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Paper Title: "Dryer Technology Update: Meeting the Unique Demands of Emerging Markets"

Emerging markets have given rise to a number of new materials processing and handling methods related to drying and curing of base materials in continuous forms such as webs, strips, tows, cast films etc. In these applications, more than ever before, drying and heating profiles must be managed in synchronization with mechanical and other processing requirements of the substrates and coatings. By handling these thermal and mechanical requirements simultaneously, new drying and curing methods are saving processing steps, improving product quality, and reducing waste, when compared to traditional step-by-step operations. This paper will highlight several market driven thermal air management challenges along with the basic methods and technologies used to provide processing solutions. Topics will include; simultaneous drying & tentering of films with unique physical and thermo-mechanical properties, drying and curing of webs that change form through the course of processing, non-web polymer materials that are processed on carrier webs, simultaneous two-side coating and drying of polymer battery electrodes, film annealing, the use of controlled drying rates to achieve targeted physical properties such as porosity or crystal structure, and non-contact web handling of permeable and porous substrates.

What Do We Mean by Emerging Markets?

For the purposes of this paper, we will define 'emerging markets' as relatively new or fast changing business segments that are either growing rapidly or show promise of such growth in the near future. Drivers of emerging markets are as diverse as the markets themselves, ranging from globalization and industrialization (i.e. the need to extend the supply base to meet fast growing demand), the advent or maturation of new technologies, social change, dwindling resources, process optimization, cost reduction etc.

Obviously, we cannot discuss in detail all the various markets that might qualify as emerging markets, and so will limit our discussion to a few examples which include; printed electronics, renewable energy technologies, metered dose pharmaceutical production, digital printing, advanced composite material manufacture and advanced filtration manufacturing. Each of these markets present different challenges relating to process drying and curing, and while some of these challenges are common to more than one market, some relate to specific process development and optimization needs that may involve new or proprietary processes or end products. As such, to protect individual company confidentiality, we will be forced to keep the discussion somewhat generic and to group product types, and potential thermal air management challenges and solutions, into common categories that can be addressed without revealing specifics about any discreet product or process.

One Common Need for All Emerging Market Product/Process Development Projects

All new products and/or processes share one common need when it comes to assessing thermal air management challenges and potential solutions; they all require advanced process modeling and testing capability to insure predictable and repeatable results. Normally, such joint development efforts begin with the careful identification of the process variables, production requirements, and end product performance characteristics. Once these specifications are defined, the drying and curing process can be modeled and potential technology approaches can be discussed. Next, lab trials are almost always required to verify assumptions and to optimize equipment configurations and processing requirements under “real-world” conditions. This step is usually guided by a mutually agreed upon set of test variables that are organized into one or more design/s of experiment (DOE) that serve to put the proposed theoretical solutions to the test of generally accepted scientific method.

Emerging Markets Product Groupings

In order to focus the discussion, basic groupings or classifications of web product/process types were established. Together, these groups embrace a broad range of specific end product performance requirements that are impacted by the drying or curing process. These categories along with a few end product examples are shown below:

I. Webs Requiring Simultaneous Thermal and Mechanical Manipulation of the Substrate
   a. High performance films such as solar and dielectric films used in renewable energy applications such as the manufacture of batteries, photovoltaic cells and fuel cells
   b. Synthetic fabric manufacturing for consumer and industrial products that require specific end product performance features

II. Webs That Change Physical or Molecular Form During Drying or Thermal Processing, Independent of Mechanical Control
   a. Foams and other similar materials used for vibration dampening, sealing and thermal and electrical insulation products
   b. Fiber tows and other non-web polymeric materials used in the manufacture of advanced composite materials destined for architectural, structural and aeronautic applications
   c. Vinyl tapes used for medical products

III. Webs or Non-Webs That Are Dried or Cured on Carrier Webs or Belts
   a. Cast film manufacturing
   b. Advanced filtration membranes
   c. Specialty soluble films used in metered product delivery systems
   d. Edible films used in pharmaceutical or food product applications

IV. Webs That Are Two-Side Coated
   a. Various printed materials
   b. Digital printing applications
   c. Battery cell production
   d. RFID circuits

V. Webs with Active Coatings or Coatings with Performance Characteristics That Are Directly Controlled by the Drying or Curing Process

a. Pharmaceutical products such as diagnostic test strips for various hospital and in-home applications
b. Temperature sensitive labels used in predicting product usefulness or shelf life.

At this point, it is worth noting, that in addition to the unique drying and curing challenges presented by each of the products and processes listed above, all of these emerging markets are simultaneously focused on optimizing the economic elements of the production process, (i.e. the desire and need for material down-gauging and increased throughput). These added elements themselves present a whole set of drying and curing challenges that rightly deserve a detailed discussion that due to time must be covered in a future paper.

<u>Webs Requiring Simultaneous Thermal and Mechanical Manipulation of the Substrate</u>

Some high-performance films and fabrics require processing in tenter-frame dryers where the web is pinned or clamped along the edges during the drying or thermal forming process. In this way, the web can either be held dimensionally stable in the cross-machine direction (in order to prevent or control shrinkage), or can be purposely stretched (in order to yield specific performance qualities such as polymer orientation, optical clarity, or crystalline cell structure). If a film substrate is destined for an optical display application, for use in photo voltaic cells, or in other applications where the film properties must be uniform across the full length and width of the product, any variations in substrate thickness can result in poor product performance.

Application Challenges:

- In tentering applications, cross-machine and machine direction thickness can be difficult to control since the web is under tension in both directions as it is heated and transported through the dryer. Poor temperature and velocity uniformity inside the dryer can contribute to non-uniform substrate thickness which in turn can result in poor or unreliable end product performance.

- Some products can off-gas during the drying process and these gases can potentially condense on cooler surfaces within the dryer, resulting in contamination of the substrate.

- Some films are extremely thin and web handling during the stretching process can be difficult.

Technology Solutions:

- Selection of optimum nozzle geometry and nozzle-to-web clearance through modeling and testing can help to insure uniform velocity and impingement forces across the face of the web. Nozzle velocity can be controlled by variable speed drives to attain target heat transfer coefficients to meet specified product tolerances.
- Cross machine and machine direction arrays of IR web temperature sensors can be used (subject to emissivity compatibility with the substrate) to assist with control of temperature within the dryer.
- Ductwork and nozzle headers can be insulated to improve system-wide temperature stability

- Tenter-frame surfaces can be enclosed and heated to maintain metal temperatures above the condensation point of process gases.

<u>Webs That Change Physical or Structural Form During Drying or Thermal Processing, Independent of Mechanical Control</u>

Composite webs such as those used in medical wound dressing applications or for the manufacture of advanced structural forming tapes, are often subject to dimensional and/or structural transformation during thermal processing. In some cases, the substrate materials can enter the dryer in a non-web form and literally become a web during thermal processing. Other webs, such as filtration materials must be kept stable for subsequent processing such as assembly into cartridges and the like. Still others require heat treatment to insure dimensional stability in downstream applications that generate heat. In all cases, as these webs change form on either a chemical or physical basis, they can present a wide range of web handling and thermal air management challenges.

Application Challenges:

- Film substrates can become very extensible creating web handling issues inside the dryer.
- Coatings can be very sensitive to airflow.
- Entering materials can be dimensionally non-uniform yet must be relatively uniform as they exit from the dryer.
- For some webs, hygroscopic effects can be aggressive, such that even slight changes in moisture can result in edge curl or other improper dimensions that can impact downstream assembly processes.

Technology Solutions:

- Often dryer length must be increased to allow for low temperature processing in order to prevent or minimize elongation of the web. Mid dryer steering may be necessary depending on web width and tension requirements to prevent web tracking anomalies.
- For webs that exhibit extensible mechanical behavior, use of nozzles placed on extended spacing with the air jets creating a stabilizing action in the machine direction can be a solution.
- For webs that require thermal forming or annealing, the dryer can be configured with machine direction IR emitter arrays that can be independently controlled to allow for cross-machine temperature profiling.
- Certain hygroscopic substrates that are subject to dimensional instability caused by humidity effects can be dried to a low moisture level, and subsequently re-moisturized to a controlled level by incorporating a temperature controlled remoisturization section.

<u>Webs or Non-Webs That Are Dried or Cured on Carrier Webs or Belts</u>

Emerging markets such as metered-dosage products, advanced membrane filtration materials, and water soluble drug delivery systems all involve webs that present unique challenges with respect to thermal processing. Many of these webs require some form of support during thermal processing in order to maintain dimensional stability as the web itself is either formed or chemically transformed in the process. In some cases, the "carrier web" is a permanent part of the drying/curing system (e.g. conveyor belts). In other cases, the “carrier web” is some form of sacrificial substrate that is removed in downstream processing or in the final application. Often, these end products are “high value-added” products, the quality of which must be carefully managed throughout the manufacturing process.

Application Challenges:

- Controlling the rate and duration of chemical reactions in order to achieve specific end product performance properties.
- Controlling dimensional stability during the drying process.
- Managing evaporation rates can be critical to quality. Over or under drying can create expensive waste.

Technology Solutions:

- Some processes involve chemical reactions within, or at the surface of, the web, requiring extremely precise control of airflow and humidity within the processing chamber. High accuracy solvent concentration or humidity sensors can be positioned strategically in the system exhaust and make-up-air ductwork as well as inside the chamber in order to monitor and provide feedback to the air handling and MUA dehumidification systems.
- Overly aggressive impingement on some webs can upset or redistribute active coatings on the face of the web, resulting in poor control of activated coating distribution. For applications using a sacrificial carrier web, dryers can be configured with quiet zones consisting of foils beneath the carrier web and various independent air supply nozzle configurations above the web. Where permanent conveyor belts are used, the nozzle system above the web can be mounted to a retractable supply air header so as to precisely control impingement velocity at the web. In cases where only co-flow or counter-flow are desired, small variations in the rate of evaporation can be controlled by incorporating an adjustable plate above the web that can be positioned such that air velocity at the web will vary based on variation of the face area between the web and the plate.
- The shrinkage of materials under drying conditions often cause curl due to hygroscopic effects. One way to counter the tendency to curl is to add a curvature to the web path. Often a sinusoidal path in flotation is sufficient. For some especially difficult webs, the web must be restrained around a rotating vacuum drum with impingement jets providing drying air, including through-air (web permeable) such that the curl is avoided.
- Clean room construction methods must be employed (in some cases, both inside and outside the equipment).

Webs That Are Two-Side Coated

Some emerging market driven products are particularly well suited to air flotation drying solutions. New advancements in digital printing for instance have resulted in ink application methodologies that apply thick coatings of water or solvent-based ink on both sides of a relatively thin paper web. Rapid growth in other emerging market segments such as battery electrode and cathode production are pushing manufacturers to reduce processing steps in order to lower costs and increase production throughput.

Application Challenges:

- Thick coatings applied to thin materials must be dried slowly and such drying can be diffusion limited.
- Some end products require very low residual solvent content (less than .5%).
- Recirculation air humidity can create product defects in some cases.
- Coat weights in digital printing can be on the order of 5 – 10 times those of a typical lithographic printing application with low to 100% coverage requirements requiring a wide range of drying capacity.

Technology Solutions:

- Dryer humidity controls are required for some of these applications.
- Long flotation dryers are used to allow for zoning and low residuals. Nozzle alignment and airflow uniformity are critical.
- Proprietary, combination flotation air bars and IR emitters provide both heat transfer <u>and</u> effective convection for mass transfer. This combination is of great advantage in drying the water in shortest possible space. Flotation + IR air bars provide efficient use of IR energy due to good view factor (IR energy wave path from emitter to web) and immediate recovery of "stray heat" into the convection air used for drying.
- Fast cooling of emitters by the combined convection air also prevents ignition of web in case of e-stop or web break without need for mechanical shutters and the like.

<u>Webs with Active Coatings or Coatings with Performance Characteristics That Are Directly Controlled by the Drying or Curing Process</u>

Some emerging market driven products involve thermal processing that is the primary driver of product functionality. For instance, for some membrane products, porosity, hole size and distribution are controlled by the drying rate and air temperature. For other products, such as diagnostic test strips commonly used in over-the-counter consumer applications, the crystalline structure of the active coatings, which are partially responsible for product performance, can vary significantly with changes in impingement velocity.

Application Challenges:

- Defining process input and output parameters is often a matter of empirical observation and testing.
- Repeatability is critical since slight changes in thermal air management equipment set points can result in drastic changes in end product performance.
- Products are often subject to FDA regulation and lengthy process qualification cycles.

Technology Solutions:

- For many applications, clean room environments are maintained inside and outside the equipment.
- Vibration dampening for fans, flanges and support structure is sometimes required for products coated with vibration sensitive coatings.
- Activated coatings on webs must be dried in a controlled temperature and vapor pressure environment, in order to maximize the diffusion and activity properties of the sorbent layer.

- Extensive computer modeling followed by lab trials is often necessary to establish optimum processing parameters.
- Recipe controls are employed in order to insure repeatability.
- CFD modeling is sometimes used to establish optimum chamber sizing and airflow control, particularly where air temperature and velocity uniformity are critical to quality parameters.

Summary

Products derived from web-based materials, and the processes used to make them, have varied over the years to meet the demands of the markets of the day. Emerging markets continue to cause shifts in demand, ranging from satisfying ongoing needs, to lowering product costs, to the generation of completely new products by novel or otherwise synergistic means. Manufacturers of the types of drying and curing technologies used in web based production, more than ever before, must be willing and able to work closely with their customers, to design, develop, test and build both new and optimized drying and curing solutions to meet the challenges of the day.