浸透しにくい連帳メディアに対する複数手段の組み合わせによる高効率乾燥

Simultaneous Multi-Type Drying Methods and Modeling on Continuous Web Semi Non-Porous Substrates

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要　旨

印刷業界の短納期及び特注需要の増加に伴い，従来からのオフセット印刷業者は，油性の枚葉給紙式印刷から水性連帳デジタルプリンターへ，円滑な置き換えを模索している．オフセットコート紙は液体吸収性が極めて低いため，印刷表面インクの速乾性が印刷の成否を決定づける重要な要因となっている．現在多くの乾燥方法が様々なプリンターに実装されているが，それらの乾燥方法の相互作用とその効果について十分に理解されていない．そこで，最終的な乾燥品質を達成するため，幾つかの乾燥方法を組み合わせた実機検討に加え，数値モデルによる解析を行うことにした．本研究の目的は，乾燥システム全体だけではなく，乾燥に必要な用紙長及びエネルギーをより節約するための達成方法を獲得することにある．

ABSTRACT

As print industry demand increases for short run and customized printing, traditional offset press printers are looking for solutions that translate easily from oil-based sheet-fed printing to continous forms aqueous ink digital printers. Offset coated media has very little fluid absorbtion so the ability to dry the ink on the surface of the paper becomes a critical boundary to sucessful printing. Many different drying methods are currently implemented within various printers but the interaction between these drying methods and their relative effectiveness is not well known. Experimental testing with various types of drying in combination, as well as simulation and mathematical modeling, is used to better understand how to achieve necessary final output drying quality. The intention of this work is to not only find the overall best drying system, but also to find how to achieve this type of drying with less paper path length and overall drying energy.

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1. Introduction

1-1 Commercial Printing and Inkjet Technology

Continuous web fed inkjet printers have had significant success in penetrating the transaction type marketplace. In general this type of application requires only moderate print quality and optical density. Customers are much more focused on the cost of the printed page than having perfect color replication and outstanding detail. As such this became a prime entry point for inkjet printers that could utilize highly absorptive media and required minimal drying. Printers such as the Ricoh InfoPrint 5000 printer line found success in a combination of speed and cost at the necessary level of print quality for this type of market application. Now that this marketplace has been highly penetrated by similar types of printers, the focus has shifted to short run publishing and promotional applications[1)]. The requirements for these applications are extremely challenging for digital inkjet due to high ink loading required for color replication quality, gloss level of the printed sheet, and the overall cost per printed page. Successful printing on coated paper types is now a requirement to enter this marketplace due to the low cost of commodity stocks and wide range of their availability.

Offset coated paper types pose a challenge for aqueous ink high-speed printers. Since the ink no longer quickly penetrates into this type of paper, the carrier fluid for the colorant must be effectively dried. There are now two requirements of this type of printing that are in opposition, one requirement is to maintain a high printing speed, the second is that drying requires long exposure times at elevated temperatures. The shorter the exposed drying time the higher the temperatures required for drying. High energy consumption and secondary impacts of very high drying temperatures can create additional challenges for maintaining acceptable cost per printed page. The issue set forth now becomes how can energy and hardware costs be reduced while maintaining high print speeds, and can drying ability meet what is needed on some of the most challenging substrates.

1-2 Investigation of Various Drying Methods

Some common types of drying technology used within the continuous forms printing domain are high temperature conductive drums, electrical or gas powered high temperature convective drying (air drying), and high energy radiant drying. In the past, these forms of drying have been considered as different approaches that can be taken to solve the same issue. However, it was found that each of these forms individually pose their own challenges and benefits which will be discussed at more length. In general there is not a well understood interaction of the ink and paper system during these drying operations. Also, effectively using multiple types of drying in a single system has not been widely investigated by system manufacturers. To better understand how each type of drying can be deployed using its inherent benefits, and to minimize wasted energy and negative impacts mentioned above, was the primary focus of this research and investigation. During the course of the experimental testing and predictive modeling, conclusions were drawn on best practices for future drying systems, and the associated challenges of their implementation. This type of system view with respect to drying, and the ink's interaction with the paper, allow for the best chance of success when printing on difficult offset coated substrates in high-speed web applications.

2. Drying System Development

2-1 Radiant Drying Process

2-1-1 Radiant Drying Theory

The focus of radiant drying in conjunction with aqueous inks has primarily been to target the inked surface instead of bulk heating the entire paper surface. This would ideally improve the efficiency of drying because only when ink is printed on the surface does it absorb a significant amount of radiant energy. The range of wavelengths which seems to have this benefit are in the near-infrared spectrum which incorporates wavelengths of 700-1400 nm. Another benefit of this method of drying is to apply very high heat fluxes, which allows for the duration of radiation on the printed page to be relatively small compared to both air drying and conductive heating. Power levels of a near infrared emitters can exceed 5 kW for a 12 inch segment. In order to control the power output at the substrate, highly reflective surfaces are necessary on both sides of the emitters to maintain the efficiency of the system.

All radiant emitters have spectral emission patterns that taper off towards the ends of their radiant spectrum. In the case of near infrared emitters there is still significant emission in both the visible and mid infrared ranges. This poses an immediate challenge for a multi-color inkjet printing system. In the visible radiation spectrum the absorption of the inks varies greatly by color. This is especially evident when looking at the difference in absorption spectrum of a black and magenta ink. Black absorbs significantly more radiant energy in the visible spectrum than magenta as demonstrated by the area under the respective absorption curves in Fig. 1.

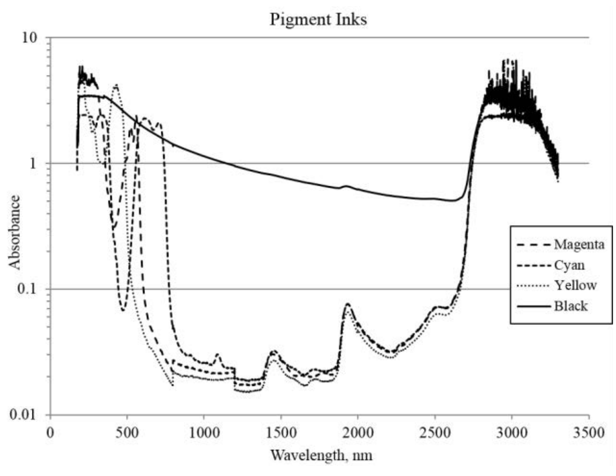

Fig. 1 Spectral absorption of various colored inkjet inks.

The amount of energy that an image absorbs using this type of radiant emission technology is highly dependent on the ink color or mixture of ink colors used to print the image. For example: for the same level of emitter output power, an image that is printed with black ink could be completely dry, but if printed with magenta ink, this image may smear and transfer ink to the paper transport rollers. Depending on the precise absorption characteristics of a specific set of inks, enough energy may be emitted to dry the magenta ink, or other combination of colored inks, however, anything printed with black ink could absorb too much energy and cause the paper surface to become damaged. For reference, paper begins to become discolored at temperatures of about 150°C, and begins to burn at temperatures above 200°C[2]. Radiant emitters can easily produce enough power to exceed these temperatures during printing.

Another challenge with using radiant technology is that volatiles contained within the ink very quickly evaporate into the air. This air must be collected and exhausted to reduce the possibility of contaminating the ambient environment where the printing systems are located. The printed surface temperatures can be elevated to the point that humectants with very high evaporation temperatures can be found in exhausted air. Finally, with the high energy density that can be emitted from a radiant emitter array, even when employing highly reflective surfaces to contain radiant emissions, there is still a significant amount of latent heat that must be managed. This waste energy reduces the efficiency of the radiant drying system, and is ultimately best used in conjunction with other drying methods, or when inks are specifically designed to absorb the spectral emissions of the radiant emitters.

2-1-2 Ricoh Product Implementation

The first implementation of near infrared radiant dryer in continuous web inkjet printer for Ricoh was started in 2010, an example is shown in Fig. 2. The goal of this implementation was to improve the range of substrates that could be successfully dried to include some coated paper types. Many of the challenges discussed became limitations due to the necessary implementation. The design was to be a minimally intrusive installation into an existing printer. One example of this was the length of emitter exposure time, which was a function of the geometry of the system and exposed paper path within the printer.

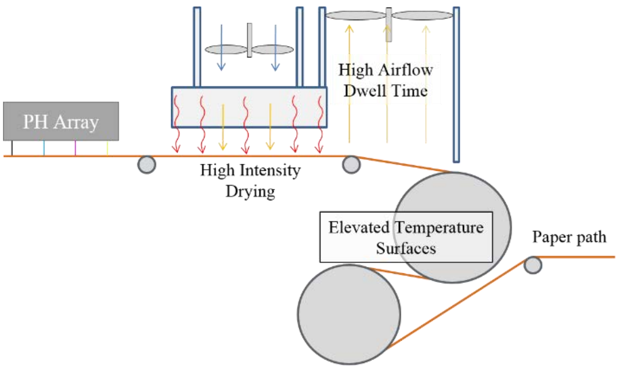

Fig. 2 Radiant dryer product implementation.

Because of the existing system constraints, the power requirements for the relatively small radiant system were very high to achieve the necessary drying targets. This meant that an operating window very close to exceeding the temperature threshold of printed black ink must be maintained. The control system was designed with feedback that could quickly respond to emergency printer stops or slowdowns without incident[3]. Due to the amount of energy that was required to properly dry the ink, steps were taken in the design of the system to ensure that potential fires could be contained within the emitter enclosure, and not damage any printer components. Another benefit of the selected near infrared emitters was the response time to changes in input power. This allowed the emitters to quickly cool below the ignition point of ink and paper, and was not readily demonstrated by other forms of high-energy radiant emitters in the mid or far infrared spectrum. As an additional safety precaution, the mechanical design of the area exposed to radiant emissions were contained within a safety enclosure. Fig. 3 shows the very specific geometry that was developed to define the small gaps necessary to quickly extinguish any ignited paper without the need for chemical extinguishers or other moving components[4].

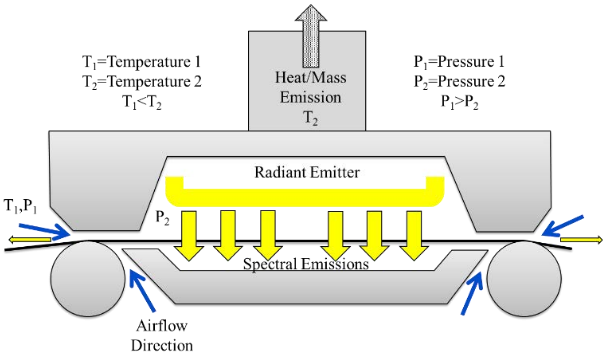

Fig. 3 Fire box encapsulated with paper feed rollers.

2-1-3 Experimental Findings

Some of the challenges posed by a radiant drying system clearly demonstrated the challenges of a multi-color ink printing system. It was discovered during testing that dryness was highly dependent on which color was printed, and on the specific size of the printed area and the surrounding areas which absorbed the radiant energy. When very large images were printed, energy requirements to dry increased and the image could tolerate more energy before discoloration was observed. Conversely, small images required less energy to dry but began to discolor at lower energy levels, especially for highly absorptive colors, i.e. black[5,6]. This discoloration continued until the size of the printed images were reduced to only a few mm^2. At this point, the printed area was not large enough to absorb the energy required to discolor the substrate, which is shown in Fig. 4.

In order to accurately characterize the performance of the system, the energy levels were limited to the worst case image geometry, and for the most spectrally absorbent ink in the system. At this point, the lowest spectrally absorbent ink, and the highest volume ink combinations were tested with larger geometry images to ensure proper drying.

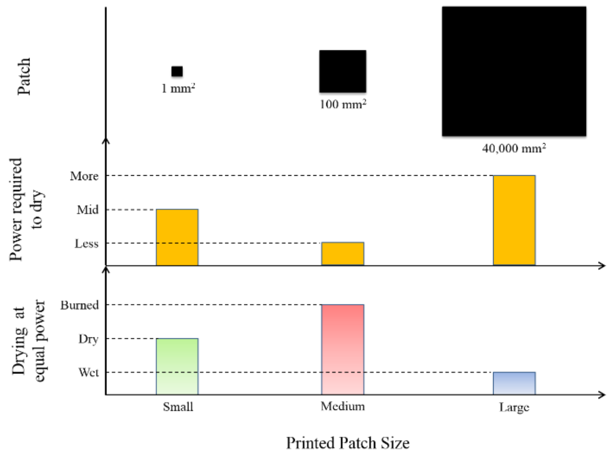

Fig. 4 Effect of printed patch size and drying.

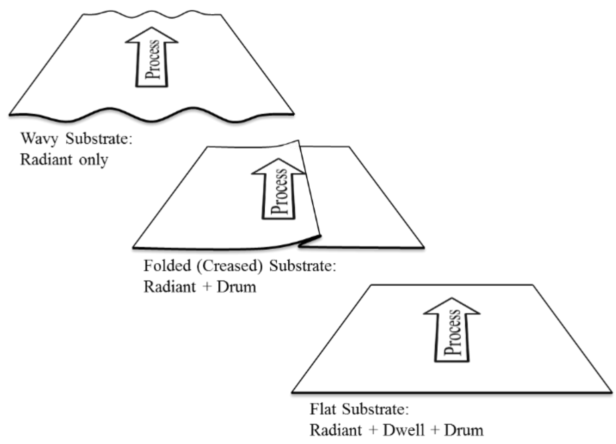

Fig. 5 Impact of subsequent drying/cooling processes.

Another challenge was discovered that was exhibited directly after the very intense radiant heating process, where the localized temperature differences in the areas of the printed page would create a wavy substrate due to the localized shrinkage. Large printed images would especially demonstrate a wavy substrate that was not acceptable for quality output. In order to counteract this behavior, a period of evaporative dwell time followed by a heated conductive roller proved to be highly effective at balancing the localized temperature differences within the page. When the heated conductive roller followed immediately after the radiant dryer, the waviness of the substrate would become permanent, and folding or creasing of the substrate was observed in extreme cases. Fig. 5 shows if an evaporative dwell time was implemented with high airflow in the region separating the radiant and conductive drying, then the temperature variations were reduced and waviness and folding did not occur. Instead, the conductive drum created two benefits. First, the high temperature, flat surface of the drum significantly reduced waviness in the printed page. Second, the extended period of elevated temperatures following the radiant dryer (added by the conductive rollers) increased the amount of ink that could be effectively dried[7)].

Although the quality of printed output and volume of ink that was capable of drying was improved greatly by the addition of radiant drying, and its use in conjunction with the evaporative cooling and heated drum processes, there were still many limitations within the specific implementation.

2-2 Combined Radiant/Forced Convection Drying

2-2-1 Theory of forced convection

When considering the imbalance of heating across multiple colored inks, it becomes apparent that the amount of energy collected by less spectrally absorbent inks is the limiting factor for a radiant drying system. One potential way to deal with this issue is to apply drying between the various color planes, printing and drying the lowest absorbing ink first such that it has multiple passes through radiant dryers. This method requires a grounds up design with this dryer in mind, and significantly increases the hardware cost and the paper path length. Instead of following this approach, a different goal was targeted: to increase the level of energy absorbed by the black ink before causing paper damage.

Forced convection is using high velocity air to transfer heat to and from a surface by driving an interaction of air molecules at the surface of a body. The driving force, similar to any type of heat transfer, is the difference in temperature between the fluid being used for its convective properties and the surface which is being heated or cooled. The larger the temperature difference between these two, the faster the heat is moved from one to the other. The rate at which heat is transferred from one material to another can be expressed as

$$q = \bar{h} A_S (T_S - T_\infty) \quad (1)$$

Where $\bar{h}$ is the average convective heat transfer coefficient, A_S is the surface area of the body, and T_S & T_∞ are the temperatures of the surface and the fluid respectively[8).

This concept was then applied to the heating process passing through a radiant dryer. If cool air is used to force convective heat transfer during the radiation process, the areas that are the hottest would lose heat at a much faster rate than relatively cooler areas. Therefore black, which reached significantly higher temperatures than other colors, would transfer significantly more energy, and the remaining colors would transfer energy at a slower rate. This method would allow for some of the variance in energy absorption by the various inks to be overcome and the localized temperatures to be more balanced. Ultimately this would enable more energy to be put into the other colors before creating problems on black printed areas.

A secondary benefit of implementing forced convection during the radiation process is the improvement of mass transfer from the surface of the printed page. As energy is applied to the printed surface it has two primary results; to increase the temperature of the absorbing material, and to convert the liquid ink suspension fluid into gas. The air that forms a boundary layer at the printed surface must absorb this gas, which is based on the difference in concentration of the vapor at the ink surface and in the boundary layer. If the air is relatively stagnant at the surface of the paper, it becomes saturated with vapor and the temperature required to evaporate the fluid becomes greater. Therefore, this can cause damage to the paper because of the rate at which the fluid must be removed from the surface for sufficient dryness. By adding forced convection and improving the ability for the liquid to vaporize at lower temperatures this prevents damage that could occur at the same energy input while also producing an improved overall dryness in the printed page.

A very efficient way to deliver forced convection that results in a high average convective heat transfer coefficient is by impinging jets. There has been much study on the geometry, spacing, and air velocity to get optimal heat transfer[9). This type of airflow also lends itself to wide width continuous form webs since the jets can be extended across the web and deliver relatively uniform airflow. For a slotted jet, the nozzle width, the distance from the surface of the substrate, the spacing between subsequent jets, and other factors must be taken into account for each specific implementation.

2-2-2 Implementation Technology

In order to incorporate a slotted jet into the radiant lamp configuration a design was developed to utilize airflow for both the jet and cooling of the emitter reflectors as shown in Fig. 6. This configuration improves the temperature balance at the substrate surface and is useful in cooling the reflector structure necessary for containing the high radiant energy emissions required for drying[10).

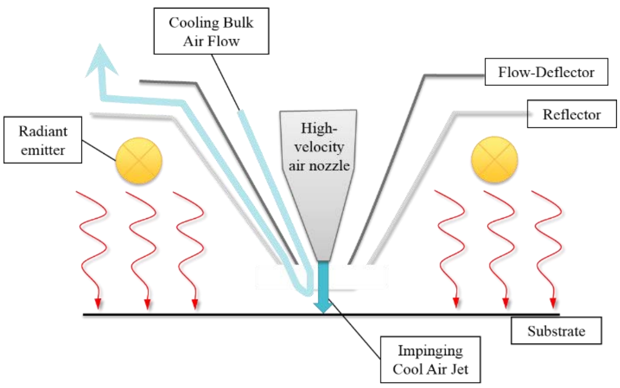

Fig. 6 Integrated lamp and jet design.

Other technologies were also developed to adjust the airflow based on the printed image in a localized region, or using alternate fluids (other than ambient air) to improve heat transfer properties[11,12].

2-2-3 Experimental Findings

Experiments were conducted utilizing a modified radiant drying system that was fitted into a large-scale continuous forms printer. An offset coated paper type was used to understand the impact and improvement of the addition of impinging jets to the radiant system. The lamp power was adjustable and also the flow of the impinging jets could be turned off and on. Following the radiated drying there was a heated conductive drum dryer similar to the previously tested configuration. This testing demonstrated the improvement that was expected by the addition of the jets but also a secondary benefit of dramatically reducing the wrinkling occurring by the high power radiant lamps on a relatively thin substrate. When printing with the exact same amount of radiant power and the same amount of printed ink it was observed that without the impinging jets the highly absorbent black printed images were completely burning through the paper. As seen in Table 1, once the jets were engaged the burning stopped and there was only slight discoloration on black images above a 50% gray level. This demonstrates a surface temperature change of up to 50°C because of the difference between the discoloration and burning temperature of paper.

Table 1 Effect of impinging jets on drying.

Test Configura-tion	Total Power (kW)	Discolora-tion (0-10)	Wrin-kling (0-10)	Drying Capacity (Ink Limit %)
A. Without Impinging Air Jets	11.19	10	5	160
B. With Impinging Air Jets	11.19	5	0	170

Another somewhat expected minor improvement was the increased drying capacity of the system with impinging air jets at the same radiant power output. Increasing the mass transfer rate at the surface of the paper allowed for more of the low energy absorbing inks to evaporate while keeping the black images relatively cooler.

By the addition of impinging air jets, improvements to drying and the amount of power that could be applied to a substrate without discoloration were improved. However, the total volume of ink dried was not sufficient for high quality printing targets on offset coated stocks. Further improvements would be necessary to meet overall print quality and color gamut expectations for applications transitioned from traditional offset presses.

2-3 Radiant/Forced Convection on Drum Surface

2-3-1 Theory of combined drying system

From experimental testing with the combined radiant and forced convection solution, it was apparent that the amount of power that could be input into the ink must be increased, while not elevating the highly energy absorbent ink (in this case, black) temperatures beyond the discoloration threshold. Due to the comparatively low heat transfer rate for forced convection with air versus conduction, and the slow rate of conduction from one printed area on the substrate to another, there needed to be another mechanism to dissipate the heat being transferred into the black areas. The geometry of a substrate leads to a design that employs a large heat sink applied to the opposite side of the paper. The distance heat must travel through the paper to reach the heat sink is relatively small compared to the distance that heat can travel laterally within the substrate to dissipate the same amount of energy. A large drum surface made from highly conductive material such as aluminum fulfills this role very well. As the ink surface of a highly absorbing color heats up quickly from the radiant emitter, a relatively large amount of heat is transferred to the reverse side of the page. If there is only exposure to natural convection in air then the heat will build up in the substrate until the temperature exceeds the discoloration threshold. The amount of time this takes to occur is not long enough for the temperatures of other color combinations to increase and be sustained at the elevated level in order for drying to complete. If the radiated energy is applied on the drum surface, then the energy that transfers through the substrate can dissipate into the drum material, and the temperature of the paper will remain lower for the same amount of energy.

In addition to dissipating excessive energy from the high absorbing printed areas, the drum spreads the heat across its surface and allows additional heat to be applied to lower temperature areas of the printed page. This will disperse more energy into these challenging color combinations, and ultimately result in improved overall dryness for the same power output. Finally, because there is a limitation to the amount of energy a heat sink can dissipate, the rate at which the energy is applied must be controlled such that the temperature level of slowly drying ink combinations can be held at a maximum level for some time, while black does not increase above the discoloration threshold. By tuning the rate of energy input into the page to hold black at a constant temperature while passing over the drum the best drying conditions for other ink combinations should occur.

2-3-2 Implementation Technology

When integrating radiant lamps external to a large drum surface a similar approach with combined impinging jets was used. An example of this is shown in Fig. 1. In order to extend the amount of elevated temperature exposure time a radiant preheating mechanism can be used prior to the drum so that the initial warm up of the substrate and ink is accelerated. Also in order to maintain adequate drying from the beginning of the printing process an internal preheating process is necessary to elevate the drum temperatures before printing begins. Depending on the amount of radiant heat flux acceptable into the inked surface versus the overall drum temperature, some internal cooling may also be necessary to maintain the drum temperatures within safety thresholds[13].

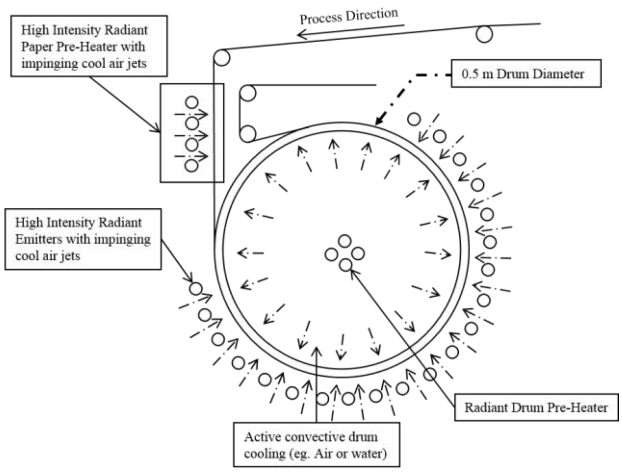

Fig. 7 Radiant and forced convection on drum surface.

2-3-3 Experimental Findings

In order to test the performance of the integrated radiant drying and forced convection on a drum surface, test fixtures for temporary mounting and airflow were designed and installed into an actual printing system. Although a full width integrated design was not possible, there was the ability to radiate the majority of the heated drum surface in a localized section of the web. Many trials were conducted to evaluate the optimal power application to achieve maximal dryness without damaging black areas of the printed substrate. The integrated impinging jets were also varied between on and off states and it was verified that the improvement found with this design was repeatable in this new configuration.

By applying the same amount of power per unit area as was applied in the radiation/convection configuration described in section 2-2 the amount of discoloration was dramatically reduced while still not creating any paper deformation such as wrinkling as shown in Table 2. Also, this power was applied in a shorter duration which further demonstrates the improved ability to keep printed black patches below the discoloration threshold. Beyond the ability to not discolor black, the maximum drying capacity was also improved. The amount of ink that could be successfully dried with the same applied power was improved 15%.

Table 2　Effect of conductive drum on drying.

Test Confi-guration	Power Density (kW/m^2)	Power Density Rate (kW/m^2s)	Dis-color (0-10)	Wrinkle (0-10)	Drying Capacity (Ink Limit %)
C. Radiate Before Drum	103	121	5	0	170
D. Radiate On Drum	103	141	0	0	200

Other experimental testing was conducted to investigate the rate at which radiant energy is imparted to the printed web. While experiment D. of Table 3 allowed for significant additional drying capacity, the desire is still to further improve this capacity to enable a broader range of colors to be dried successfully. In order to accomplish this, the total power that can be applied to the substrate must be improved. However, for the specific configuration, the black temperatures were already at the threshold of substrate discoloration. By decreasing the rate at which power is applied and extending the exposure time, the total amount of power applied was improved by 55% while still maintaining no substrate discoloration at black printed images. This resulted in the amount of ink which was successfully dried to increase by 30%, as shown in Table 3. This is a drastic improvement from the initial tests of radiating before the drum, with reduced black temperatures. Research has shown with a printer ink limit of 200% more than 90% of the colors in gamut are printed accurately with appropriate color management. For 260% ink limit, more than 99% of the colors in gamut are printed accurately[14].

Table 3　Effect of power density rate on drying.

Test Configu-ration	Total Power (kW)	Power Density Rate (kW/m^2s)	Dis-color (0-10)	Wrinkle (0-10)	Drying Capacity (Ink Limit %)
E. Radiate On Drum (Short Exposure)	9.59	141	0	0	200
F. Radiate On Drum (Long Exposure)	14.92	40	0	0	260

3. Mathematical Model for Web Drying

3-1　Theory of Mathematical Model

In order to better understand the interaction between various heat transfer mechanisms and the process of drying ink, a mathematical model was developed. This model is meant to aid in understanding the relationship between the various types of heating processes that could be performed simultaneously or in series. The model maintained assumptions of constant temperature conductive heating from a drum surface and a constant average convective heat transfer coefficient within each defined region of drying. Also, the initial implementation assumed that only the aqueous portion of ink would be evaporated due to the lower achievable temperatures without radiant lamp drying. The structure of the substrate/ink composition is assumed to be a uniform thickness of substrate and ink based on the percent coverage of defined maximum ink volume. The initial ink chemical composition is determined by the chemistry of each specific ink type and as solvent within the ink is evaporated by heating, the chemical composition and related properties change accordingly. During the first phase of drying, drum conduction is applied to the nonprinted side of the substrate and heated forced convection is applied directly to the printed surface. An elevated temperature dwell time is held after the initial drying where natural convection drives heat transfer through both surfaces of the substrate.

By balancing both the energy and mass entering and exiting the system, we can define the governing equations for the drying process. The first source of energy entering into the system is the heat conducting into the substrate from the drum surface which is defined as

$$q = \frac{1}{R_{tot}} \Delta T \tag{2}$$

Where R_{tot} is the sum of all the thermal resistances and ΔT is the temperature difference between the materials[8]. For this case, the thermal resistance is composed of contact resistance between the drum and substrate, which is derived from empirical measurement, and the ink, which is derived from the individual chemical components and their instantaneous phase thickness. The next source of energy entering the system is from heated forced convection air from impinging jets. The governing equation for this convection is from equation (1). Finally, a source of energy exiting the system is that which is lost to evaporation, which can be determined by

$$q = \dot{m} h_{fg} \tag{3}$$

Where $\dot{m}$ is the rate of evaporation and h_{fg} is the latent heat of evaporation of the evaporating solvent.

All of these energy components must equal the rate in which the stored energy in the system is changing. This is the time rate of change of the system mass, system specific heat, and the Temperature

$$\frac{d}{dt}\left(m_{sys} c_{p-sys} T\right) \tag{4}$$

With the assumption that the system mass and specific heat are changing very little relative to the temperature change. By incorporating the components together, the first ordinary differential equation becomes

$$\frac{dT}{dt} = \frac{\bar{h} A_s}{m_{sys} c_{p-sys}} \left(T_{air} - T\right) + \frac{1}{R_{tot} m_{sys} c_{p-sys}} \left(T_{drum} - T\right) - \frac{\dot{m} h_{fg}}{m_{sys} c_{p-sys}} \tag{5}$$

The second equation constraining the system is the conservation of mass. The mass that is driven away through evaporation must be equal to the change in mass of the fluid. Since the boundary layer concentration is the driving principle in the rate of evaporation, the mass transfer coefficient is analogous to the average convective heat transfer coefficient. Using the mass transfer rate equation and the Chilton-Colburn analogy from heat to mass transfer the equation is defined as

$$\dot{m} = \left(\frac{\bar{h}}{\rho c_{p-air} Le^{2/3}}\right) A_s M \left(C_{ink} - C_{air}\right) \tag{6}$$

Where ρ is the gas density, c_{p-air} is the specific heat of the drying air, *Le* is the Lewis number, the ratio of thermal to mass diffusivities, A_s is the effective surface area, *M* is the molar mass, and *C* is the concentration of solvent in the ink and in the air. Since all equations are normalized by surface area to understand drying at each point of the printed sheet, the effective surface area can be defined as a ratio of the volume of solvent in the ink at any given time.

The mass transfer can be related to the changing thickness of the ink layer. Also, using the ideal gas law and taking into account the interaction of the solvent within the greater mixture of ink to reduce the effectiveness of evaporation, we arrive at

$$\frac{dx_s}{dt} = -\frac{\dot{m}}{\rho_s A_0} = \frac{1}{1+\frac{x_k}{x_s}} \left(\frac{\bar{h}}{\rho c_{p-air} Le^{2/3}}\right) \frac{M}{\rho_s R_u} \left(\frac{P_{air}}{T_{air}} - \frac{P_s x_s M_s}{T_s x_k M_k}\right) \tag{7}$$

Where x_s is the material thickness of the evaporated substance and x_k is the thickness of the entire ink composition layer. R_u is the universal gas constant, $x_s M_s / x_k M_k$ is the mole fraction of solvent to ink, P_{air} is the partial pressure of the evaporated substance in the drying air, and P_s is the saturation pressure for the same substance. Assuming a continually resupplied source of drying air from ambient conditions, P_{air} remains fixed but P_s is a function of the solvent temperature. Additional details for defining the equations can be found in A. Avcı et al[15].

All of the detailed constants are defined by the exact system of chemical components in the ink, ambient environmental conditions, volume of ink dispensed by the printer, specific material properties of the substrate used, as well as the driving temperatures and durations of the drying processes. A numerical solver for a system of differential equations is used to simultaneously find the thickness of ink remaining and the temperature at the surface of the ink. This is performed while considering a constantly changing ink composition and associated physical properties.

Fluid flow analysis of a specific hardware configuration can be used to determine the average convective heat transfer coefficient, $\bar{h}$. Using simulation to achieve the often difficult task of determining an analytical solution for $\bar{h}$ is very important for getting an accurate representation of a system in the results of the model.

As this initial model implementation showed promise for predicting the level of water remaining in an aqueous ink solution that was printed on a substrate, it did not show over time how ink on paper would ultimately dry. It also did not accurately show that ink, even after all water is evaporated, may not necessarily be deemed dry due to other fluid components in the carrier fluid. It is for this reason that a secondary source of change, besides drying, was added to the model, namely ink penetration into the semi-nonporous substrate.

The rate at which ink penetrates into paper, which behaves as a system of capillary pores, is highly dependent on the specific substrate. The Washburn equation describes this type of penetration for fully wetted capillaries as

$$L = \sqrt{\frac{R\gamma\cos(\theta)t}{2\eta}} \qquad (8)$$

Where L is the penetration depth into the capillary pores, R is the capillary radius, γ is the surface tension, θ is the capillary channel contact angle, t is the time, and η is the dynamic viscosity. In order for this equation to be accurate, a substrate would need identically shaped pores and distribution of fluid on the surface. This is not the case, so the specific capillary channel properties cannot be used. Instead, this is used as a model where the effect of dynamic viscosity of the ink can be utilized and, based on experimentation, the ultimate rate of penetration can be modeled[16].

Using this type of fluid flow model as a rate and changing it to represent the change of ink height at the surface of the substrate where the total remaining ink volume can be modeled, we see that

$$\frac{dx_p}{dt} = \frac{\varepsilon\gamma cos\theta R}{4\eta} = \frac{\varepsilon^2\gamma cos\theta R}{4\eta x_p} \qquad (9)$$

Where x_p is the ink height which has penetrated into the substrate and ε is the void fraction. The void fraction is the percent of the surface area that is capillary channels. Initial conditions for x_p have to be described at the beginning of the drying process, which has allowed for an initial amount of ink to wick into the substrate since the printing process. This does not take into account the change in penetration rate as the composition on the surface is becoming more filled with solids. The solid volume fraction remaining on the surface restricts the flow of ink into the substrate. When the solid volume fraction becomes unity on the surface, the flow rate of ink into the substrate will stop. The previous equation then becomes

$$\frac{dx_p}{dt} = \frac{\varepsilon^2\gamma cos\theta R}{4\eta x_p}\phi_f \qquad (10)$$

Where ϕ_f is the volume fraction of fluid remaining in the ink. This must be solved with the temperature dependence of viscosity included so that the correlation of heat transfer and penetration rate can be accounted for.

Now, this equation is solved simultaneously with the heat transfer and mass transfer equations. The total ink thickness remaining on the surface of the substrate is effected by the mass being evaporated and the mass being absorbed by the substrate. In order to properly understand the substrate specific impacts on fluid penetration, experimental testing at fixed temperature is conducted to populate the physical property constants for penetration rate. Once these constants are determined and plugged into the mathematical model then overall drying rate accuracy is improved.

3-2 Model Results vs. Experimentation

The mathematical model was then used to compare various system parameter effects on the level of final dryness of the printed page. The importance or limitations of improvements to different areas of the drying process could be better understood without making changes to the actual printed configuration. These tests could be validated in concept and then used to improve focus areas for future improvements. For the specific configuration that was available for experimental validation, the parameters that could be modified were number of impinging jets, temperature of impinging jets, and temperature of heated drum dryer. The level of dryness would be measured based on ink being able to transfer from the printed sheet to another sheet under pressure after printing.

For a given printing system, energy can be used to elevate the temperature and pressurize impinging jets. Energy can also be used to further elevate the surface temperature of a heated drum. The model can predict the effectiveness of these choices with the output of dryness levels. Energy can be applied through the most effective method to have the best final dryness. The model was used to create Fig. 8, where for a given printing system dryer it would require roughly equivalent energy to maintain 5 full width impinging jet nozzles at a temperature of 100°C and a drum surface temperature of 100°C or to only use 4 full width impinging jet nozzles at a temperature of 80°C and a drum surface temperature of 120°C. By modeling these two cases and an intermediary case, the model predicts that the dryness with elevated drum temperature will produce a drier final output for a given amount of printed ink on the surface, as given by the remaining fluid volume on the sheet. From this data we can see that the rate at which the temperature increases is improved with elevated dryer temperature, and it is the length of time the sheet is held at this temperature that is most critical to fluid decrease.

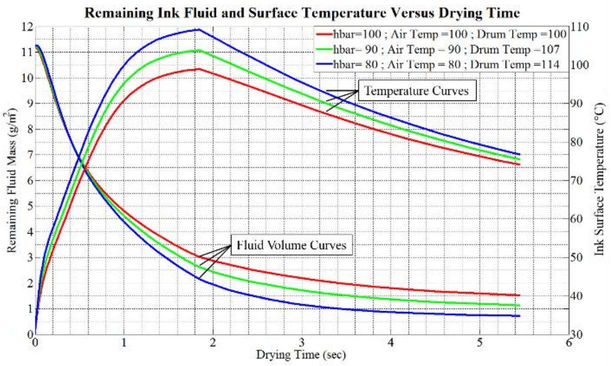

Fig. 8 Model result of drum temperature versus impinging jet temperature and drying.

The data generated by the model was validated by using a printing system to control the various temperatures and the number of active impinging jets. To access dryness immediately after printing, a 50 kPa pressure is applied for 12 hours to mimic potential conditions applied to a printed sheet in either a large stack of individually cut pieces or a large roll that may be resting on the floor. A blank piece of substrate that is pressed against the printed sheet under known pressure is then measured for a % color change from ink offset in La*b* color space and compared to the original blank sheet. The printed pattern that was used is the worst combination for drying at a specific ink volume with regards to a printing system. This accurately establishes a threshold for dryness that can be correlated with a volume of remaining ink after drying. A full correlation is necessary but changes below 2% are considered dry or no perceivable offset. Other model validation was conducted and checked versus threshold for color change % by changing the printer speed and modifying the amount of ink placed on the printed page. Good correlation was found for multiple printed and model parameter configurations.

Table 4 Model prediction vs experimental results.

Test Case	Drum Temp (°C)	Air Temp (°C)	% Total Airflow	Model Prediction Ink Remaining Mass (g/m^2)	Experimental % Color Change Ink Offset
1	114	80	80	0.72	0.85
2	100	100	100	1.53	3.09

Beyond the temperature, amount of airflow, and the trade off with using the energy to elevate the drum temperature, the model also was used to determine the impact of other variables. Recirculating heating air to elevate impinging jet temperature at the cost of increased air humidity was modeled. The effect of increased cavity temperature at the expense of reduced exhaust ventilation was also modeled. It was found that because of already highly elevated temperatures, the saturation pressure in the drying air compared to the pressure at the ink/air interface remained high. The temperature of the drying air did not have nearly as much of an impact on drying while on the drum because of the improved heat transfer efficiency through conduction. This meant that energy used to elevate the drum temperature had much greater final impact on drying ability as demonstrated in Table 4. Because of the temperature and time dependency of both evaporation and penetration, the key point to achieving successful drying is to achieve high temperatures and maintain them for some time. The model also allows for much flexibility to determine success of a specific configuration based on printer speed (drying time), amount of ink printed in various color mixtures, environmental conditions, and many other factors which can be used to understand the impact on final drying level.

4. Conclusions

4-1 Combined method drying system

Through many iterations of experimental drying configurations, a successful pattern to integrating various drying methods was discovered. Radiant lamps showed the ability to greatly improve the drying ability compared to a conductive-only drying solution. However, using just radiant lamps caused deformation from localized paper shrinkage. A combination of high powered heating, high airflow dwell time, and sustained elevated temperature on a drum delivered superior quality print output. The high power input into the printed surface was desirable from radiant lamps, but the variation between the different colored inks caused issue with adequately drying all color combinations without overheating other areas. The addition of impinging jets to reduce the surface temperature of the ink and promote mass transfer delivered improvement from the variability between colors but still did not overcome many of the limitations. Finally, the integration of a combined radiant energy/ impinging jet solution onto a heated drum surface delivered a much improved performance from any of the individual solutions or any combination of these in series.

A model was developed to understand the impact of various configuration and environmental/chemical conditions that affect overall dryness. This model has begun to be experimentally confirmed with the tradeoff of applying heat through heated impinging jets or conductive drums. The model and experimental results demonstrated that elevating the ink temperature is the primary improvement in drying and that the conductive drum is the best method to do this between conduction and convection; even while operating simultaneously. Many other system impacts, such as recirculation of drying air and elevated dryer cavity temperatures, will be modeled and verified to see the sensitivity to overall system drying.

4-2 Future experiments and modeling

Next steps for improving the current drying system and understanding the experimentation that is necessary to progress is to integrate radiative drying into the mathematical model. This will need to incorporate how individual and mixed inks combine to form a specific absorption spectrum. The energy absorbed by the system will then become dependent on the image printed as well as the specific emission spectrum of a radiant configuration. Other improvements to the model will also become necessary at this point because of the elevated temperatures that will be achieved by the radiative drying process. There will now be humectants that will reach temperatures for evaporation that were not previously considered. This will change the chemical composition of the ink at the air interface at a faster rate and will be more volatile. Also, improvements to the penetration model will be considered so that a standardized paper test method will be able to determine necessary variables for penetration rate so that many papers can be modeled without needing extensive empirical testing.

Also, energy requirements and hardware costs can be associated with different contributing drying factors to help determine a most cost effective way to achieve a drying goal. This additional data from the model will allow for testing of future drying configuration to optimize the energy input versus the drying output.

Vast improvement from traditional single method drying techniques have been verified and, with improved understanding of tools and energy cost tradeoffs, more improvements will continue.

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