Micro Scale Temperature Field Analyses for Robust Fusing System Design in High-Speed Heavy-Duty Laser Printers

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Abstract

Recently, the development of high-speed heavy-duty laser printers is rapidly shifting from a conventional test-based approach to a virtual design procedure using numerical analyses because the later approach is more time efficient. The authors have developed a three-dimensional (3-D) analysis for a roll fuser design.

Peculiar difficulties in a high-speed heavy-duty roll fuser design are due to the nature of significant heat supply in a nip region during short period and an insufficiently short period for temperature recovery in an outer nip region. Therefore, the only use of the 3-D analysis gives little reliability growth.

The authors analyze the thermal mechanisms, and then identify problems giving the difficulties for the fuser design. The problems are significant temperature gradient occurrences, and their rapid and complex changes in the fuser, toner and paper in micro scale distance in the nip and the outer nip regions during printing. For instance, even in the outer nip region, several degrees to several ten degrees Celsius temperature difference occurs in several hundred microns below a fuser roll surface; in consequence reduces reliability due to high temperature occurrence on an interface between a surface layer and a core metal in the heat roll.

Combining the 3-D analysis and the analysis for the thermal mechanisms, the authors obtain knowledge for the robust fusing system design in the high-speed heavy-duty laser printers.

Introduction

A heat roll fuser has been widely used for laser printers since its invention.[1] Especially, it is indispensable for high-speed heavy-duty use in monochrome and color because of its high reliability in paper handling and fusing. Its peculiarities are from a significant heat supply during short nip period and an insufficiently short period for temperature recovery in an outer nip region. Problems caused by it are below.

- Large temperature distribution on the heat roll surface.
- Unstable temperature during print condition changes (i.e. print start, print stop, paper width change, and/or paper thickness changes).

To solve above problems, temperature control technologies with multi-temperature sensing on the heat roll surface and multi-heater are employed. Optimization for multi-heater arrangement and sensing points is needed. Usually the optimization process is time-consuming task if it is done by test-based examinations. The authors have developed the 3-D numerical analysis method for the heat roll fuser to design the multi-heater arrangement and their control; achieved a robust design technique to obtain highly reliable heat roll fuser system.

However there is a disadvantage of the large-scale 3-D simulation – a lack of considerations of microscopic temperature fields. Therefore, understanding heat flow mechanisms and the considerations of the unsteady temperature distribution in the microscopic region are needed; and should reflect the design process using the 3-D simulations. The simulated thermal behaviors in the microscopic region and their use for reliable fuser design are described in this report.

Three-Dimensional Numerical Analysis

Heat Roll Fuser

Figure 1 shows a schematic cross-section diagram of the heat roll fuser. Basic components are: a heat roll, a back-up roll, paper strippers for cut sheet feed, and a cleaner. The heat roll is composed of a metal core, a surface layer, and heaters. Normally, the core is made of aluminum and the surface layer is made of fluoride resin or silicon rubber. Thickness of the core is several millimeters and the surface layer is several tens to hundreds microns. Halogen lamp bulbs are used for the heaters.

Analysis Model

Function, application, and impact to the fuser design of the 3-D analysis have been described in previous Japanese report.[2] The model building process and the technical characteristics of the 3-D analysis are discussed in this chapter. Prior to it, the previous report[2] is reviewed and summarized in this section to understand the 3-D analysis.

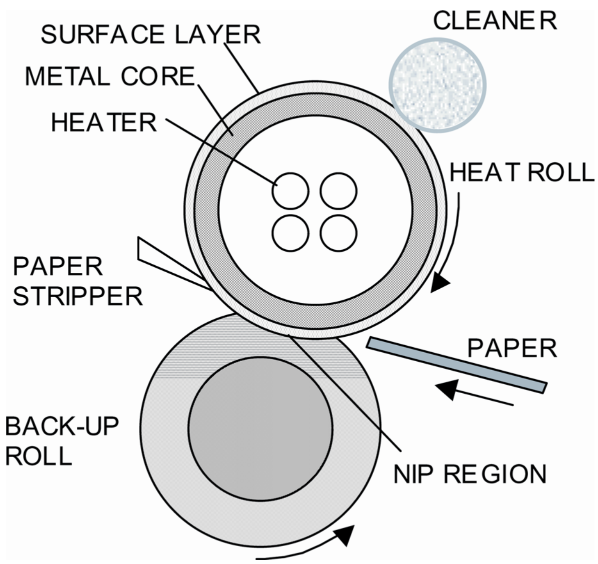

Figure 1. Heat Roll Fuser

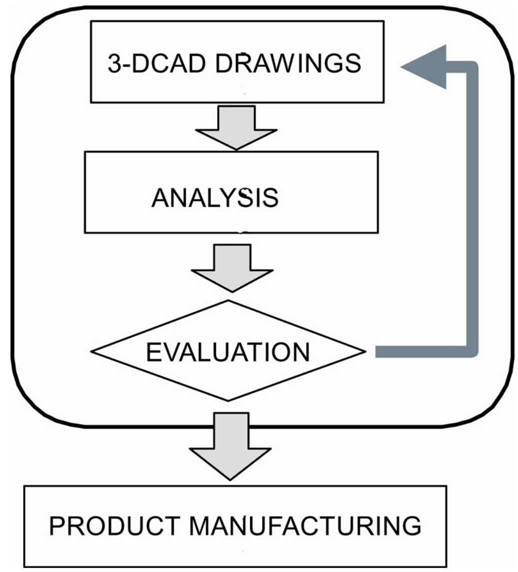

Figure 2. Analysis Leads Design Concept.

Figure 2 shows an analysis leads design (ALD) procedure using 3-D simulation. Geometries are provided from 3-D CAD drawings. Simulations are applied to the geometry with input conditions (design parameters); the calculated outputs (performance) are confirmed if the outputs satisfy the target performance. This process is iterated until the satisfaction is obtained. Following the obtaining of satisfaction, manufacturing and test processes are carried out. Employing ALD procedure, trial and error in manufacturing process can be extremely reduced.

An example of 3-D model for the ALD is shown in Figure 3. The analysis object is the heat roll fuser in the high-speed heavy-duty laser printers for continuous feed. The calculation is performed under 3-D unsteady conditions. The temperature distribution changing with time on the heat roll surface can be observed. A schematic diagram of the model is shown in Figure 4. The devised points are described below.

- Components to which heat is penetrating from the fuser are replaced to the objects, which have equivalent heat capacity and surface heat transfer with the components. The authors refer it as a virtual heat capacity and a virtual heat sink respectively. They are useful for reducing calculation load and avoiding complex geometry of the model.
- The heat roll surface layer is replaced to an equivalent thermal resistance, because thickness difference between the surface layer (several tens to hundreds microns) and the core (several millimeters) is large.

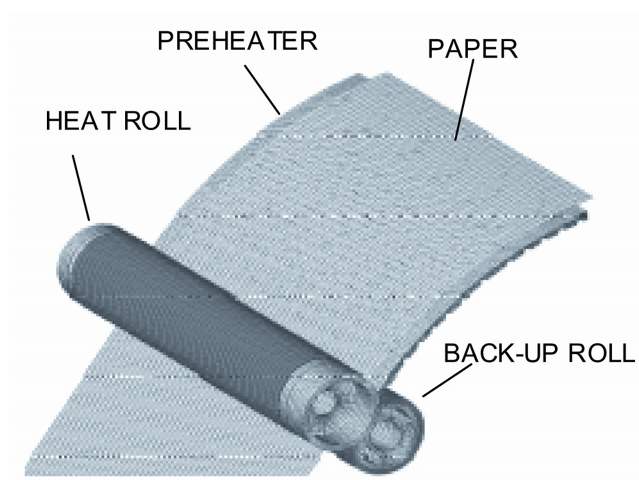

Figure 3. Example of 3-D Model Geometry

- Heat supply from heater is defined as heat flux at an inner surface of the heat roll, leads to reduction of the calculation load by avoiding radiation calculation.

The 3-D heat roll surface temperature can be calculated with relatively small calculation load.

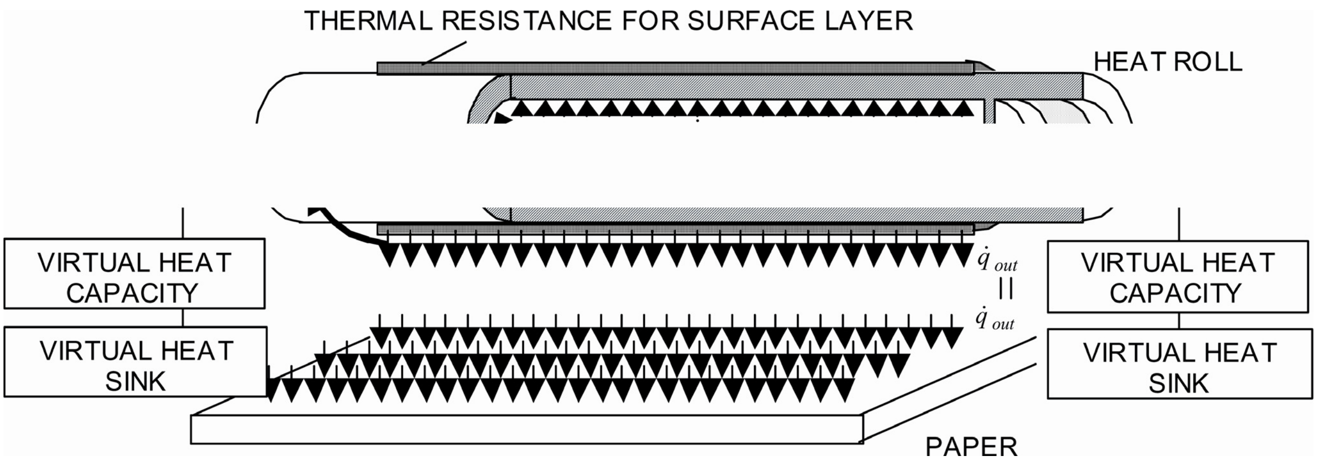

Figure 4. 3-D Model.

Component-by-Component Approach

To obtain accurate calculated results, validation steps are indispensable for the 3-D analysis. The validation process is carried out by a component-by-component approach. Figure 5 shows an example of a validated result. Although the practical heat roll has four heaters, a combination with one heat roll and one heater is modeled and tested as a first approach for the validation. For the 3-D model, testing in conditions of rapid temperature change is not so important because it does not support the rapid condition changes as mentioned in the next section. For each heater, the calculated surface temperature is fitted to the tested result. For the fitting process, a small adjustment for heat absorption efficiency at the heat roll inner surface is carried out for the each heater. In the next validation step, the model is systemized as shown in Figure 4, which is a superposed heat fluxes of the four heaters; the virtual heat capacity is adjusted by comparison between calculated and tested results. Accurate calculated results can be obtained by employing component-by-component approach using the complex 3-D model.

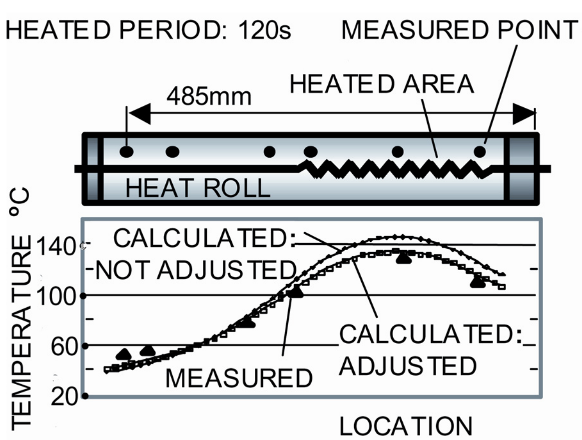

Figure 5. An Example of Validation Result

Validity of 3-D Analyzed Results

In the 3-D analysis, during a period before printing and a period during stable printing, calculated temperatures are good fit to the tested results. However, at the print condition changing stages (i.e. print start, print stop, paper width change, and/or paper thickness changes), difference between calculated and tested results increases. However, it is necessary for the fuser system design to obtain a good fit at such rapid condition change.

A significant temperature gradient in micro scale distance around the surface layer during short period occurs with rapid thermal condition changes. In the 3-D analysis, a fine mesh and a short time step are not suitable to obtain effective calculation speed. It is for analyzing the time averaged heat transport phenomena in relatively long time scale. Therefore, it is difficult for the 3-D analysis to follow the temperature changes with the rapid thermal condition changes. The surface layer is modeled as composed of just the thermal resistance. The validation is made at the heat roll surface temperature. Therefore, even in relatively long time scale, an internal temperature of the heat roll has less accuracy than the surface one. Typical situations with such difficulties are below.

- Temperature changes on the heat roll surface at the print start timing
- Temperature changes on the interface between the core metal and the surface layer
- Temperature changes on the heat roll surface and paper during the nip and the outer nip periods

Figure 6 shows a comparison between tested and 3-D calculated results at the print start timing. A temperature drop occurs and it is important factor for the fuser design. In the calculated result, a very slight temperature drop is recognized. And recovery temperature, after the drop, shows much higher in the analysis. This is an example for above difficulties.

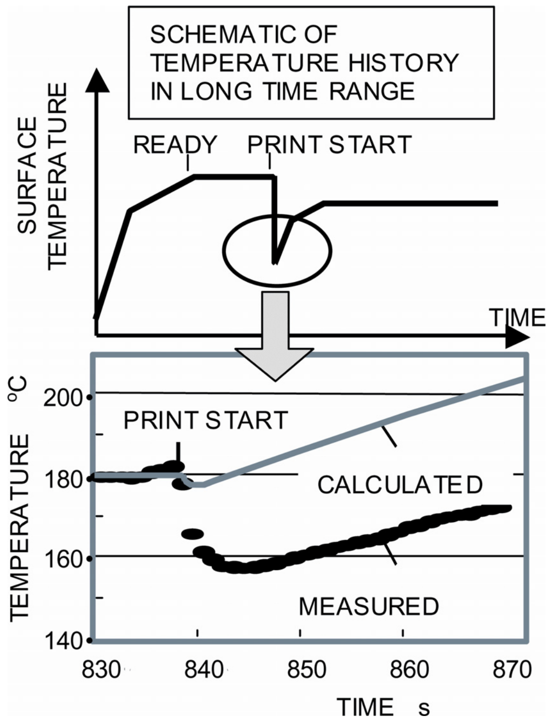

Figure 6. 3-D Calculated Result at Print Start Timing.

One and Two Dimensional Numerical Analysis

Analysis Model

For obtaining accurate temperature field including the internal temperature of the heat roll, in very short time scale that is sudden changes in the thermal condition, a model from one and/or two-dimensional micro scale geometry that have very fine mesh and very short time step is needed. Figure 7 shows micro-scale geometry and its model. It is composed of two-dimensional (2-D) heat roll and one-dimensional (1-D) paper geometries. The heat roll and the paper are thermally connected via heat fluxes with thermal resistances at a boundary. In the heat roll geometry, significant heat flux during the very short nip period of several milliseconds and very small heat flux on the outer nip region due to free convection occur. To calculate these two types of the heat flow, 2-D model is employed. Particularly, in the surface part in the heat roll, significant temperature gradient in very short distance of several tens to hundreds microns occurs. Therefore, the mesh in the surface layer should be much finer than core metal. Thus, rapidly changing significant temperature gradient in micro-scale distance during very short period and transition temperature from the nip region to the stable outer nip region can be calculated.

The paper is modeled as 1-D. Temperature gradient for the paper depth is significant in micro-scale distance and its distribution is complexly changing. So, 1-D model, which is focused on the paper depth only, is employed. At the time one point on the paper enters into nip region, heat flux q, which is from the heat roll surface and changes with time, is supplied to the surface of the paper. It maintain during the nip period. After the nip period, the heat flux q is reduced to 0. Thus, for each time step, new connection, q, ---, is generated between the 2-D heat roll surface and the 1-D paper surface. They are moving along with the heat roll surface and it seems as if the heat roll is rotating.

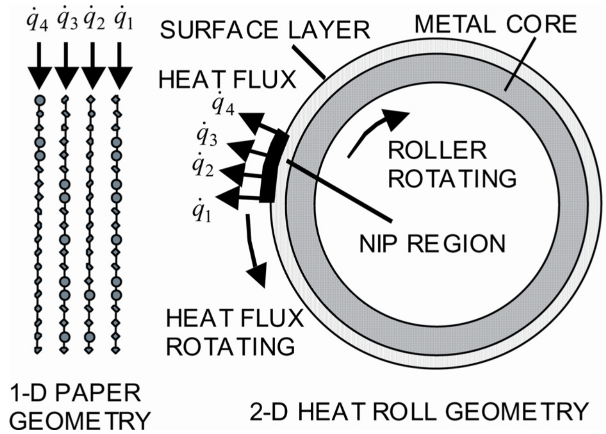

Figure 7. 1-D and 2-D Combined Model.

Analysis Results of Temperature Changes on Heat Roll Surface at Print Start Timing

The temperature drop at the start timing is significant in the high-speed fuser. To know the magnitude of the drop is important for the initial temperature setting.

Two conditions of the analyzed results are shown in Figure 8. One is with toner layer, and another is without it. Several percentage of the print coverage is employed in the measurement. In both analyzed cases, the temperature drop at the print start occurs. And the recovered temperature after the drop shows good fit between the analyzed and measured results. Comparing to the 3-D analyzed result in Figure 6, the temperature drop and recovering behavior at the print start timing is much improved. However, magnitude of the temperature drop in the analysis is a little smaller than the measurement. Therefore, it should be estimated that temperature is several degrees lower in the practical system. It should be mentioned that existence of the toner affects much in the quickly temperature changing conditions.

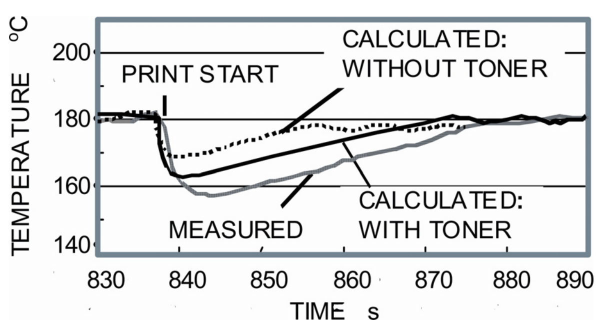

Figure 8. Calculated Results at Print Start Timing with 1-D and 2-D Combined Model.

Temperature Changes at Interface Between Core Metal and Surface Layer

The temperature increase at the interface between the core and the surface layer is an important factor especially for heavy- duty use because exceeding the temperature limit of the surface layer at the interface shortens life of the heat roll.

Figure 9 shows analyzed results of the surface and the interface temperatures changes in the long time scale for thin surface layer, 40 microns, and for thick surface layer, 250 microns, respectively. In the thin surface layer, difference between the surface and the interface temperatures is very small for all print stages and it is negligible for the fuser design. However, in the thick surface layer, though the difference is small before printing, it becomes large during printing. Though the results are not shown, the difference during printing is much larger in the thicker surface layer than 250 microns thick. For the surface temperature setting, the interface temperature increase should be considered for avoiding exceeding the temperature limit of the surface layer material.

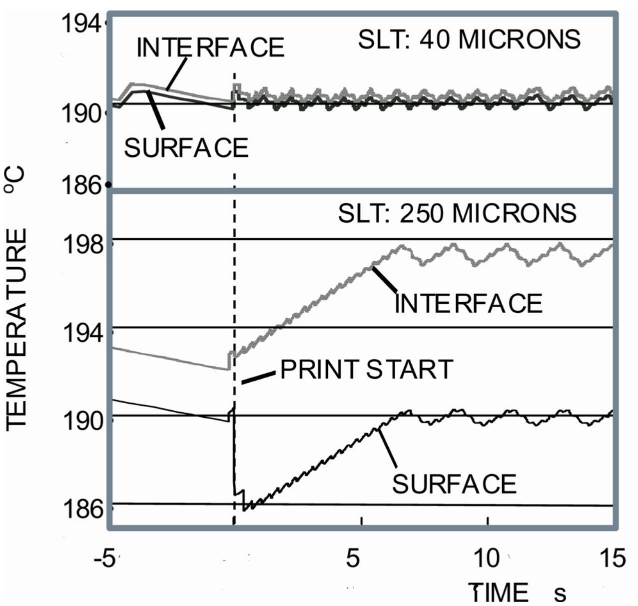

Figure 9. Calculated Results of Surface and Interface Temperatures Changes with 1-D and 2-D Combined Model.

Temperature Changes of Heat Roll and Paper During Nip and Outer Nip Periods

This item is important for understanding the heat transfer mechanism in the fuser. Temperature changes and heat flow magnitude in the nip region have been discussed in previous literatures.[3,4] However, although they are discussions of heat supply levels and one example of measured temperature and heat flux, they are not enough to solve the heat transfer mechanism with the temperature changes in the nip and outer nip regions. It is important for the fuser designer to understand it for obtaining the robust fuser design.

Figures 10(a) and (b) show calculated results in the nip and outer nip regions. The horizontal axes show a rotated angle from an inlet of the nip region. It represents time passage. The results in Figure 10(a) are for the thin surface layer, 40 microns, and those of Figure 10(b) are for thick one, 250 microns. Roughly speaking, the surface temperatures rapidly drop at the inlet and quickly increase at the outlet of the nip region and recovers to the inlet temperature with the rotation, regardless of the surface layer thickness. There are some differences, which imply heat transfer mechanism in the nip region, in the detail behavior with the surface layer thickness. In the thin layer case, the temperature starts recovering at the middle point of the nip region. In the case of the thick surface layer, the surface temperature monotonously decreases to the outlet of the nip region. To understand the heat transfer mechanism, the heat flux from the core to the surface layer and the surface layer to the paper are indicated in Figures 10 (a) and (b). At the first stage in the nip region, the heat flux to the paper is significant and rapidly decreases to the outlet of the nip region, and finally it is reduced to no heat flux in the outer nip region, regardless of the surface layer thickness. On the other hand, the heat flux from core to the surface layer of the thin layer thickness case increases gradually in the nip region and reaches the same level with the heat flux to the paper. Therefore, the temperature recovery starts in the nip region in the thin surface layer case. In the thick surface layer case, the heat flux from the core to the surface layer increases after the outlet of the nip region. This causes the monotonous decrease of the surface temperature. In more detail observations of the surface temperature recovery in the thin surface layer case, the temperature recovery in the nip region starts before the point the heat flux from the core reaches the same level as the heat flux to the paper. This means that quite a few amount of the heat supply from an inner part to an outer part in the surface layer exists. Actually, in the thick surface layer case, the monotonous temperature drop in the nip region has saturated with time. This phenomenon is also from the heat conduction in the surface layer.

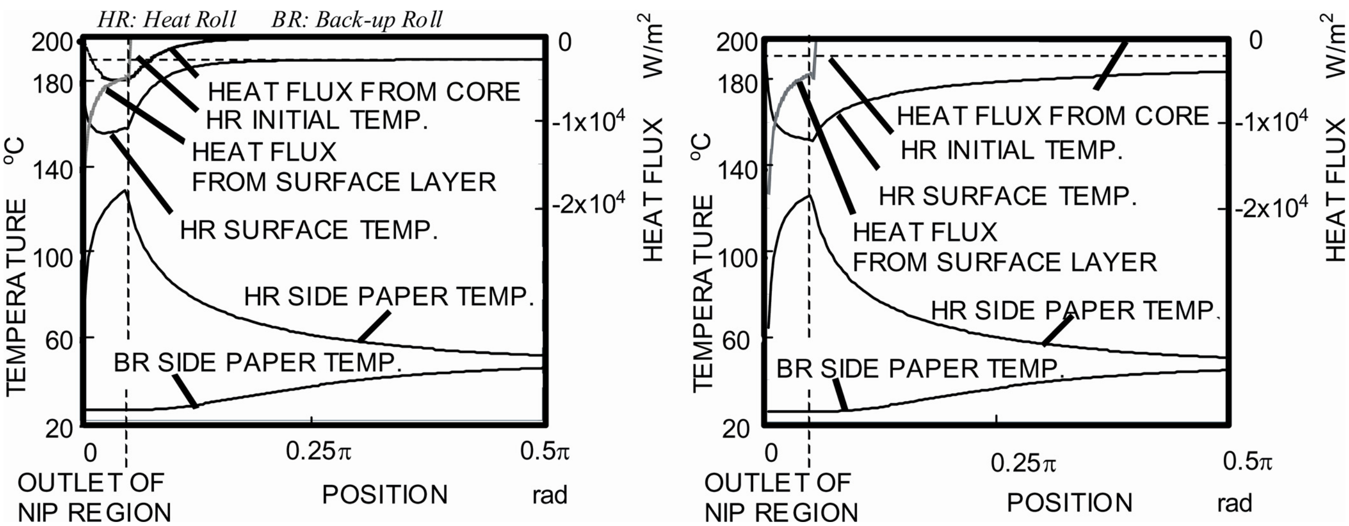

Figure 10. Calculated Results in Nip Region and its neighbors with 1-D and 2-D Combined Model.

In the outer nip region, the surface temperature recovers quicker in the thin surface layer case. This is because the heat flux from the core to the surface layer arises earlier in the thin surface layer case. For the design, the heat roller diameter can be set smaller in the thin surface layer case than thick one from the present calculations, because of the quick surface temperature recovery.

On the other hand, a paper temperature changes and their levels are similar between the thin and thick surface layer cases in these calculations. This is because the levels of the heat fluxes to the paper are roughly same with the two cases; even the temperature recovery arises in the thin layer case. Although the results are not shown, the heat flux to the paper are increased in thinner surface layer than 40 microns.[3] For more fusing energy and increasing the paper temperature, the surface layer thickness should be reduced below 40 microns.

Conclusions

For obtaining the robust fusing system design in the high-speed heavy-duty laser printers, the micro scale temperature field analyses by the 1-D and 2-D combined model, with the use of the 3-D large-scale model, have been carried out.

In the 3-D model building, the component-by-component approach has been employed in the validation step for obtaining accurate results.

In the 1-D and 2-D combined model, the important thermal behaviors for the design are obtained as described in the following. The calculated results of the temperature drop on the heat roll surface at the print start timing have been improved from the 3-D analysis. The temperature changes at the interface between the core and the surface layer are clarified. The temperature field in the heat roll and the paper and its heat transfer mechanism during the nip and the outer nip periods are revealed

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Biography

Teruaki Mitsuya received his M.E. and D.E. degrees from Gifu Univ., Japan in 1984 and from Tokyo Inst. Tech., Japan in 1997, respectively. He has been researching imaging technologies for laser printers, in Hitachi, Ltd. from 1984, Caltech from 1994, Hitachi Koki Co., Ltd. from 1995, Hitachi Printing Solutions, Ltd. from 2002 and Ricoh Printing Systems, Ltd. since 2004. He is a Professional Engineer in Mechanical Engineering and in General Technological Project Management, and members of IS&T, ISJ, ASME, JSME, etc.