216.6 kg/hr-m)*
Water Removed	Ctg	31% of the Drying Required	
	Sizing	22% of the Drying Required	



Case #4 couples the 3 air bar stabilizer with the 8 rows of gas IR. This arrangement provides a slight improvement in performance resulting in 38% of the water removal in the coating application and 27% for the sizing operation.

<u>Case #4</u>

Gas IR + 3 Air Bar Stabilizer

Sheet Moisture	A	B	C
Ctg	16.9%	13.3%	12.2%
Sizing	27.1%	22.8%	21.8%

Ev. Rate (Ave.) (lbs/hr-ft^2) *(lbs/hr-m^2)*

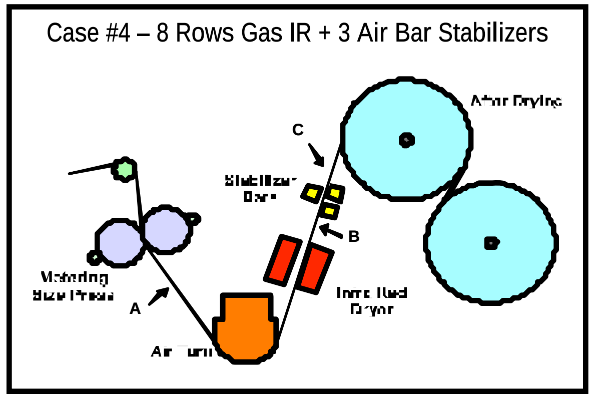
	IR	AF
Ctg	30.2 *(147.5)*	16.9 *(82.5)*
Sizing	36.4 *(177.7)*	20.1 *(98.1)*

Drying Rate (lbs/hr-ft) *(lbs/hr-m)*

	IR	AF
Ctg	120.8 *(179.7)*	28.7 *(42.7)*
Sizing	145.6 *(216.6)*	34.2 *(50.4)*

Water Removed

Ctg	38% of the Drying Required
Sizing	27% of the Drying Required



Case #5 expands on Case #4 whereby a 12 foot (3.65 m) air flotation dryer is placed in the configuration immediately following the 8 rows of gas IR. This configuration will provide a balanced drying arrangement resulting in an exiting sheet moisture of 8.9% for the coating application and 18.2% for the sizing arrangement. The combined systems will result in 64% of the drying for coating and 44% for the sizing arrangement.

<u>Case #5</u>

Gas IR with 12 foot (3.65 m) Air Flotation

Sheet Moisture	A	B	C
Ctg	16.9%	13.3%	8.9%
Sizing	27.1%	22.8%	18.2%

Ev. Rate (Ave.) (lbs/hr-ft^2) *(lbs/hr-m^2)*

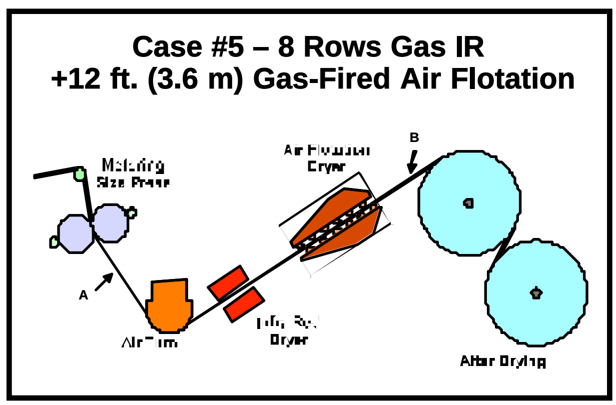
	IR	AF
Ctg	30.2 *(147.5)*	11.0 *(53.7)*
Sizing	36.4 *(177.7)*	12.3 *(60.1)*

Drying Rate (lbs/hr-ft) *(lbs/hr-m)*

	IR	AF
Ctg	120.8 *(179.7)*	132 *(196.4)*
Sizing	145.6 *(216.6)*	147 *(218.7)*

Water Removed

Ctg	64% of the Drying Required
Sizing	44% of the Drying Required



Case #6 looks at placing a 6.5 foot (2 m) high performance air flotation dryer with 8 rows (4 per side) of gas IR. This combination will result in an exiting sheet moisture of 4.2% for the coating application and 14.7% for the sizing configuration. The configuration occupies the least space while providing all the necessary coating drying and 59% of the sizing drying.

Case #6

Gas IR + High Performance Air Flotation Dryer

Sheet Moisture	A	B	C
Ctg	16.9%	13.3%	4.2%
Sizing	27.1%	22.8%	14.7%

Ev. Rate (Ave.) (lbs/hr-ft^2) *(lbs/hr-m^2)*

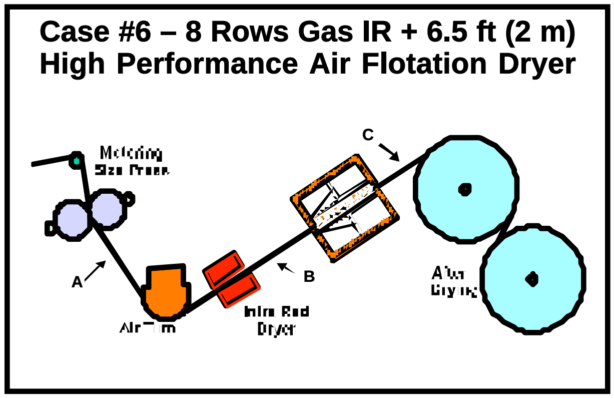
	IR	AF
Ctg	30.2 *(147.5)*	33.3 *(82.5)*
Sizing	36.4 *(177.7)*	37.5 *(183.1)*

Drying Rate (lbs/hr-ft) *(lbs/hr-m)*

	IR	AF
Ctg	120.8 *(179.7)*	218 *(324.4)*
Sizing	145.6 *(216.6)*	245.8 *(365.7)*

Water Removed

Ctg	100% of the Drying Required
Sizing	59% of the Drying Required



Case #7 looks at using a 14 foot (4.3 m) gas fired integrated air turn dryer-flotation dryer after the metering size press. In this case the integrated air float system differs in operation from the more traditional air turn air dryer unit in that the system operates as a high performance flotation dryer from web entry to web exit. This configuration will provide a balanced drying arrangement resulting in a exiting sheet moisture of 5.3% for the coating application and 15.2% for the sizing arrangement. The combined systems will result in 89% of the drying for coating and 60% for the sizing arrangement.

Case #7

Integrated Air turn with Air Flotation Dryer

Sheet Moisture	A	B	C
Ctg	16.9%	14.9%	5.3%
Sizing	27.1%	25.1%	15.2%

Ev. Rate (Ave.) (lbs/hr-ft^2) *(lbs/hr-m^2)*

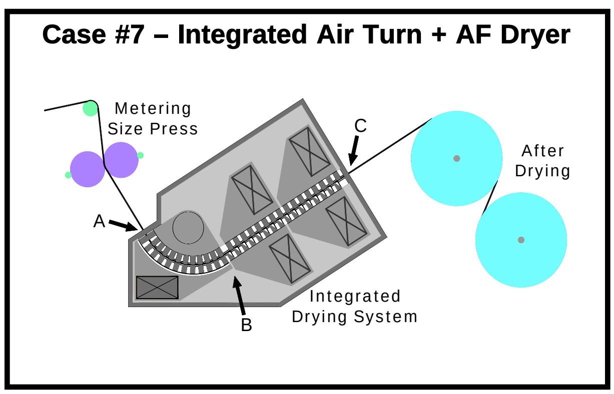
	Turn-Dry	AF
Ctg	18.7 *(91.5.5)*	30.8 *(150.3)*
Sizing	18.3 *(89.1)*	32.7 *(159.6)*

Drying Rate (lbs/hr-ft) *(lbs/hr-m)*

	Turn-Dry	AF
Ctg	77.1 *(114.7)*	308.4 *(456.8)*
Sizing	75.2 *(111.9)*	327.0 *(486.5)*

Water Removed

Ctg	89% for the Drying Required
Sizing	60% of the Drying Required



Summary

The objective in each case was to determine the performance of the selected drying system as applied to the "typical" MSP application data. In each case, reference is made to the ending sheet moisture, dryer drying rate with the total water to be removed will provide a useful comparison of the drying equipment performance.

Having a general understanding of the design attributes of each dryer type and how the systems can be beneficial in making the right drying strategy selection.

LITERATURE CITED

1. K. Hagen, "Effect of Drying", Chapter 3 in Binder Migration in Paper and Paperboard Coating, TAPPI Press: Atlanta 1993, pp. 39-59.

2. W.L. Bracken, et., "Drying", Chapter 3 in The Coating Processes, TAPPI Press: Atlanta 1993, pp. 153-173.

3. P. Collette, "Surface of Coated Grades Enhanced by High Intensity Infrared Drying", *Pulp & Paper*, May 1990, pp. 89-95.

4. E.D. Cohen, E.J. Lightfoot, and E.B. Cutoff, "A Primer on Forming Coatings", *Chemical Engineering Progress*, September 1990, pp. 30-36.

5. J. Perry, "Flotation, Infrared Drying Boosts Efficiency of Paper Coating Stage", *Pulp and Paper*, May 1989.

6. T. Smith, "Heat Transfer Dynamics" *TAPPI Journal*, August 1994, pp. 239.

7. D.W. Lawton, "Drying Systems for Coated Paperboard", 1995 Coated Paperboard Short Course notes, TAPPI Press: Atlanta 1994, paper 2-2.

8. N. Plowman, "What is Paper Coating", *Graphic Arts Monthly*, January 1992, pp. 104.

9. K. Hagen, TAPPI Journal 72(5): 77 (1989)

10. G. Engstrom, *Svensk Papperstidnung*, B107 (1983).

11. E. Bowden, "Non-contact Drying and turning—the 'On-Machine' Technology of the Nineties". Paper presented at the 44th Annual General Conference, 1990.

12. Mr. Trefz, "Theoretical Aspects and Practical Experiences for Film and Coated Offset Grades", *TAPPI Journal*, Vol 79, No. 1, January 1996.

13. J. Dunlop, "Contactless Web Handling and Drying", 1991 Coating Conference, TAPPI Press: Atlanta 1991.

14. L. Lee, "Choice of Gas versus Electric IR Drying Hinges on Energy Costs Mill's Needs", *Pulp & Paper*, May 1992, pp. 108-111.

15. L. Lee, "Gas Infrared Drying: Update on Technology", *Pulp & Paper Canada*, 95:12, pp. 102-104, 1994.

16. G. Swift, "Drying Options Following Size Press Metering Coaters", presented at the PITA Water Removal Conference, York, UK, 5/6 December 1995.