AN INVESTIGATION INTO THE EFFECT OF PROCESS PARAMETERS ON THE INK SUPPLY CHARACTERISTICS TO A ROLLER TRAIN IN AN OFFSET PRINTING PRESS

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ABSTRACT

This paper describes an experimental investigation into the effect of process parameters on product quality in web offset printing. A production printing unit, part of an eight-station press, was instrumented to record strategic temperatures and speeds. A series of orthogonal array experiments were carried out to investigate the sensitivity of the process to changes in important press parameters. The changes in product quality were measured using densitometry in the test strip. The speeds of certain rolls and press temperatures were found to dominate. The response of the press to ink temperature changes was non-linear and interacted with the image coverage. This was shown experimentally and by a numerical model that was used to provide the physical insight to this interaction.

NOMENCLATURE

C	Ink specific heat capacity
L	Blade length for analysis
Q	Flow rate
T	Temperature
U_1	Sliding speed
a,b	Walther equation coefficients
h	Film thickness
h_i	Ink key/duct roll film thickness
k_f	Film thermal conductivity
k_s	Blade thermal conductivity
p	Pressure
u,v,w	Velocity components
x,y,z	Coordinate directions
a	Film convergence angle
µ	Ink dynamic viscosity
r	Ink density
u	Ink kinematic viscosity

INTRODUCTION

High quality printing is a complex manufacturing process having a high hourly operating cost, so the experimental time for the investigation of parameter effects needed to be minimized and the results obtained maximized. Orthogonal array techniques were utilized for the experimental programme as they have several advantages over other methods including the reduction in the number of tests to evaluate the effects of process parameters and the ability to investigate interactions between parameters. This allows the time and cost of experiments to be minimized. This is of importance as the trials were carried out on a production web offset printing press which was subject to a multitude of production constraints including, for example, job scheduling and time to good copy.

The optimization of an existing process necessitates the identification of the important parameters in the process. It is necessary to identify those parameters that will significantly affect the product quality, and also those which do not affect the process but are generally perceived as being important and for which an appropriate control system is in operation. Traditional methods include: full factorial trials; the adoption of an elimination approach; or the use of experience to optimize the system. The full factorial approach requires a large number of experiments to be completed. For example, to evaluate completely eight variables at two levels only (inferring a linear behaviour) requires 2^8 (256) tests, if three levels are investigated this will increase to 6561. This number of tests can not be carried out on a commercial printing press. Therefore, a technique that reduces the total number of tests, from the full factorial, is required.

A second technique which can be used to reduce the number of experiments is an elimination approach. This involves holding every parameter constant except one and then optimizing for the one parameter. This is repeated for all the parameters which are believed to be important. The elimination approach is a random subset of the full factorial trials. Two assumptions are made during the elimination process which can lead to significant errors in the results. First, it assumes there is no variability in the process and that identical trials lead to identical results. In the best case, a near optimal setting can be achieved, however, this is by coincidence and it is not easy to validate because the way it was achieved is not defined. The most dangerous assumption,

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however, is that none of the parameters interact which is not the case in many processes.

The third traditional approach is to optimize the process using experience. The set of parameters from the full factorial trial is reviewed and reduced in number until a full factorial is practicable. In processes such as printing where the detailed physics is not well understood, this can lead to the elimination of significant parameters.

Orthogonal arrays allow the detailed investigation and evaluation of all the parameters effectively and systematically in the minimum number of tests. Orthogonal arrays are balanced subsets of the full factorial. No two experiments are either repeats or mirror images of each other and each variable setting occurs the same number of times. The use of these arrays allows the number of runs per experiment to be minimized and the possible interactions between the parameters to be investigated. In addition, it is possible to compound the interactions allowing a larger number of parameters to be investigated (for example, seven parameters at three levels and one parameter at two levels in 18 tests).

The L_8 orthogonal arrays[1] were utilized for the majority of the trials. These allow four parameters at two levels to be evaluated simultaneously with three possible interactions occurring. Changes in the process were evaluated using a quality characteristic, in this case either the print density or the CIE colour space values. Although analysis of the results will reveal the dominant parameters along with interactions, knowledge of the process is an advantage. The design of the experiments will then allow the parameters to be identified and the interactions to be easily detected.

In the following sections, the orthogonal array techniques used in the experimental programme are discussed in detail. This is followed by a description of the background theory used in the modelling of the ink key/duct roll junction. The significant findings from the orthogonal array investigation are presented and discussed, with the numerical results being used to explain the physical phenomena that are present in the experimental trials. Finally, conclusions are drawn highlighting the important findings from the work.

EXPERIMENTAL METHODOLOGY

Parameter selection

Printing is a complex process with a large number of different parameters affecting the quality of the printed product[2]. An initial list exceeding eighty parameters was generated. It was not practical to investigate all of these on a commercial press and therefore the effect of some of these were investigated by instrumenting and controlling strategic variables on a single test unit. This allowed the investigation of some parameters, together with the provision of boundary conditions, to be used in numerical modelling techniques[3,4].

The remaining parameters selected were divided into those relating to control and process stability. The control parameters were those which could normally be adjusted by the print crew to achieve and maintain colour on the press. The process stability parameters were those that varied through or between print jobs and over which the press operators had no control.

Strategic approach to the experimental programme

The experimental programme was carried out using a commercial eight-unit printing press, with no loss of production. Initially, a monitoring exercise was carried out — prior to the invasive orthogonal array experimental programme. This monitoring was used to determine the process variability and the natural fluctuations present in the product colour and was completed without loss of product.

A single unit was fully instrumented for the measurement of temperatures and roller speeds. The top roller train on magenta unit seven was chosen for this purpose (Figure 1). This unit was selected because any changes in magenta have a significant impact in the image, and also because it was located near to the dryer. The measurements on the printed copy were taken on the magenta printed on the upper side of the web and analysed using densitometry. Samples were not collected until the press had stabilized following parameter changes, the total time being dependent on the parameter that was altered. In all circumstances, a minimum time of five minutes was allowed once a change had been implemented.

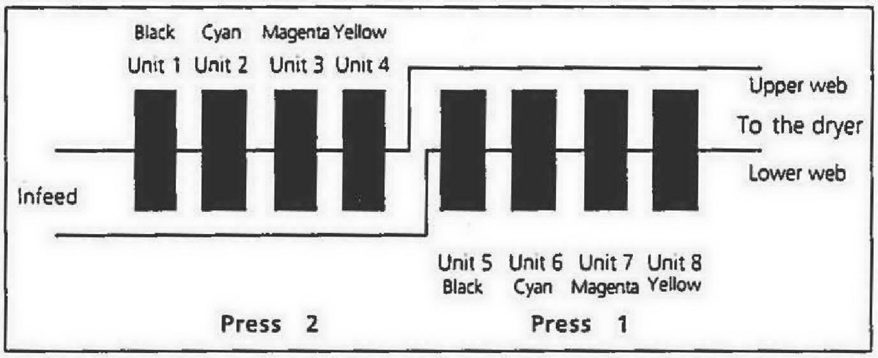

Figure 1 *Schematic of the eight-unit press*

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Table 1 *List of orthogonal array experiments*

Orthogonal array	**Parameters investigated**
Array 1A (L8 array)	Ink key setting, duct roll speed, pan roll speed
Array 1B (Two L4 arrays)	Pan roll speed, CUIM roll speed, temperature of ink in duct, temperature of fount in pan
Array 1C (L4 array)	Temperature of ink in duct, temperature of fount in pan, temperature of the copper roll cooling water
Array 1D (L4 array)	Temperature of ink in duct, temperature of fount in pan
Array 1E (L4 array)	Temperature of ink in duct, temperature of fount in pan
Array 1F (L9 array)	Temperature of ink in duct, temperature of the copper roll cooling water
Array 1G (L2 array)	Temperature of ink in duct

The monitoring exercise showed that there are large thermal transients in the printing press during the start-up period. For example, the temperatures of the ink in the duct took approximately two hours to stabilize. The press needed to be stable before any quantitative assessment of the process could take place. These temperatures were monitored throughout the entire experimental programme and the orthogonal array trials did not proceed until they had reached equilibrium.

To perform analysis of the printed copy, measurements were carried out on a test strip printed as part of the job. Sequential copy analysis[5] has shown that the ink densities vary between samples throughout the complete run and that these variations are cyclical. Fourier analysis was used to calculate the frequency of the density variation. Based on this work, it was identified that 32 sequential samples were required for each test condition investigated during the orthogonal array trials.

A large number of orthogonal array experiments were carried out to investigate control and process parameters and these are summarized in Table 1. By experience, it was found that the largest practical array was an L9 (three levels). This was due to the time constraints caused by the requirement to obtain thermal stability, a pass to be achieved, together with unforeseen press stops (web breaks etc). Generally, however, experiments were based on the L8 array and were designed such that when terminal problems occurred, the first four runs could be analysed as an L4 format.

The physical experimental data from the press unit seven was recorded primarily on computer using a data acquisition system. Thermocouples were mounted in the ink ducts and at strategic positions on and around the units to be measured along and across the press. The coolant supplies to and from the press were also recorded. The temperature of the ink in the duct and on the rollers was monitored using an infra-red thermometer. The instrument was calibrated to ensure the measurements were of the ink on the roller surface and not the roller surface itself[6]. Inductive probes with slotted discs were used to measure the roller speeds.

A numerical model will be used to establish the insight into the processes taking place. It is appropriate to summarize this model here as it will be applied later in the analysis of the printing trial results.

NUMERICAL MODEL THEORY

The flow of ink through the ink key/duct roll junction controls the quantity of ink passing to the ink roller train. A schematic of the junction local to the end of the key is shown in Figure 2 and a hydrodynamic wedge exists in which there will be an increase in pressure through the junction. The shearing of the film will generate heat, which is convected through the ink and conducted through the ink key and duct roll.

The assumption that ink is a Newtonian fluid has been made in this work — this assumption has also been made in much of the published data[3,7] analysing printing. Printing inks are well known to be non-Newtonian and this will affect the details of the flow characteristics. However, for the purpose of physical insight, good qualitative understanding can be achieved by modelling the ink assuming a Newtonian behaviour. At the junction between the ink key and duct roll, the hydrodynamic behaviour can be approximated by the generalized pressure equation[8]. For a two dimensional film this is given by

$$\frac{d}{dx}\left[G\frac{dp}{dx}\right]+\frac{d}{dz}\left[G\frac{dp}{dz}\right]=U_1\frac{dh}{dz}-U_1\frac{dF}{dz} \qquad (1)$$

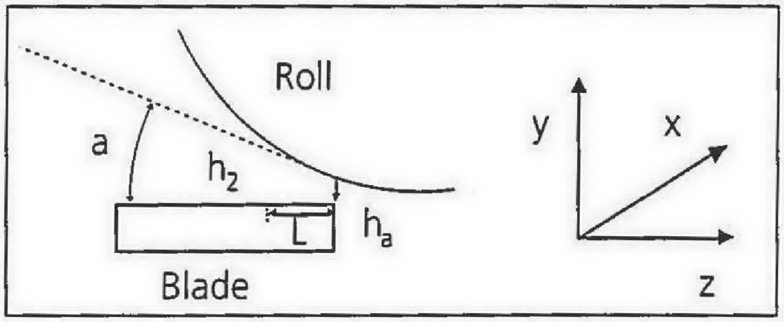

Figure 2 *Schematic of the ink key/duct roll junction*

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where

$$G = \int_0^h \frac{y}{\mu}(y - F)dy, \quad F_1 = \int_0^h \frac{y}{\mu}dy, \quad F_0 = \int_0^h \frac{1}{\mu}dy, \quad F = \frac{F_1}{F_0}$$

This equation allows for the inclusion of the cross film variation of viscosity () either with respect to temperature or non-Newtonian behaviour. In this work, it will be restricted to temperature only.

In describing the thermal behaviour the ink key and duct roller need to be considered. In the ink film the physics is described by the balance of convection, conduction and generation and is expressed in the following differential equation.

$$\rho C\left(w\frac{\partial T}{\partial z}+v\frac{\partial T}{\partial y}\right) = k_f\left[\frac{\partial^2 T}{\partial z^2}+\frac{\partial^2 T}{\partial y^2}\right]+\mu\varphi \qquad (2)$$

with the heat generation term written as

$$\phi = \mu\left[2\left(\frac{\partial w}{\partial z}\right)^2+2\left(\frac{\partial v}{\partial y}\right)^2+\left(\frac{\partial w}{\partial y}\right)^2\right]$$

The heat is transferred by conduction only in the blade and the mechanism is described by the following equation

$$k_s\left[\frac{\partial^2 T}{\partial z^2}+\frac{\partial^2 T}{\partial y^2}\right] = 0 \qquad (3)$$

Closure of these equations requires a description of the film thickness profile and the relationship between the viscosity and the temperature. At the ink key/duct roll interface the film thickness can be approximated by the following equation

$$h(z) = h_f + (L - z)\tan\alpha \qquad (4)$$

Assuming the ink is a Newtonian fluid the temperature dependence on the kinematic viscosity can be described using the Walther equation

$$\log_{10}\left[\log_{10}(v + 0{\cdot}6)\right] = \alpha\log_{10} T + b \qquad (5)$$

where T is expressed in Kelvin and a and b are constants obtained by curve-fitting equation (5) at two temperatures. The solution of equations (1) to (5) was accomplished using numerical techniques and, in this application, the finite element method was employed.

Thus, having explained the strategy of the experimental programme together with the applicable modelling tools, their use in the analysis of the printing behaviour will be illustrated in the following sections.

RESULTS AND DISCUSSION

The orthogonal array experiments were performed during normal production with minimal loss of copy or production time. The experimental results have been grouped and presented to depict the significant variables. The associated results, in order of discussion, are the ink temperature in the duct, the ink key setting, the duct roll speed and the CUIM roll speed. These parameters were all shown to affect the printed ink density. No significant interactions, where the combined effect of two parameters is different from the sum of the independent effects, were found between the parameters investigated. A number of repeat investigations of certain parameters, principally temperatures, occur in the orthogonal arrays (see Table 1). This was mainly dependent on the results, some of which at the time appeared to be conflicting.

Temperature of the ink in the duct

The effect of changes in the ink duct temperature was investigated in six orthogonal array experiments. This was due to the differing results obtained both within the tests and between tests. The changes detected were in both magnitude and direction and are summarized in Table 2. The '*areas*' represent a number of measurement positions taken across the width of the web.

In each case, the temperatures of the press frame, the ambient and the fount were similar in each experiment. In addition, the paper used in each case was of a similar type. However, the coverage varied significantly both within some of the individual print jobs and between jobs. These varied from a low coverage of 5% up to high coverage of 35%. Following extensive analysis to capture thermal effects clearly, the relationship between the scanned coverage and a modified density response, |L1–L2|, per 10°C is shown in Figure 3. This shows an approximately linear response. The modified density response, |L1–L2|, represents the difference between the levels, L1 and

Table 2 *Ink density changes for orthogonal array experiments with respect to changes in the ink temperature.*

Experiment	Array					
	1B	1C	1D	1E	1F	1G
Area 1	0·10	–0·05	–0·01	0·00	–0·14	–0·08
Area 2	0·02	0·41	0·43	0·33	–0·15	–0·16
Area 3	0·00	–0·06	0·01	–0·03	–0·11	
Area 4	0·06	0·25		0·22	–0·14	
Area 5		0·20			–0·19	

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Table 3 *The effect of the minimum film thickness and temperature on the global parameters,* $U_l = 10{\cdot}0\ ms^{-1}$

Gap h_1 (mm)	TD (K)	Pressure (N)	T (K)	Flow Q (l/s)
0·08	303	1048	315·1	0·034
0·08	313	766	320·0	0·025
0·32	303	300	306·9	0·096
0·32	313	209	315·0	0·101

L2, used in the orthogonal array programme. Experimentally, the temperature change between these levels varied, depending on the individual trial, and the responses were scaled linearly to compensate. This allowed the experiments to be compared directly. For areas of low coverage, the printed ink density decreased as the ink temperature was increased, while in high coverage areas the printed ink density increased. Therefore, linking this to practice, when the temperatures are not controlled in the ink duct, the operators will need to adjust the press controls in different directions to achieve a pass copy dependent on the print coverage level. Once the pass has been attained, any further temperature changes will again result in changes in the product quality and clearly the change in ink density is dependent on the coverage of the individual print job.

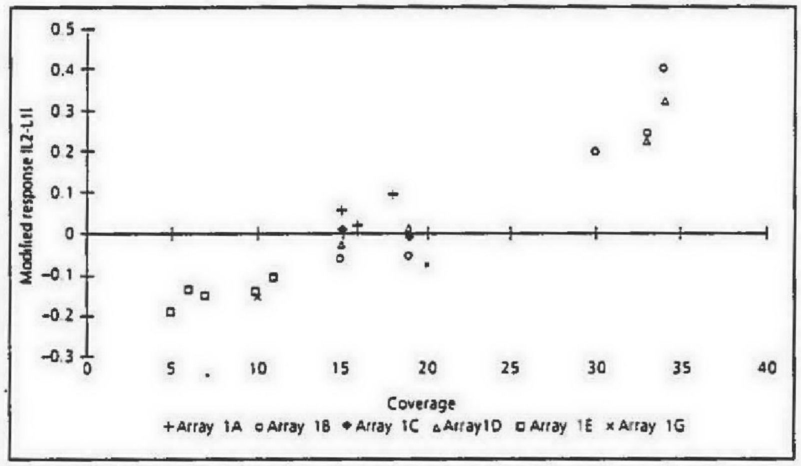

Figure 3 *Relationship between scanned coverage and ink density for a 10°C temperature change*

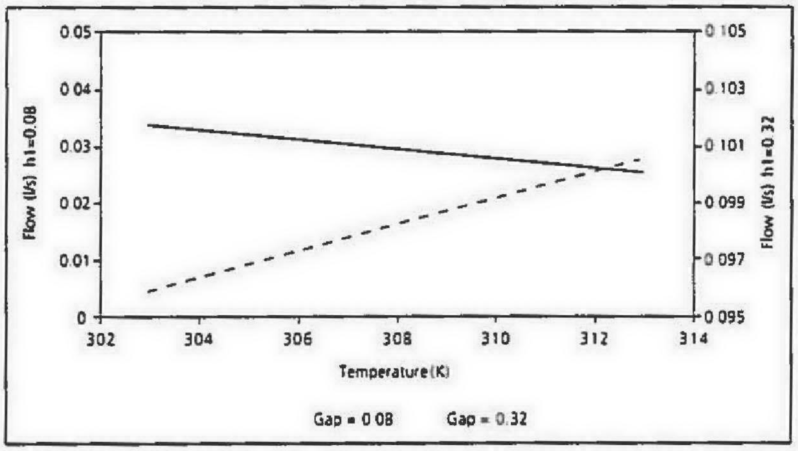

Figure 4 *Relationship between ink flow rate and temperature for different ink key/duct roller gaps.*

To establish an understanding of the phenomenon that is present required the application of the model described in the previous section. A parametric study of the conditions at the ink key/duct roll interface was carried out focussing on the minimum film thickness (h_a) and the duct temperature (T). Model output comprised blade load, nominal film temperature in the junction and the flow rate. The results are presented in Figure 4 and Table 3. These show that for the same 10°C temperature increase the flow rate decreases for the smaller gap while increasing with the larger.

This occurs since the flow at the ink key gap comprises both roller rotation and pressure induced components and this is further complicated by the temperature changes that occur at the ink key/duct roll junction. For the thinner gap, the pressure levels induced at the junction are high and so this component of flow is important. This is also markedly affected by the viscosity that varies most extremely in the case of lower duct temperatures combined with the higher temperatures generated in the junction. The net effect is a small decrease in nip flow as the temperature is increased. For the larger gap, the roller rotation induced flow is more dominant and as the duct temperature increases, so the pressure component becomes a smaller contribution. In this case, the net result is an increase in the flow through the junction.

In the printing application, the deflection of the keys in the segmented blade is also an important issue that is excluded in the thermohydrodynamic model explained previously. However, by referring to Table 3 the pressures generated in the junction for the smaller gap are largest. This high pressure will result in a more significant deflection of the ink key due to hydrodynamic action. The shearing action in the ink in the narrower gap is also reflected in a larger increases in the bulk film temperature (T), through the contact (Table 3), contributing to the warm-

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