Investigation of Transient Temperature Response of Papers in a Thermal Transfer Printer

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Abstract

This study describes thermal conduction of papers in a Direct Thermal Printer (DTP). DTP produces an image by heating thermal papers using a thermal head. The print quality of DTP is significantly dependent on thermal conduction phenomena of the printing paper.

Our research targets to optimize a printing process of DTP in order to reduce the power consumption while maintaining the printing quality. In this report, our special attention is paid to investigate the thermal conduction process of the printing paper and the thermal head. Especially the effects of thermophysical properties and contact resistance between the printing paper and the thermal head on the temperature response of the paper were investigated. Thermophysical properties of several papers were measured. Moreover, in order to evaluate contact thermal resistance between the paper and the thermal head, a transient thermal network analysis is performed and we estimated the contact resistance of several types of test papers. Finally, we investigated the effects of the thermophysical properties and the contact resistance on the temperature response of the paper by using the thermal network analysis. It is found that transient temperature response of the paper is strongly dependent on the thermophysical properties and the existence of the contact resistance. To achieve an optimization of DTP process, the accurate estimation of thermophysical properties and contact resistance should be strongly needed.

Introduction

Direct Thermal Printers (DTP) produce printed images by selectively heating thermal papers when a thermal head which includes a dot heater contacts thermal papers directly. DTP have advantages of a low noise level, compact dimension and running cost over other printing technologies such as laser printers and ink-jet printers. A payment process by using credit cards has been needed to avoiding a security problem in developing countries and a strong demand of portable POS (Point-of-Sale) terminals have been growing. Especially, since the Beijing Olympics which was held in 2008, portable POS terminals have quickly spread. The demand of portable POS terminals is still developing. Here, in order to mount a miniaturized printer in POS terminals and print receipts on site, we are focusing on DTP. However, in order to increase a battery life of portable POS terminals, a decrease of a power consumption of DTP should be achieved while improving printing quality and doing color printing. Therefore, the further investigation of printing process of DTP is thus needed. Several studies have been investigated about the design of thermal printers [1] – [4]. However, previous studies did not focus on the details of heat transfer phenomena around printing papers. Presently, a typical value of thermophysical properties can be obtained from some data books [5]. However, there are several types of papers for a digital printing. The difference in thermophysical properties of each paper may affect the printing process. Therefore thermal conduction phenomena of the printing papers should be investigated in order to optimize the printing process of DTP. Especially, the further investigation of a relationship between the thermal conduction and thermophysical properties of the papers should be performed.

With this as a background, our study aims to investigate heat transfer phenomena of DTP process in order to reduce power consumption while maintaining a printing quality. Our special attention was paid to investigate effects of thermophysical properties of printing papers and contact resistance between printing papers and thermal heads on a thermal conduction around the papers and the thermal heads. Firstly, thermophysical properties, which are density, specific heat, thermal conductivity, heat capacity and thermal diffusivity, were measured. Secondly, a transient thermal network analysis [1] [6] was proposed to estimate contact resistance between the paper and the thermal head. Finally, by using the measurement result of the thermophysical properties and the estimated contact resistance, we investigated the relationship among temperature response of the printing papers, the thermophysical properties and the contact resistance. Especially, we focused on a temperature gradient of the papers when the heat input from the thermal head is started, which affects the printing speed and the printing quality of the paper. We investigated the relationship among the thermal diffusivity, the contact resistance and the temperature gradient by using the results thermal network analysis.

Measurement of Thermophysical Properties

Firstly, in order to evaluate a level of a difference of thermophysical properties of the papers, measurements of thermophysical properties are performed. Density, specific heat and thermal conductivity of the papers were measured directly. By using the measured thermophysical properties, heat capacity and thermal diffusivity of each paper were calculated. Then the difference of the thermophysical properties was compared.

Measurement Methods

Table 1 shows measurement apparatuses of thermophysical properties. Density was measured by an analytical balance (TE-64, Sartorius, see Fig. 1). Specific heat was measured by a differential scanning calorimetry (DSC6220, SII, see Fig. 2).

To measure thermal conductivity, a simple measurement system as shown in Fig. 3 was prepared. The details of the system are as follows: The system consists of a layer of the test paper, a heater, a copper plate, a cooling block, a polycarbonate plate and a weight. The test paper has a footprint area A_{pa} of 40 × 80 mm^2. A footprint area of the heater, the copper plate and the polycarbonate plate was same as A_{pa}. The paper layer is sandwiched between the plate heater and the copper plate. Heat flow Q_{in} was applied from the heater. The copper plate was cooled by using the cooling block in which cooling water flows. The released heat flows from the heater to the cooling block through the paper layer. Hence we can evaluate effective thermal conductivity of the test paper in a thickness direction. Temperature difference between upper and lower surface of the paper layer ΔT_{pa} was measured using T-type thermocouples. Here, the thickness of some types of the test paper was very thin. Hence the temperature difference between upper and lower surfaces of the paper became small and could not be measured. In this case, some papers were stacked and a total thickness of the paper layer d_{pa} become 0.6 mm regardless of the type of the paper. In this case, we assumed that contact resistance between the papers was small. A contact pressure of 5.21 kPa was applied using the weight. The value of the contact pressure was decided from a contact pressure of an actual platen roller of DTP. Here, a part of Q_{in} leaks. In order to insulate the heat leak from the side of the test section, the measurement system was covered by a glass-wool. In addition, the heat leakage to the weight Q_{leak} was estimated from a temperature of a polycarbonate plate sandwiched between the weight and the heater. Effective thermal conductivity of each test paper λ_{pa} was determined by following formulas.

$$\lambda_{pa} = \frac{d_{pa}\left(Q_{in} - Q_{leak}\right)}{A_{pa}\Delta T_{pa}} \quad (1)$$

$$Q_{leak} = \lambda_{pc} A_{pa} \frac{\Delta T_{pc}}{d_{pc}} \quad (2)$$

Where ΔT_{pc} is temperature difference between the upper and lower surface of the polycarbonate plate, λ_{pc} is thermal conductivity of the polycarbonate (0.23W/(m·K)) and d_{pc} is thickness of the polycarbonate plate. By using obtained thermophysical properties, we calculated heat capacity C_{pa} [J/K] and thermal diffusivity α_{pa} [m^2/s] by using the following formulas.

$$C_{pa} = \rho_{pa} c_{pa} b_{pa} l_{pa} d_{pa} \quad (3)$$

Table 1 : Measurement Method of Thermophysical Properties

Parameter	Apparatus
Density ρ_{pa}	Analytical Balance TE64 (Sartorius)
Specific heat c_{pa}	Differential scanning calorimetry DSC6220 (SII)
Thermal conductivity λ_{pa}	One-dimensional measurement

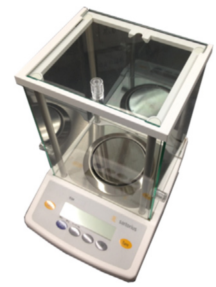


***Figure 1**. Analytical balance*

***Figure 2**. Differential scanning calorimetry*

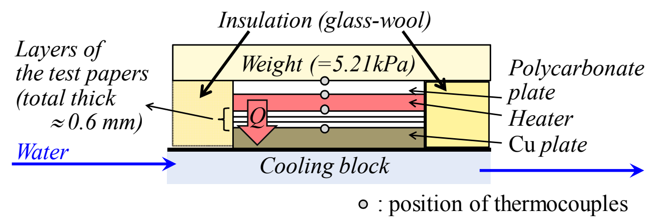
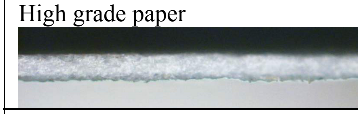
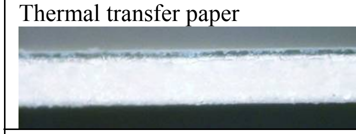


***Figure 3**. Schematic of the measurement system of thermal conductivity*

Table 2 : Properties of Test Papers

Type of paper	Thickness d_{pa} [mm]
Thermal paper 	0.05
Xerographic paper 	0.065
High grade paper 	0.1
Thermal transfer paper 	0.2
Inkjet paper 	0.3

$$a_{pa} = \frac{\lambda_{pa}}{\rho_{pa} c_{pa}} \quad (4)$$

Where b_{pa} [m] is width of the paper, l_{pa} [m] is length of the paper and d_{pa} [m] is thickness of the paper.

Test Papers

Table 1 shows the details of test papers used in this study. In order to compare the difference of the thermophysical properties from the type of the papers, five types of papers were evaluated.

Measurement Results

Table 3 and Fig. 4 show the measurement results of the thermophysical properties. Table 3 denotes the measured values and Fig. 4 shows the ratio of the thermophysical properties of each test paper to those of the thermal paper. It can be seen that each thermophysical property varied according to the type of the test paper. The maximum differences of the thermophysical properties were 31% of the density, 25% of the specific heat and 20% of the thermal conductivity respectively. It can be said that the thermophysical properties vary from type of the paper and this affects the difference of thermal conduction phenomena in the test paper. Heat capacity and thermal diffusivity were also varied according to the change of each thermophysical property. Here, the heat capacity was also dependent on the thickness of the test papers as shown in Fig. 4 (b). The heat capacity of the thermal paper was smallest because the thickness of the thermal paper was thinnest. The inkjet paper has the largest heat capacity because the thickness of the inkjet paper was thickest. From these results, we conclude that thermophysical properties of papers are varied. This may affect the thermal conduction around the printing paper and the thermal head.

Evaluation of Contact Resistance

Contact resistance between printing papers and thermal heads also affects thermal conduction from thermal heads to papers. In this chapter, we tried to evaluate the difference of contact resistance of each paper by using both an experiment and a transient thermal network analysis [1]. Firstly, the analytical accuracy of the transient thermal network analysis was evaluated by comparing an analytical result with an experimental result. Secondly, we investigate a value of contact resistance from the result of the thermal network analysis.

Test Model and Experimental Method

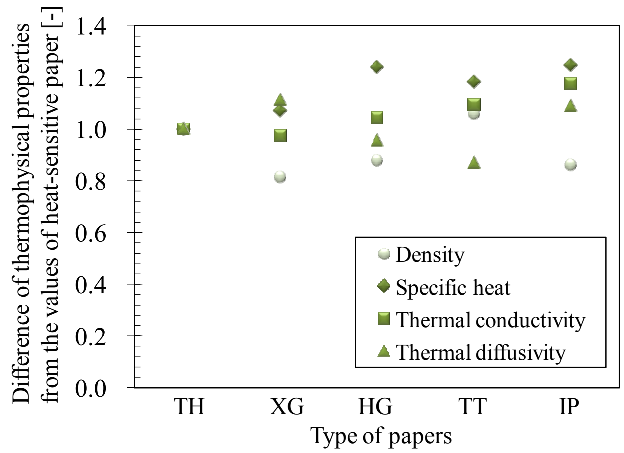
Figure 5 shows the schematic of the test model. This model is made up of a piece of the test paper and a test thermal head. The test paper, which has length of 60 mm and width of 10 mm, was put on the thermal head and was taped by a cellulose tape. The thermal head includes a dot heater has a footprint area of 48 mm × 0.12 mm. A heat was generated from a center part of the dot heater as shown in Fig. 5 (length of 3.75 mm).

In the experiment, we measured a temperature response at the center of the paper surface when the heat applied. In order to observe the transient temperature response, the heat dissipation from the dot heater is given impulsively at 0 second and was off at 20 seconds. A temperature transient of the paper was measured using the digital infrared temperature sensor (KEYENCE, FT-H10, Range: 0 ~ 500 °C, Measuring distance / View diameter : 35 mm / 1.5 mm in diameter).

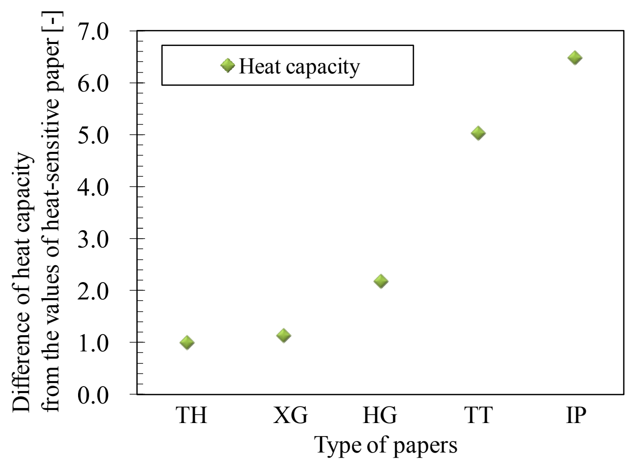
Table 3 : Measurement Result of Thermophysical Properties

Paper type	Density [kg/m^3]	Specific heat [J/(kg·K)]	Thermal conductivity [W/(m·K)]
Thermal	1114	1240	0.064
Xerographic	909	1330	0.062
High grade	981	1540	0.067
Thermal transfer	1192	1470	0.070
Inkjet	963	1550	0.075

Paper type	Heat capacity [J/K] (when b_{pa}= l_{pa}=1)	Thermal diffusivity [10^{-8} m^2/s]
Thermal	69.1	4.62
Xerographic	78.6	5.15
High grade	151.0	4.42
Thermal transfer	347.4	4.02
Inkjet	447.8	5.03



(a) Density, specific heat, thermal conductivity and thermal diffusivity



(b) Heat capacity

* **TH : Thermal paper**
XG : Xerographic paper
HG : High-grade paper
TT : Thermal transfer paper
IP : Inkjet paper

***Figure 4**. Difference of thermophysical properties from the values of thermal paper*

Thermal Network Analysis

In order to evaluate contact resistance, we performed the transient thermal network analysis [1].

The thermal network method is based on the analogy between heat transfer phenomena and electrical circuit. Thermal network is composed of thermal resistance *R* and nodes that have heat capacity *C*. Nodes are connected to each other through the thermal resistances. Here, the following Kirchhoff's law can be obtained at each nodal point.

$$C_n \frac{dT_n}{dt} = \sum Q_{in} - \sum Q_{out} \tag{5}$$

Where C_n is the heat capacity of the target node, T_n is temperature of the target node, t is the time, Q_{in} is the heat flow from the upstream resistance to the target node and Q_{out} is the exhaust heat from the node. Thermal resistance can be represented as following equation.

$$\Delta T_r = Q_r R_r \tag{6}$$

Where Q_r is the heat flow value which passes through the thermal resistance R_r. ΔT_r is a temperature difference at the thermal resistance. Here, thermal resistance of thermal conduction is defined as the following formula.

$$R_r = \frac{L_r}{\lambda_r A_r} \tag{7}$$

Where L_r is the reference length, λ_r is thermal conductivity of the resistance and A_r represents the heat transfer area. Thermal resistance by natural convection heat transfer is calculated by using the following equation with natural convection heat transfer coefficient α_r.

$$R_r = \frac{1}{\alpha_r A_r} \tag{8}$$

The radiation resistance from object with temperature T_a [K] to ambient air with temperature T_b [K] is obtained by the following equation with radiation shape factor = 1.0.

$$R_r = \frac{1}{\varepsilon_r \sigma A_r \left(T_a^2 + T_b^2\right)\left(T_a + T_b\right)} \tag{9}$$

Where, ε_r is emissivity, σ is the Stefan-Boltzmann constant which equals 5.67×10^{-8} W/(m^2·K^4). Thus, the above Eqs. (5) ~ (9) can be obtained at all thermal network nodes and resistances. These can be solved to determine the heat flow and the temperature distribution if *R* values are given.

Figure 6 shows the developed thermal network for evaluating thermal conduction in the test model. This is composed of a paper part, a thermal head part, boundary thermal resistances, which include natural convection and radiation on surfaces of the thermal head and the paper, and contact resistances between the paper and the thermal head. A number of the nodal point is 21 and a number of the resistance is 38. Temperature nodes are located at the upper and lower surface of the paper and the thermal head. Thermal conduction resistances were located in the paper part and the thermal head part. The heating node which simulates the heat dissipation from the dot heater was located on the upper surface of the thermal head. Thermophysical properties are quoted from our experimental results.

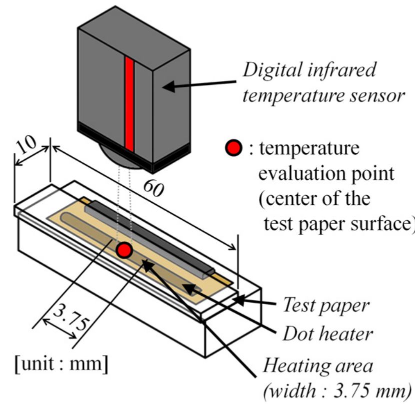


Figure 5*. Schematic of test model with IR temperature sensor.*

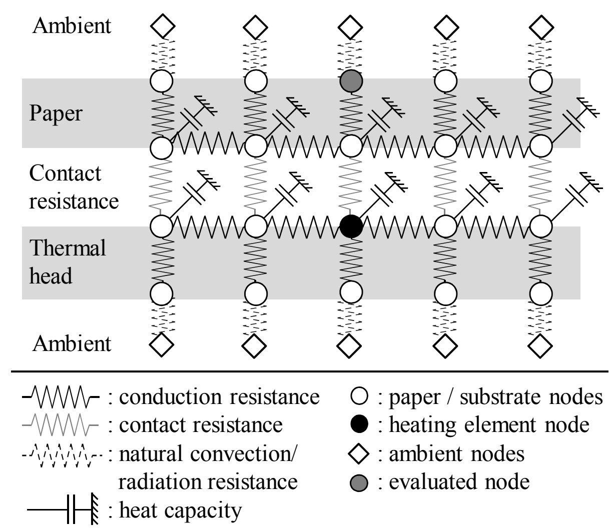


Figure 6*. Thermal network of test model*

Here, since contact resistance between the paper and the heater cannot be measured directly, the accurate contact resistance cannot be estimated previously. Therefore in order to estimate a level of the difference of the contact resistance on the paper, the contact resistance value was adjusted while comparing the analytical result with the experimental result. Through the process, we estimated the contact resistance of each test paper.

Comparison between Experimental Result and Analytical Result of Thermal Network Analysis

Figure 7 shows the comparison of the temperature history between experimental results and analytical results of the thermal network analysis when the input power of 1.08 W was applied to the test paper from the thermal head. We can see that a temperature rise of the paper depends on the type of the test paper. This is caused by a difference of the thermophysical properties and the contact resistance. Here, the analytical results show good agreement with experimental results regardless of the type of the test paper. From this graph, we confirmed the reliability of our thermal network analysis.

Estimation of Contact Resistance

As we confirmed the accuracy of the thermal network analysis, we confirm the difference of the contact resistance. Figure 8 shows estimated contact resistance between the test paper and the thermal head by using our thermal network analysis. It can be seen that the value of the contact resistance is severely varied according to the type of the test paper. Therefore the existence of the contact resistance also affects the thermal conduction around the paper and the thermal head.

Effects of Each Factor on Temperature Response of Paper

Finally, we investigated the effects of the factors discussed in the previous chapter on the temperature response of the paper. In this paper, we especially focused on the relationship among a temperature gradient of the papers when the heat input from the thermal head is started, thermal diffusivity and the contact resistance by using the thermal network analysis.

Figure 9 shows the relationship between the type of the test paper and a temperature rise after 1 second from the start of the heating in the case of the test model as shown in Fig. 5. The circular plots show the result if there is the contact resistance as shown in Fig. 8 between the paper and the thermal head. We can see that the temperature rise becomes higher when the thermal diffusivity increases expect for the thermal paper and the inkjet printer. The thermal paper shows the notable temperature gradient. This is because the thickness of the thermal paper is thickest and the thermal paper has the smallest heat capacity. In addition, the estimated contact resistance of the thermal paper is smallest as shown in Fig. 8. The surface of the thermal paper is coated with a leuco dye and a developer. There is a possibility that a cause of a contact resistance is inhibited by the existence of the coating. Moreover the heat capacity is smallest. Therefore the paper temperature increased rapidly. On the other hand, the inkjet paper shows the smallest temperature rise regardless of the highest thermal diffusivity. This is because the thickness of the inkjet paper is thickest and the temperature difference between the front side surface and the back side surface of the paper becomes highest. Therefore the calculated temperature rise becomes smaller.

Here, the square plots of Fig. 9 show the result when the contact resistance between the paper and the thermal head is zero. In this case, the temperature rise increases significantly regardless of the type of the test paper. The existence of the contact resistance significantly affects the temperature rise of the paper. In addition, when the contact resistance become zero, the difference of the temperature rise of each paper becomes more significant. There is a possibility that the effects of the thermal diffusivity on the temperature rise increases when the contact resistance become small because the heat flow in the paper become high.

From the analytical results, we conclude that both the thermal diffusivity and the contact resistance affect the temperature response of the paper after starting heat input. In order to control the power consumption while improving printing quality, we should develop the control method of the heating from the thermal head based on the authoritative thermophysical properties and a

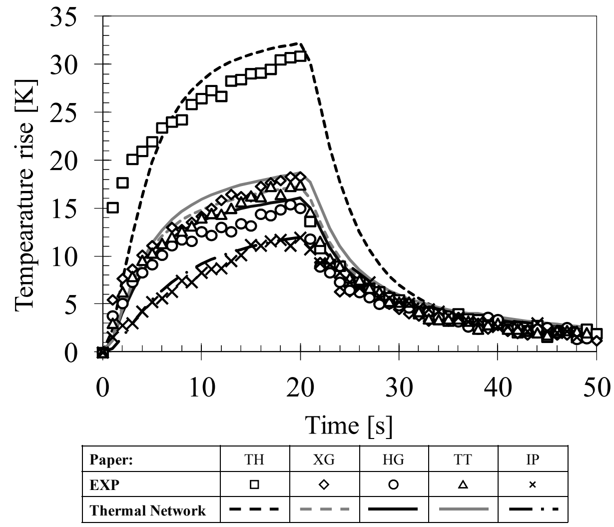


Figure 7. *Comparison of temperature history of papers between experimental result and thermal network analysis when 1.08 W of heat is applied from the dot heater*

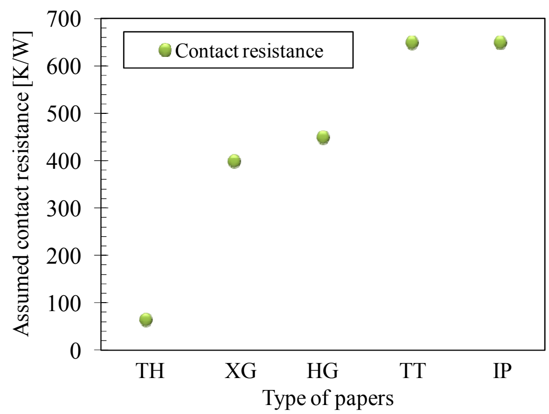


Figure 8. *Contact resistance between paper and thermal head used for our thermal network analysis*

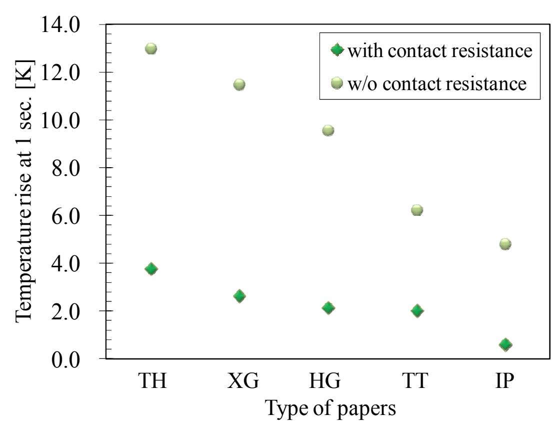


Figure 9. *Relationship between type of paper and temperature gradient between 0 and 1 sec. These are in the case of input power = 1.80 W. These results were obtained from the result of thermal network analysis.*

value of a contact resistance. Therefore the details of a contact resistance and thermophysical properties of papers should be investigated to obtain the authoritative database.

Conclusions

Our study aims to investigate heat transfer phenomena of a printing process of DTP in order to reduce power consumption while improving a printing quality. We especially focused on the effects of thermophysical properties of printing papers and contact resistance between the papers and the thermal head on the thermal conduction around the paper and the thermal head. Through the measurement of the thermophysical properties and the estimation of the contact resistance by using the thermal network analysis, we investigated the relationship among temperature response of the printing papers, the thermophysical properties and the contact resistance. Especially, we investigated the temperature rise of the papers when the heat input from the thermal head is started. We investigated the relationship among the thermal diffusivity, the contact resistance and the temperature rise.

The following information was obtained: Thermophysical properties varied according to the type of the test paper. The maximum differences of the thermophysical properties were 31% of the density, 25% of the specific heat and 20% of the thermal conductivity respectively. Heat capacity and thermal diffusivity were also changed according to the thermophysical properties of each paper. In addition, the contact resistance is also severely varied according to the type of the test paper.

Both the thermal diffusivity and the contact resistance influence the temperature response of the paper after starting heat input. In order to achieve the optimization of the DTP process while decreasing power consumption and improving printing quality, we should investigate the novel control method of the printing process based on the accurate database of the thermophysical properties and the contact resistances. A further investigation of contact resistance and thermophysical properties of papers should be investigated to develop the database.

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