For more than a century, forced air, convection-style drying technology has been widely applied within the converting and printing industries. Like any mature technology, this method of drying and curing has undergone relatively few dramatic changes over the past ten to twenty years. Nevertheless, high-efficiency, convection air-dryers continue to be an effective and popular choice for a wide variety of coating and laminating process-drying requirements.

The goal of this paper is to briefly review the evolution of heated, forced air, convection drying technology as it relates to coating, laminating and printing processes and subsequently, to examine some of the more recent technology refinements that help define the current state of the art. For the sake of time and focus, the paper will cover only roll support and flotation style, forced air dryers (ignoring other convection style dryers that feature web support mechanisms such as belts, conveyors, edge grips etc.). An emphasis will be placed on key equipment features and design improvements that have expanded the utility, the effectiveness, and the efficiency of forced air, convection roll support and flotation drying technology. Finally, recognizing the current industry-wide movement toward the processing of thinner substrates and coatings, at ever increasing line speeds, the author will highlight some of the technology capabilities and developments that relate specifically to web handling and process control issues.

Any number of approaches could be used to organize the flow of this presentation and reduce the content to “bite-sized” bits of useful information. The author has elected to organize this paper around the four broad areas of interdependent technologies (i.e. air handling systems, web handling systems, heat sources, and control systems) that together comprise what one might call a “typical” forced air, convection dryer. Aspects of dryer design that do not fall within these four groups will be addressed under the heading of “Miscellaneous Design Features.”

What is “State of the Art”?  

The American Heritage® Dictionary of the English Language, Fourth Edition defines “State of the Art” as:

“The highest level of development, as of a device, technique, or scientific field, achieved at a particular time. Despite including the word art, this term originated in technology and its first recorded use appears in a 1910 book on the gas turbine.”

For a mature technology like convection drying, state-of-the-art probably consists more of the ‘tried and true’ than the ‘truly new.’ This is especially the case if we focus solely on the hardware (and software) aspects of the dryer design. However, if we expand our definition a bit, to include the synthesis and application of existing methods and technologies into process specific solutions, we will come closer to the meaning of SOTA as it relates to convection air drying in our industry. In other words, when it comes to forced-convection drying, it is more important to consider the State or Your Art, than the State of The Art.
State of the Art - Web Handling

Roll Support Technology

Arched roll support dryers have a long, successful track record of drying performance in the printing and converting industries. And, they continue to be a very effective, low cost solution for a variety of single-side coated and printed product applications.

From a historical perspective, a typical roll support dryer would likely support and transport the web on a live-shaft idler roll system, relying upon web-to-roll face contact to drive the rolls. By arching the roll path (usually with a wrap angle of 2-5°) the web can be kept in positive contact with the rolls. For sensitive webs, to minimize marking or scratching of the bottom side of the substrate, rolls are often tendency driven or direct-driven (Fig. 1), at or near line speed. Depending on operating temperature, and other design factors such as web width and material deflection considerations, idler rolls are usually fabricated from either steel or aluminum alloy material.

Fig. 1 Typical Tendency Driven Arched Roll Support Dryer Configuration

SOTA roll support dryers are available with alternate or additional web handling features such as:

- Flat-path roll configurations, where roll contact is induced via direct vacuum, air impingement on either side of the roll, or via placement of airfoils below the web on either side of the roll. (Fig. 2)
- Individual servo-motor driven idler rolls for more precise control of drive speed (e.g. for applications involving extensible webs)
- Low inertia roll designs such as those that feature extruded profiles to reduce mass.
- Lightweight, low deflection, carbon-fiber composite rolls (generally for operating temperatures less than 200° F). Particularly useful for extremely wide webs and in high-speed applications.
- Solid-lube bearings for high temperature applications or PTFE sleeve type bearings for clean-room applications where graphite could create particulate dust.

Fig. 2. Induced roll contact using topside impingement, airfoil draw, or direct vacuum draw.
Air Flotation Technology

The concept of supporting a web between opposing impingement airstreams has been around for over a hundred years. However, true non-contact, air flotation dryers (i.e. dryers that transport and support the web on a cushion of air, in a sinusoidal wave pattern that is induced by nozzles mounted both above and below the web, in a staggered configuration) (Fig. 3) were only introduced in the late 1960’s. Whereas typical impingement nozzles (such as slot nozzles, hole bars, and jet tubes) are generally viewed as heat delivery devices designed to speed the convection drying process, air flotation nozzles (often referred to as ‘air bars’) are both a heat transfer and web support device. The principle known as the “Coanda” effect (Fig. 4) is used to create the air cushion, and the relationship between nozzle velocity and line tension along with nozzle geometry, determines the amplitude of the sine wave pattern and the distance between the web and the surface of the nozzles. Some traditional nozzle configurations have slightly higher heat transfer coefficients than flotation air bars, however, they do this at the expense of good web stability.

Shortly after the introduction of the “Coanda” air bar, single-side flotation nozzles (Fig. 5) were developed. These specialized nozzles, referred to as ‘airfoils’, float the web from the bottom side only, using a jet of air that flows along the face of the nozzle in the direction of the web, followed by a wing or airfoil. Some airfoil designs achieve higher heat transfer by partially impinging on the web with the jet of air. In either case, the airfoil itself creates a negative pressure zone above it that in turn, pulls the web down into the familiar sinusoidal wave pattern (using much the same aerodynamic principle as an airplane wing).

Today, improved web handling performance is available in SOTA air flotation dryers thanks to a number of equipment and design features including:

- A wider array of nozzle designs to optimize flotation web handling performance over a broader range of substrates and processes. Designs include; wider face-area nozzles that provide added clearance between the nozzle and substrate (often used in PSA applications), adjustable wing airfoils and dual slot airfoils that offer increased stability over a broader range of substrates and web tensions. (Fig. 6)
- Unique nozzle configurations that provide stable web performance with higher heat transfer than standard flotation designs. (Fig. 7)
- Accumulator designs that alternate airturns with rolls in order to eliminate web face contact with rolls.
- Mid-dryer web steering devices for extremely long dryers. (Fig. 8)
- Zone specific nozzle configurations optimized for the specific drying stages.

![Multiple nozzle configurations](image1)

![Airbars with hole bars for higher heat transfer](image2)

![Typical mid-dryer steering section](image3)

**State of the Art - Air Handling Systems**

The air handling technologies that are incorporated into a forced convection dryer include; fans, plenums, air distribution headers, nozzles and the ductwork (both internal and external) that connect the component parts. As previously discussed, in the case of flotation dryers, nozzles perform both the heat transfer and web handling functions. It is important to note, for either type of dryer, the air handling components and design, can either positively or negatively impact web handling (this is particularly true in flotation dryers).

For the air handling section of a dryer, SOTA is usually defined by performance capability in two primary areas of design; uniformity of air and temperature distribution in the cross and machine directions, and compactness of the design. Important features include:
- Low profile, plug style fans to minimize plenum size and to allow for modular construction.
- Spark resistant fans for high LEL applications.
- Multi-blade versus single blade dampers for more finite airflow control.
- Individually dampered nozzles (particularly at the web slots for fine-tuning initial impingement velocity).
- Variety of nozzle designs for varying heat transfer and impingement velocity and direction.
- Tapered air distribution headers for improved machine direction air and temperature uniformity. (Fig. 9)
- Cross-machine exhaust air headers for uniform exhaust flow to minimize web steering and web drying defects (e.g. web weave, web flutter and asymmetrical edge drying effects). (Fig. 9)
- Finger style supply air headers to allow for uniform exhaust airflow across the web (particularly important for wide web applications. (Fig. 9)
- Tapered nozzle construction for end-fed designs to maintain constant velocity across the nozzle for improved cross-machine air and temperature uniformity.
- Adequately sized exhaust air relief areas within the dryer enclosure and between nozzles to reduce exhaust velocity to minimize web flutter and other web-handling problems that can be created by poor exhaust airflow. (Fig 9)
- Integrated (i.e. built into dryer enclosures) air handling components to save valuable floor space and reduce structural support platform requirements.
- Automated air distribution header retraction systems to allow a broader range of heat transfer and impingement velocity adjustment.
- Unique zone configurations (quiet zones) for sensitive coatings.
- Computational Fluid Dynamic (CFD) computer modeling of airflows.

**Fig. 9. Air distribution uniformity features.**

**State of the Art – Heat Sources**

Heat sources have undergone relatively few significant changes over the past ten to twenty years. Most converters continue to use direct or indirect, gas-fired, nozzle-mix burner systems
due to familiarity, cost, controllability, and availability of fuel. Electrical resistance coils, thermal oil coils, low and high-pressure steam coils, and hot water coils are the other most commonly used heat sources.

One of the most notable advancements in the area of heat generation for convection dryers is not so much a technology-based advancement as it is an industry wide refocus on energy conservation and cost reduction through the use of existing heat recovery technologies. As energy costs continue to rise, there will be even more interest in this area particularly for solvent based converters that operate pollution control systems. There are, however, a few SOTA heat source features worth noting:

- Modular gas trains that take up less space than traditional piped individual components.
- Advanced thermal fluids that can operate at higher temperatures without breaking down.
- Pollution control devices integrated into the dryer and functioning as the dryer heat source. (Fig. 10)
- Low NOx burners.

**State of the Art – Control Systems**

As might be expected, many of latest advancements in convection drying technology have taken place in the area of control systems, in particular, in the field of solid-state electronics. Whereas older drying systems were typically equipped with relay logic based controls, single function temperature controllers and manually adjusted damper systems, today’s SOTA dryer is often equipped with a variety of sophisticated PLC and/or PC based systems that are capable of controlling virtually every dryer function “on the fly.” The following are just a few of the SOTA control capabilities:

- PLC or PC based controls that work in conjunction with automated dampers, pressure transmitters, RTD temperature probes and various other system sensors to enable recipe operation. Huge strides in process control and product quality repeatability have resulted from these advancements. (Fig. 11)
- Trending and reporting of process parameters can be accomplished with the addition of PLC or PC software programs and communication cards, or stand alone data loggers.
with analog and digital communication capability can be installed to accomplish similar functions.

- Trouble-shooting is quicker and more reliable thanks to first out fault history that can be captured in the PLC.
- Service and maintenance diagnostics, and often real-time PLC maintenance programming downloads, can now take place via modem communication.
- Preventative maintenance can be simpler and timelier with the advent of PLC annunciated maintenance schedules.
- Reactive control systems using feedback from temperature, pressure, LEL, moisture and humidity sensors can make machine adjustments "on the fly" to maintain uniform processing conditions to insure uniform product quality. (Fig 12)

Fig. 11. Example of a recipe-control, operator interface touch-screen.

Fig. 12. Two examples of a reactive control system.
Miscellaneous Design Features:

Some areas of technological advancement do not fall conveniently into the categories of air handling, web handling, heat sources or controls. They are, nevertheless, important to understanding the current capabilities of forced convection dryers. Some of these features include:

- Various enclosure retraction systems for web up access and cleaning. (Fig. 13)
- Removable nozzles for easy cleanup.
- Specialized clean-room construction methods including; laser-cut stainless steel forms to eliminate 90° corners, the use of advanced gasket materials and coatings, continuous seam welded construction, computerized robotic welders that use amperage draw feedback to reduce weld splatter, minimized use of fasteners, ground and polished welds etc.
- Hybrid forced convection/IR systems to increase heat transfer particularly in water-based applications.
- Accurate computer modeling software for dryer sizing and performance prediction along with state of the art engineering design practices such as the use of Failure Mode and Effect Analysis (FMEA), Finite Element Analysis (FEA), Pugh analysis and other Six Sigma-type tools.

![Fig. 13. Various enclosure retraction systems for ease of web-up and maintenance.](image-url)

Summary

“State of the art”, as it pertains to forced-air convection drying, may well be best defined as, the appropriate application of existing technology and engineering process knowledge to a set of specific process drying challenges. In other words, simply applying the most advanced hardware technology available to the basic physics of forced convection drying, will not automatically result a SOTA solution. In fact, what might be considered state of the art for a particular converting application, could actually be considered a “low tech,” or for that matter “hi-tech,” disaster for another.

In the end, what matters most is that your convection air dryer matches the state of your art.
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