# Numerical Simulations of Electrophotography Processes

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## Abstract

*This paper provides an overview of the recent progress of simulation technology in Japan for the development of electrophotography processes—charging, exposure, development, transfer, fusing, cleaning, and paper handling. By utilizing highly efficient hardware and software, the simulation technology has been improved significantly. Because charging, exposure, and fusing processes are based on the mechanics of continuous media, they are formulated as a set of multi-component, nonstationary, and nonlinear partial differential equations and are numerically solved by the iterative finite element method or finite differential method. In contrast, the discrete element method is used to simulate the dynamics of toner and/or carrier particles in the development, transfer, and cleaning processes. The method of direct observation with a high-speed microscope camera and particle tracking velocimetry are used to improve physical models and to confirm the adequacy of calculation results. Thus, the electrophotography processes are no longer a black box.*

## Introduction

Electrophotography is used in laser printers and virtually most printers. It is a complex process that generally consists of six distinct steps—charging, exposure, development, transfer, fusing, and cleaning—which are schematically shown in Fig. 1. In step 1, electrical gas discharge is used to uniformly charge the photoreceptor film that acts as an insulator in the absence of light. In step 2, a laser beam is used to discharge the normally insulating photoreceptor film, thereby producing a charge pattern on the photoreceptor (latent image). In step 3, toner particles, attracted by the electric field created by the charges on the photoreceptor, are transported

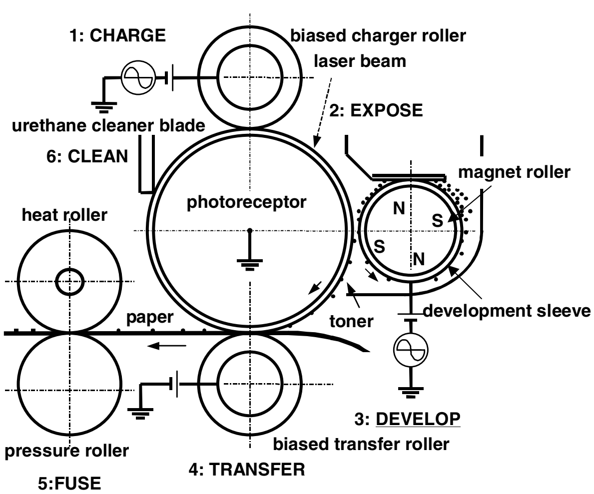


***Figure 1**. Electrophotography processes.*

from the development sleeve and adhere to the latent image, thereby transforming it into a real image. In step 4, the toner particles are transferred to a paper that is electrically charged with polarity opposite to that of the toner particles. In step 5, the image is permanently fixed on the paper by melting the toner on it. Finally, in step 6, excess toner particles are removed from the photoconductor surface.[G1-G4]

With rapid development in information technology, there has been a strong demand for improvements in printing technology (e.g., high printing speed, high image quality, low cost, low energy consumption, and low environmental impact). However, the development of high-performance electrophotography machines by trial-and-error is a time-consuming and expensive process. Therefore, active research and development have been conducted for investigating basic physics, clarifying mechanisms of unexplained phenomena, and developing practical simulation tools. Because electrophotography consists of complex processes that include the transport of particles and it is sensitive to the environmental conditions, it had been considered that the simulation is ineffective in the development of electrophotography machines. However, recent advancements in computer software and hardware have enabled the practical use of numerical simulation for the development of electrophotography machines.[G4]

This paper provides an overview of the recent progress of simulation technology particularly conducted in Japan for the development of electrophotography processes—charging, exposure, development, transfer, fusing, cleaning, and paper handling.

## Charging

Two types of chargers are commonly used in commercial printers: a corotron or scorotron and a contact charger. The former is used in high-speed machines, while the latter is used in low-speed machines.

The former utilizes ionized gases generated in a corona discharge field on the surface of the wire electrode. Many mathematical models have been developed to explain the effects of the parameters of the charger and charging system on the performance of the charger. Watanabe [C1] has calculated a time-dependent two-dimensional corona discharge field that is determined by the conservation of negative and positive charges and Poisson's equation and has utilized the calculation results to improve the charging system. Ozone generation in the corona discharge field, which is one of serious issues of the charging system, has been modeled by Kawamoto.[C2] Ionic wind induced by the migration of ions in the corona discharge field was calculated by Okamoto and Mori.[C3] They have utilized the calculation results of three-dimensional ionic wind for the improvement of the airflow in the scorotron to prevent nonuniform charging and the formation of dust blur.

A contact charger roller has been developed by Nakamura et al. [C4] as a new charging device for a low-speed printer, because it generates extremely small amounts of ozone. Kawamoto et al. have modeled the basic characteristics of photoconductor charging

[C5], ozone generation due to microdischarge [C6], and acoustic noise [C7] due to electrostatic alternative force using simple one-dimensional models. Kadonaga et al. [C8] have extended the charging model in the two-dimensional field and explained the mechanism of the formation of a scale-like nonuniform image defect. Haseba et al. have also conducted two-dimensional modeling to clarify the pin-hole leak phenomenon caused by photoconductor defects.[C9]

## Exposure

Watanabe et al. [E1] have performed a numerical simulation of the formation of a latent image on an organic photoconductor (OPC) using a time-dependent electric conduction model in a semiconductive OPC film. This model is similar to the model used in a gas discharge field [C1] and consists of three partial differential equations; the conservation of negative and positive charges and Poisson's equation. They have also explained the effects of the laser beam diameter, laser power, and OPC thickness on the latent image.

## Development

Development is the key process of electrophotography. Two approaches have been adopted for the simulation of this process. One is based on the continuous flow model where principles of classical fluid mechanics are applied to the bulk flow of the toner and/or carrier particles.[D1, D2] Although this approach could partially simulate the flow of bulk particles in an auger, for example, it cannot be used to evaluate the development process, that is, the process to form a real image on a latent image created on the photoconductor. The distinct element method (DEM) is the only effective method to simulate microscopic particle motion, although it has many drawbacks such as uncertainty of parameter determination, limitation of particle number for evaluation, and extremely long calculation time. Many papers have been published on the successful use of the DEM to improve the development process; for example, the DEM has been used to examine the static chain formation of carrier particles [D3, D4], determine the dynamics of the magnetic carrier chain [D5], clarify the bead-carry-out phenomenon [D6, D7], and evaluate the dynamic behavior of carrier particles in the development area.[D8–D11] Recently, the DEM has been extensively used by Japanese companies because it has become a practical approach for the efficient analysis and optimization of the development system within a reasonable calculation time. The development of a large-scale DEM is supported by the Japanese government.[D12] In addition to the conventional DEM, the hard-sphere model [D13] and the hybrid model [D9] have been developed in order to reduce the calculation time. Parallel computing and periodic boundary conditions are also effective in reducing the calculation time without reducing the calculation accuracy.[D10] The DEM that was originally developed in the civil engineering field has been improved and successfully used for the simulation of carrier and/or toner dynamics.

The design of the magnetic roller is also supported by numerical simulation.[D14–D16] A sophisticated technique of direct observation with a high-speed microscope camera and particle tracking velocimetry are used to refine the model and confirm the numerical calculation.[D4, D10, D13, D17, D18]

## Transfer

Two types of transferring devices are used for commercial printers: one is the corotron and the other is a biased transfer roller (BTR). Using a simple one-dimensional model, Ito and Kawamoto [T1] have modeled the basic characteristics of the BTR system and ozone generation due to microdischarge. Nakayama and Mukai [T2] have explained the mechanism of generation of a hollow defect by the application of the DEM, and Kadonaga et al. [T3] have calculated toner scattering in a transfer region.

The belt transfer system that a paper clings to an electroresistive belt is used in some electrophotography machines. In this system, the separation discharge between the paper and the belt causes image degradation under certain conditions. Kadonaga et al. [T4] have modeled this phenomenon and explained the effect of electrification of the belt. Aoki et al. [T5] have established a numerical simulation method for toner transfer, considering the voltage distribution of the transfer belt. The DEM is effective not only for the development process but also for the transfer process.

## Fusing

The traditional and conventional method of heat transfer is used to design the fusing process.[F1] It is a challenge to develop a model for simulating the fixing of toner particles to the surface of a paper; the fixing process involves melting, adhesion, and solidification of toner particles. These are the specific features of electrophotography, and they have been analyzed using the viscoelastic theory.[F2]

## Cleaning

Friction-induced chatter vibration of a cleaner blade is one of the most serious issues of the cleaning process. It has been clarified that two different mechanisms are responsible for the vibrations of the cleaning blade; negative speed dependence of the friction coefficient [Cl1] and friction-induced coupling of certain vibration modes.[Cl2] Methods to prevent such vibrations have been proposed in the literature.[Cl1, Cl3]

## Paper Handling

Because technologies for handling flexible media are commonly used in many industrial applications such as automated teller machines, postal automation systems, and automatic ticket checkers, a Japanese academic committee, established by the Japan Society for Precision Engineering, is promoting the development of this technology. General-purpose programs have been developed by many companies and utilized for the detail design of the paper handling system for the electrophotography machine.[P1, P2, P3]

## Concluding Remarks

The Imaging Society of Japan (ISJ) and the Information, Intelligence and Precision Equipment Division (IIP) of the Japan Society of Mechanical Engineers (JSME) have established committees to promote the modeling and numerical simulation of electrophotography processes. Members of these committees are not only academic researchers but also researchers and engineers working with industrial companies. The objectives of the committees are to exchange mutually benefiting technologies on a give-and-take basis and to educate young engineers. Although the members compete with each other, it is believed that cooperation is constructive for both the companies and consumers of electrophotography machines.

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