Design and Operational Characteristics of a High-Speed Contactless Fuser

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Abstract

Océ's VarioStream 9000 series of high-performance digital production printers features a non-contact fusing unit with unique properties. The printer's dual-engine architecture and simultaneous-duplex capability posed a challenge for the selection of the best suited fusing technology. Another challenge were the printer's changing paper movement modes due to its multi-pass operation. Monochrome printing runs with steady web motion, while dual, triple, and full-color print modes require the web to run, stop and retract in a multitude of fashions depending on the actual document content. The process speed must be adaptable to the requirements of light and heavy paper stock and special media.

Traditional hot-roll fusing in combination with contact pre-heating was ruled out for the obvious reason of process incompatibility and high running cost. Contactless infrared fusing held the promise to meet the abovementioned challenges. Other pros were its durability, wide operating range, and low TCO figures. Shutter curtains allow for waste-free printing in continuous and noncontinuous printing modes, even when the web starts and stops periodically every few seconds. A web cooling section effectively suppresses hot offset on drive rolls and blocking of printed material. While the printed web runs through hot and cold process sections the respective atmospheres are kept separate by means of support rollers. If required, these can be actively engaged to smoothen the surface of the soft toner image.

Process control employs pre-set parameters in start-up situations and a bunch of non-contacting sensors for infrared power and web temperature control.

The fusing unit is able to process papers from 40 g/m² to 160 g/m² with full speed (1 m/sec) and up to 240 g/m² with reduced speed. Toners with tailored rheological properties have been developed to achieve good balance between power consumption, process time, and web dehydration. The fusing process delivers excellent toner adhesion and crease resistance for a wide range of media.

This paper also gives a breakdown of the physics involved in design and operation of the fusing system. Radiator types, print media, toner properties, and heat transfer are discussed. Engineering aspects like shutter movement, power control, safety concept round off the picture.

Background

The requirements of the fusing unit presented in this paper are closely coupled to the concept of a digital production printer whose foundations were laid in the mid-90s. The printer family, branded Océ VarioStream 9000, is available in several configurations. Figure 1 shows a schematic cross-section of the system. We will use it as a guideline to explain the operating principle of the printer and of the fusing unit.

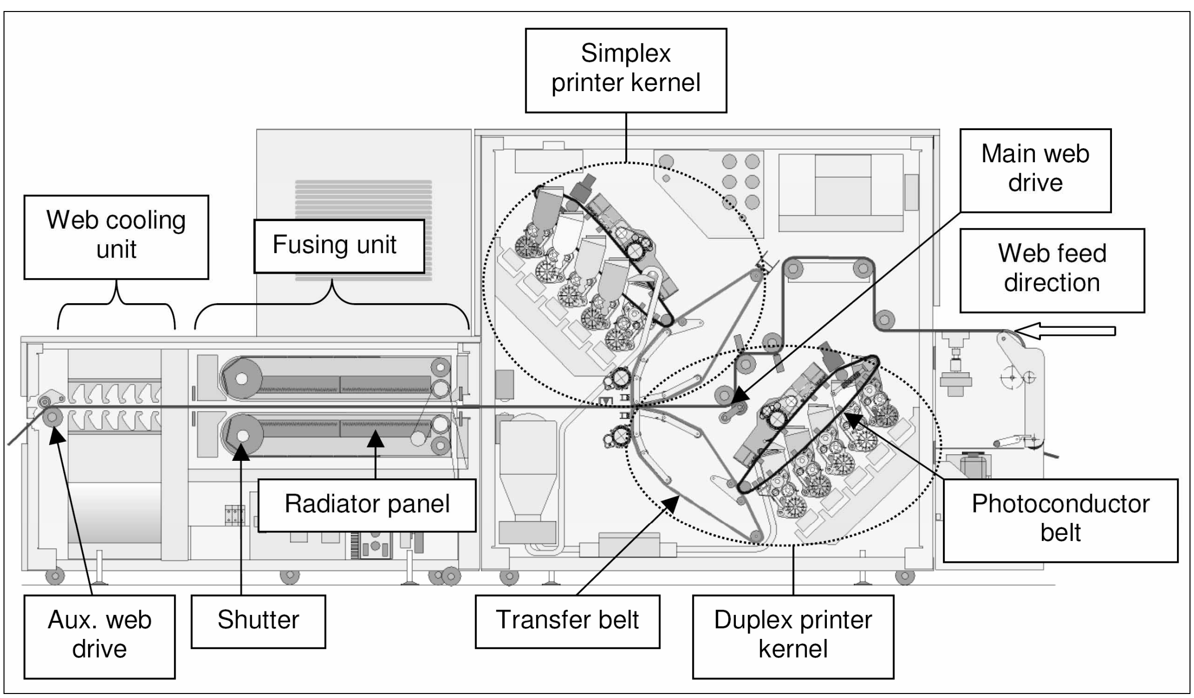

***Figure 1**: Cross section of a VarioStream 9000 prototype printer*

The goals set for the new printer were as follows:

- Single- and multi-color capability
- Highest performance in black, good performance in multi-color modes
- Simultaneous duplex printing
- Very low consumables and maintenance cost
- No paper waste
- Print quality close to offset print

A market analysis gave us confidence that the mainstream of digital print output would be black-and-white in the mid-term and that migration into color applications would take several years. Customers would only pay for the extra color capability if they had the option to use it flexibly without the overhead cost of a full-color machine. As a result, the VarioStream 9000 series was designed as a single-pass black-and-white duplex printer with a flexible set of multi-pass color operating modes. Since we are talking about a web printer there are consequences for many parts of the machine, especially for paper transport and fusing unit.

As can be seen in Figure 1, there is one electrophotographic kernel for each face of the web. The kernel consists of a photoconductor belt with its surrounding components, and a transfer belt with some auxiliary engines.

In black-and-white operating mode a continuous stream of images is generated and developed on the photoconductors, transferred to the transfer belts and – once again – transferred to the steadily moving web.

In all color operating modes each color plane is generated separately on the photoconductor belts and sequentially transferred to the transfer belts while the web stops and waits until the desired number of color planes has been collected. Then the web speed will ramp up and the collected image is transferred to the web. If more multi-color images are to follow, the web stops, retracts and stops again to wait for another collected image. The photoconductor and transfer belts have a circumference of roughly 1,700 millimeters; which is sufficient for processing five 12-inch pages in one collecting cycle, for instance. Depending on the customer's color needs the printer can be equipped with up to five developer stations per kernel.

Selecting a fusing method

At the time of project definition we had working experience and experimental results with several fusing methods for thermoplastic toner. Table 1 gives an overview of the pros and cons for each basic principle in the light of above goals.

Principle	Pros	Cons
Hot roll	• Proven technology • Reliability • Image smoothness	• Pre-heating required for high speed • Consumables cost (rolls, fuser oil) • No simultaneous-duplex capability • Limitations with very light paper grades
Solvent	• Very wide range of substrates • Low temperature process, no dehumidification	• Explosion hazard with "green" solvents • Ozone depletion potential with non-explosive solvents
Microwave radiation	• Switchable • No moving parts • No consumables	• Bulky equipment • Electromagnetic compatibility issues
Xenon flash	• Very wide range of substrates • Compact unit	• High consumable cost • Ozone generation • Color compatibility needs special absorbants in toners • No proven simultaneous-duplex process
Hot air	• Wide range of paper grades • No consumables • Simultaneous-duplex capability • No color sensitivity	• Air valves needed for dynamical control • Bulky engine • High noise level • Very long unsupported web path
Infrared radiation	• Wide range of paper grades • No consumables – lowest operating expenses • Simultaneous-duplex capability • Low color sensitivity with appropriate wavelength	• Mechanical shutters required for dynamical control • Long unsupported web path

***Table 1**: Fusing principles*

Obviously only a contactless fusing system would meet the requirements, because any kind of contact fusing was ruled out by the discontinuous web movement that comes along with multi-pass operation. We did not want a contacting fusing element to disengage from a semi-fused image. Solvent fusing would have been an interesting option, but with the risk of acceptance problems and future legal restrictions of substances. Color capability and simultaneous-duplex operation ruled out flash fusing, and the intricacies of microwave radiation were regarded as too risky. So we ended up with infrared radiation and had to develop all the subtleties to make it work with a discontinuous, multi-modal printing process.

Basic considerations of radiation fusing

In order to effect contactless fusing, toner particles and their substrate neighborhood need to be heated to a point where the toner resin liquefies and spreads on the substrate driven by capillary forces. On paper substrates the resin penetrates the pores and wets the fibers of the paper felt. The result is a very stable bond between toner and almost all substrates.

Radiation sources

Many technical processes rely on heat absorption from a radiation source. Most of these processes are of a quasi-stationary nature with rare interrupts. Our challenge was to find an economical solution for our multi-modal print process which relies on stop-and-go web movement whenever more than one color has to be printed. For practical purposes electricity was the only energy source to be considered; therefore many kinds of electric heaters had to be checked for their suitability.

Some basics on radiating heat

The most common radiator designs can be approximated by a black body radiator's characteristics. For the following discussion it helps to recall the underlying physics.

The total power output of an ideal black body radiator follows Stefan-Boltzmann's law (1):

$$P_S = \sigma A T^4; \text{ with } \sigma = 5.996 \cdot 10^{-8} W m^{-2} K^{-4} \qquad (1)$$

and emitting area A, absolute temperature K.

The emission spectrum of a black body radiator follows Planck's law (2):

$$dP = \frac{2hc_0^2}{\lambda^5} \frac{1}{e^{\frac{hc}{kT\lambda}} - 1} A d\lambda \qquad (2)$$

Figure 2 plots examples of the radiation emitted across a wavelength interval for a given absolute temperature of a black body. The diagram also illustrates Wien's law (3), which gives the most intense wavelength for a certain absolute temperature:

$$\lambda_{\max} = \frac{\alpha}{T}; \text{ with } \alpha = 2.898 \cdot 10^{-3} mK \qquad (3)$$

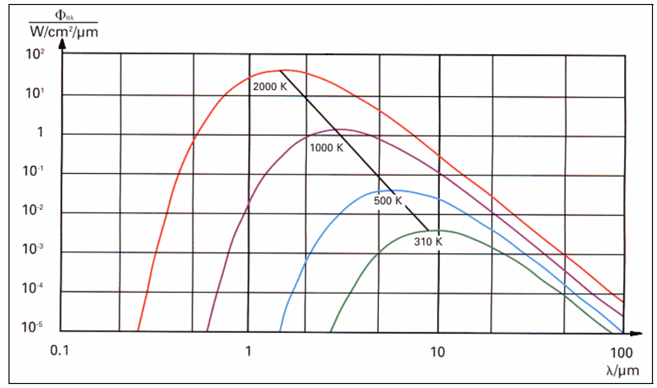

***Figure 2**: Emission power versus wavelength of black body radiators with different absolute temperatures*

Real emitters

Real emitters are somewhat different from the ideal black body radiator, and we have to know their spectral emission characteristics to judge their usability for radiation fusing. A second important aspect is the absorption characteristics of the web – paper in most instances – and of the different toners to be fused. The radiator has to heat the web in the most efficient way with negligible differentiation of the toner colors. Figure 3 shows the spectral absorption of some toner samples and paper. From this diagram it becomes clear that the paper web itself must be heated to fusing temperature in order to achieve good fusing conditions for all toner colors, and that the heating should be done with infrared radiation in the IR-C range.

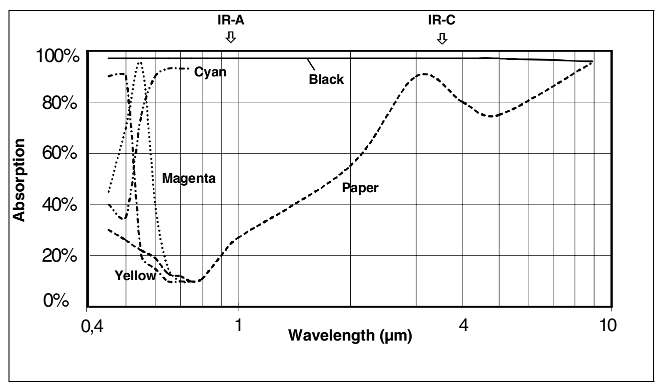

***Figure 3**: Spectral absorption of black, cyan, magenta, yellow toner samples, and paper*

Figure 4 gives an overview of the radiation spectra of commercially available infrared sources. According to the criteria stated above, only the ceramics radiator type seems to fit. But there is one disadvantage: Radiators of this type do not lend themselves to dynamic control; therefore a different type was chosen and finally approved.

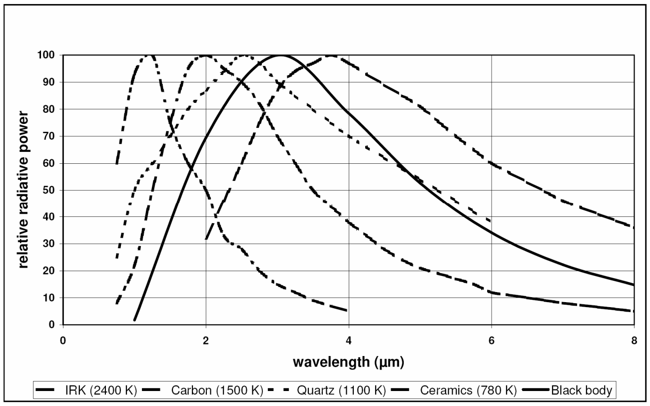

***Figure 4**: Relative spectral emission of various infrared radiators*

Corrugated metal strip radiator with ceramics backing

After thorough investigations we arrived at a solution which offered a good compromise between spectral emission, dynamic control, durability, and cost. A flat ceramics block is equipped with corrugated strips made of a special alloy. A thin ceramics textile layer keeps the strips at a small distance from the block to suppress conductive heat flow. The metal strips are interconnected and grouped to work with different web widths and source voltages. Figure 5 shows an experimental radiator panel.

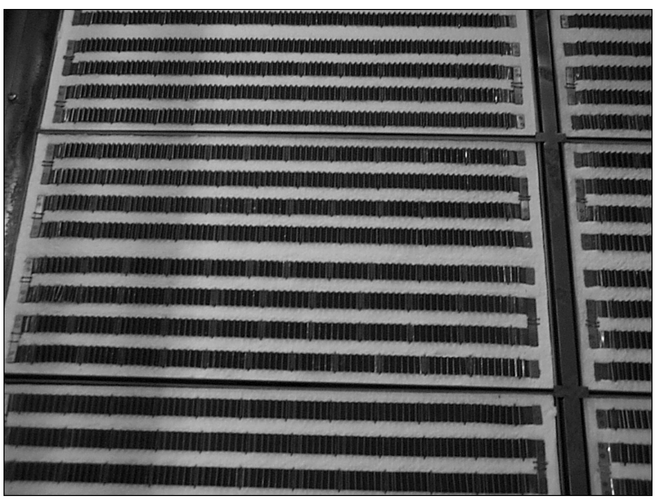

Figure 5: Radiator Panel

This radiator type can be tuned to achieve the desired power per area output by varying the strip width, corrugation factor, and strip density. In our example, a radiator area of approximately 0.8 x 0.5 m² is used for each face of the web. At a peak wavelength of approximately 3µm, the total power output lies in the range of 36 to 40 kW. This output power is sufficient for fusing images on paper web of up to 160 g/m² at a speed of 1 m/s. How and where a major fraction of this power is consumed can be derived from Figure 6.

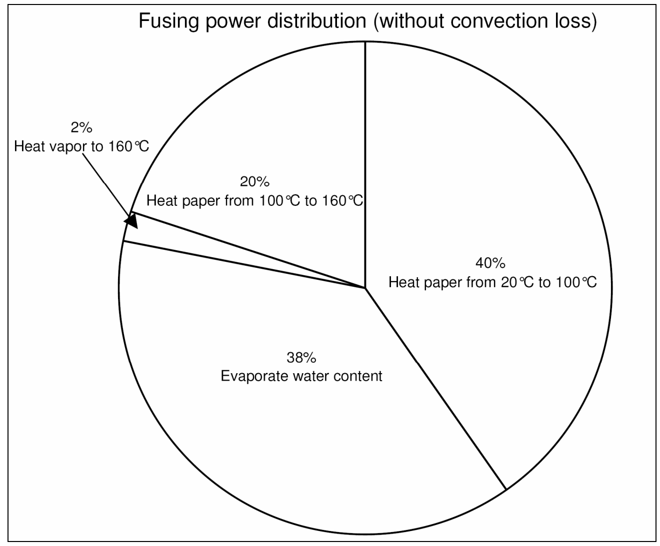

***Figure 6**: Power budget of IR fusing with paper web*

Temperature differences between black toner and white paper due to spectral absorption have bee investigated experimentally. Lower temperature differences mean less influence of toner color on fusing quality. A comparison of the color differentiation for the radiator types of Figure 4 and the metal/ceramics radiator is shown in Figure 7. The longer the peak wavelength, the smaller the exit temperature range of toner surfaces.

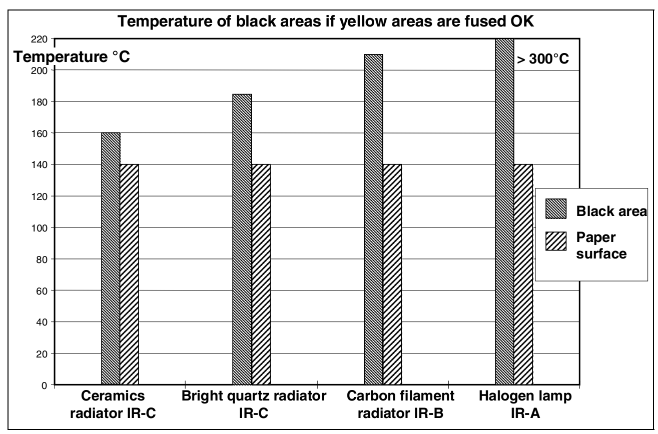

***Figure 7**: Exit temperatures of paper and black toner for good "yellow" fusing conditions with different radiator types*

Toner characteristics for infrared fusing

Because the forces acting in hot roll and infrared fusing processes are fundamentally different, the toner characteristics should be, too. For hot roll fusing the toner needs to soften under heat to make it easily deformable, but not as much as to cause hot offset on the fuser rolls. For infrared fusing, hot offset is of minor importance, instead the toner is required to become "self-flowing" under heat to achieve good wetting of the web. Chemically spoken this different behavior can be achieved by different degrees of cross-linking of the resin. The effect of such modifications can be seen in Figure 8. In the targeted fusing temperature window, an IR toner's dynamic viscosity may be about an order of magnitude lower than that of a hot roll toner.

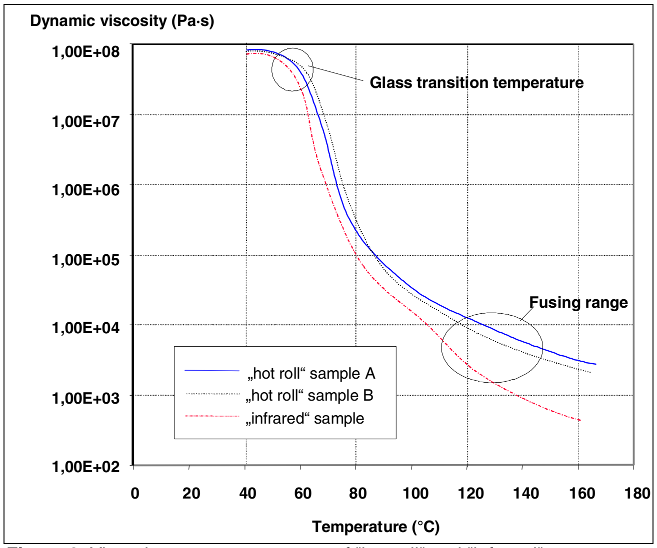

***Figure 8**: Viscosity versus temperature of "hot-roll" and "infrared" toners*

Fuser device concept for discontinuous web movement

The goal to print waste-free with varying forms lengths and color planes poses the question of how to control the incident radiation in a repeatable and reliable way. Because the radiator panels keep emitting stored heat for a while after the power is switched off, shutters are required to block radiation temporarily from the web during the printer's phases of multi-pass image generation and collection, and during forced stops. The final design features concatenated double-walled segments which are moved by tooth belts in a curtain-like fashion. Figure 9 shows an image of closed shutters in a test engine.

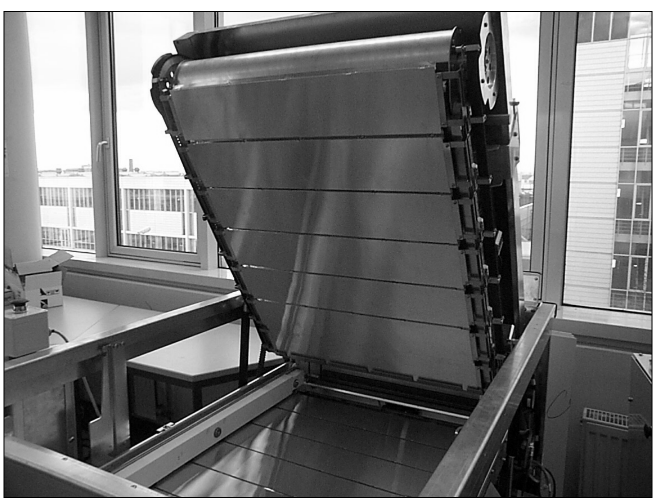

***Figure 9**: Closed shutters in a test engine*

In contactless fusing it is absolutely necessary to prevent the web from touching mechanical parts throughout the fusing and cooling sections of the printer. This is achieved by two drive systems for web motion control. The main drive sits upstream of the electrophotographic kernels and governs all forward and backward movements of the web. An auxiliary drive sits downstream of the web cooling section and maintains steady web tension by torque control.

Power control

Several factors influence the fusing power requirements. Some of them are listed below:

- Web input temperature
- Web area weight
- Web water content
- Surface coatings
- Web speed
- Pre-set fusing level by operator input
- Run time of the fusing unit

In order to maintain uniform fusing results, closed-loop temperature control is employed.

While the web moves, several contactless sensors are sampling its exit surface temperature. Filtering and plausibility checks make sure that emission differences between blank and printed surfaces are suppressed. The target temperature is maintained by pulse width modulation of the AC power going to the radiator strips.

This concept works well for equilibrium conditions of overall device temperature and continuous black-and-white print mode. Starting conditions after a web stop require special control parameters for the first few seconds of web movement. In discontinuous print modes things get more complicated, and a mixture of theoretical considerations and empirical knowledge is used to keep the exit temperature on track.

Shutter and web movement optimization

Printing in continuous and multi-pass mode poses a special challenge for fusing process control. One principal target is to maintain uniform web exit temperature under all conditions. Three control systems have to interact properly to approach this target: Radiator power control, shutter motion control, and web motion control. The only feedback comes from the web exit temperature sensors.

For a better understanding of the complexity a description of a dual-pass cycle follows:

- The web has come to a standstill after the previous cycle; to achieve high print performance and good positioning accuracy from page to page, the web retracts as soon as the transfer is finished. One part of the image is fused, the remaining part of the image is still unfused with a partly fused strip inbetween
- The transfer belts are disengaged from the web
- The shutters are closed
- Radiator power is kept at a constant level
- The printer kernels produce a 2-over-2 image by rotating the photoconductor and transfer belts synchronously twice
- Towards the end of the second rotation, the web ramps up to meet the beginning of the image on the transfer belt while the transfer belts engage with the web
- The shutters move into open position when the partly fused image strip arrives at the fuser chamber

- The web and all belts are running at constant speed for one belt circumference or less, depending on the page length; in the meantime a new image developing cycle starts on the photoconductor belts
- After image transfer, the transfer belts disengage, the web speed is ramped down, the shutters move into their closed position, and the web is retracted to prepare for the next ramp-up

So far, the state transitions look logical and easy to handle. Things get tricky if the radiator power is reduced to avoid overheating of the shutters, or if the shutters heat up and become secondary radiators by themselves. The borderline between irradiated and non-irradiated sections of the web is not well-defined, but blurred, etc. A lot of modeling, experiments and empirical optimization has been done to compensate for other less obvious side effects.

The interdependencies of shutter and paper ramp-up timing have been studied extensively. Figure 10 shows an example how uniformity in terms of cumulated radiation can be achieved by variation of web retraction and shutter movement timing.

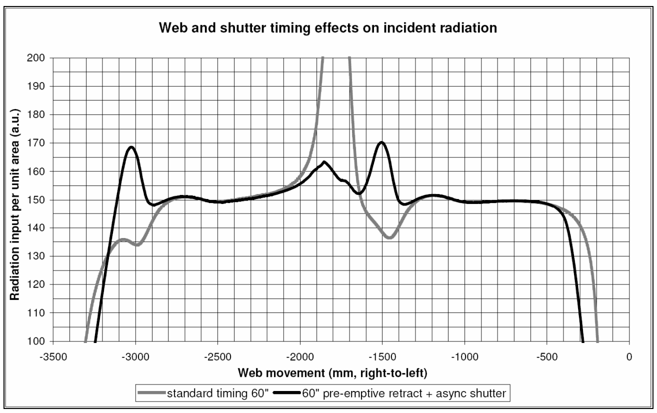

***Figure 10**: Timing optimization for uniformity improvement*

Web cooling

The web leaves the fusing chamber with a temperature of up to 150°C. It must be cooled to a temperature of less than 70°C before the exit drive rolls can touch the surface without the risk of hot offset. Cooling is done by powerful air blowers; slit nozzles accelerate the air stream towards both faces of the web in order to break the boundary layers.

Smoothing rollers

During prototype testing it turned out that pressure differences between hot and cold sections of the fusing unit caused unwanted flow of hot air into the printer kernel. A separating member was required to block the air flow along the web surfaces. A small-diameter PTFE-coated roller pair is now integrated between the fusing chamber and the cooling section. To avoid hot offset, a thin silicone oil film is applied to the roller surfaces.

During experiments we found that wear resistance and image gloss could be improved when the rollers are pressed against each other with increased line force. The pressure flattens the still soft toner surface after fusing and can be varied according to the customer's needs.

How to make it safe

During operation the surface temperature of of the radiator panels rises up to 800°C. If the web breaks or if power failure leads to a stop the web must be shielded from the radiators immediately to avoid web damage. A two-level safety concept was implemented into the printer to cope with all possible failure modes.

A basic hardware layer detects failures fast and without control interaction. A scatter light detector detects overheated paper independently and leads to the closing of shutter flaps by loaded spring actuators. Damage to printer parts and outside the printer can thus be avoided.

A second software layer monitors the process parameters closely to detect safety hazards as early as possible. The damage of paper web can be almost excluded by this means.

Conclusion

Simultaneous-duplex web printing in variable continuous and non-continuous modes poses various challenges for design and operation of an associated fusing process. A contactless fusing unit was developed which is characterized by a unique combination of infrared radiators, mechanical shutters, and sophisticated motion control, hereby ensuring high performance and low TCO.

Author Biographies

Wolfgang Schullerus studied mechanical engineering at the "Technische Universität München", where he received his diploma in 1979. He has been working in non-impact printing technologies ever since, most of the time in DOD ink-jet technology with Siemens AG. Since 1996 he is working with Océ Printing Systems GmbH in Poing, Germany, where he heads laboratories for electrophotographic component development and fusing technology.

Roland Wolf studied mechanical engineering at the "Technische Universität München", where he graduated in 1997. He continued his studies at the "Lehrstuhl für Feingerätebau, Technische Universität München" and obtained his doctor's degree in the research on laser ablation of microstructures in 2002. Since that time he has been working with Océ Printing Systems GmbH in Poing, Germany and is team leader of the development laboratory for fusing and paper transport units at this time.