Process stability in five-colour pad printing of contact lenses

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Abstract: This paper describes an experimental investigation into process stability and the effects of temperature on changes in wet ink transfer onto a contact lens. A production printing press was instrumented with thermocouples and thermal imaging camera to record strategic temperatures. The overall result from the thermal audit of the press shows that the excursions of the temperature are small and are not likely to have a significant effect on print quality.

The changes in product quality were measured using spectrophotometry. The main finding from colour measurements is that the process is stable. However, during the pre-production print runs most of the ΔE values lie outside the acceptable limit. There are a number of reasons for this, the most likely being that the viscosity of the ink lies outside the correct operating band.

The application of a cone on plate rheometer was suitable for measuring viscosity variation during the trial. The results showed a significant increase in ink viscosity. This was attributed to solvent evaporation and polymerization reaction.

Introduction

Contact lenses are optical devices used primarily to correct defective vision. The use of contact lenses has steadily increased over the years. With their increased popularity, many different types of contact lenses such as conventional or soft, rigid gas permeable (RGP), disposables (daily/weekly/monthly), extended wear, toric, bifocal, coloured and special effect contact lenses have been developed.

Coloured contact lenses are designed to change the eye colour and available in soft or extended version. They are also available with visual or non-visual correction including toric contact lenses. Colour contact lenses come in four

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tints: visibility, light filtering, enhancement and opaque colour. Opaque colour lenses are used to drastically change eye colour, no matter how light or dark the natural colour of the iris. They are usually available in hazel, gray, violet, green and blue. Opaque colour lenses have a ring of colour that covers the iris, while the middle of the eye is left clear so the pupil receives light signals as usual. Virtually all novelty or special effect contact lenses are opaque.

Soft contact lenses have become the most popular among all the types of contact lenses. They are made from flexible water absorbent polymers called hydrogels that are comfortable to wear. They contain hydroxyl groups, which allow them to absorb and hold water. A majority of soft contact lenses are composed of 2-hydroxyethylmethacrylate (HEMA) with small amounts of cross-linking agents that provide a hydrogel network. Polymers are the current most suitable material for manufacturing contact lenses; they have a variety of physical properties: amorphous (transparent), low density, hydrophilic, flexible in most cases, gas-permeable, unreactive, mouldable, easy to manufacture and in abundance.

The soft contact lenses for this investigation were formed of the HEMA polymer, cured with heat followed by printing and packaging.

Pad printing was used for printing opaque hazel colour on soft contact lenses as it has the ability to print onto curved surfaces and characteristics that are ideally suited to high precision: thin ink films (typically limited to a dried film thickness of 4 microns), excellent dot reproduction, the ability to print fine line rulings, superior registration and no moiré (Kiddell, 1999 (no. 3, no. 11)).

The dimensions and the quality of the printed dot, hence the quality of the entire image, is determined by the ink characteristics, the pad surface characteristics, the engraving definitions, the lens surface characteristics and the pad press parameters. The technological status of the cliché plate and silicone pad development and rotary pad printing machine parameters are not limiting factors. For an experienced pad press operator it is feasible to combine the different, and generally conflicting parameters and come to an acceptable printing result. The ink characteristics, however, are the least controlled, and yet they have an enormous impact on not only the printing behaviour, but also on the final dot definition and colour quality. A limiting factor is the availability of inks with appropriate printing characteristics. Up to now inks for printing on lenses have been developed for their adhesion and hydro expansion behaviour, rather than to accommodate printing requirements.

This paper describes the press trial which was carried out in order to evaluate the stability of the pad printing process and the ability to produce a repeatable and acceptable print on the lens. At the same time the thermal audit was carried out. The temperature of the pad press and the pressroom was monitored by means of thermocouples and thermal imaging camera in order to establish the effect of temperature on ink viscosity, hence ink transfer and, finally, the quality of the printed colour. As thermocouples placed onto rotating parts of the press could not be connected to the PC all the time for continues temperature monitoring the press was stopped twice for the thermal imaging camera calibration. The thermal data of the rotating parts of the press was collected by the thermal imaging camera in auto mode every 5 minutes.

During the trial two-component inks were printed onto a single lens type. The temperature is considered to be important from a printing viewpoint since previous work has highlighted its impact on ink, pad temperature and mechanical properties. The measurement of temperature on the press is important since it affects product quality and consistency of printing. The purpose of the investigation was to evaluate the temperature variations during printing and the effect of temperature on wet ink transfer, drying and print quality. Two measuring instruments notably thermocouples (Doebelin, 1990) and a remote infrared camera (Hurst (1970), Richmond (1985)) were employed for monitoring temperatures during printing. To carry out the thermal audit, the pad press was instrumented to measure temperature at twelve locations using thermocouples as well as taking thermal images every 5 minutes during printing using the remote infrared camera. Data was recorded via a computer system. The remote infrared camera (NEC San-ei Instruments Ltd, 1999) was used for temperature measurements of moving parts of the pad press such as the cliché plate, the doctor blade, the ink cup and the pads, which surfaces could not be reached or could not be touched during printing.

During the trial samples of three printed lenses were collected at equal intervals (every 1 minute during first 10 minutes and every 10 minutes for the rest of the trial) for post analysis of print quality. After printing for 30 minutes 32 lenses were collected consecutively to explore the possibility of cyclical variation through the application of Fourier analysis. After printing for 40 minutes the press was stopped for three minutes for monitoring temperatures of the cliché plate, the doctor blade and the ink cup body using thermocouples. After that the press printed for 65 more minutes. Four more sets of samples were collected after the press stopped as the lenses were still coming out the oven. The temperature of the press was then monitored during cooling for about an hour. Temperatures were measured at eight locations during the entire trial. Thermocouples were sampled at 1 Hz for the whole duration of the trial and cooling after the trial. The speed of the press was set at 55% of its maximum.

Temperature

Twelve thermocouples were used to monitor the temperature of the press and pressroom. To monitor the air temperature above the press, two sheathed stainless steel thermocouples 8 and 16 were fixed onto to the surface of the room ceiling, 8 to measure laminar flow input from the centre and 16 - from rear right.

One more sheathed thermocouple 12 was placed above the printing carousel. To monitor the printer bed temperature, three wire thermocouples 9, 13 and 15 were placed onto the printer bed, 9 at the front (operator side) of the press and 13, 15 at the rear side of the press. These will capture any temperature difference/gradient between the two sides of the printer bed. Three more wire thermocouples 4, 6 and 7 were suspended in the air by the base of the printer (operator side) being ready to measure the temperatures of the moving parts during press stoppages: 6 -the cliché plate, 4 - the doctor blade and 7 - the ink cup body. Since these are attached to moving parts, they are only used twice when the press has been stopped. These will also be used for the thermal imaging camera calibration. In total, eight wire thermocouples were fixed onto the surfaces that required temperature monitoring. The locations of the thermocouples are itemised in Table 1 and Figure 1. The temperatures at these twelve positions were recorded continuously every second during the entire press run.

Thermocouple/channel No	Location	Legend Abbreviation
4	Doctor blade (during stoppage)/air (during printing)	4
6	Cliché plate (during stoppage)/air (during printing)	6
7	Ink cup body (during stoppage)/air (during printing)	7
8	Laminar flow input from center	8
9	Front of printer bed	9
10	Ambient (above the floor)	10
11	Tape dispenser	11
12	Air above printing star	12
13	Right hand side of printer bed (rear)	13
14	Static elimination air nozzle (pad clean)	14
15	Left hand side of printer bed (rear)	15
16	Laminar flow input from rear right	16

Table 1. Summary of thermocouple locations

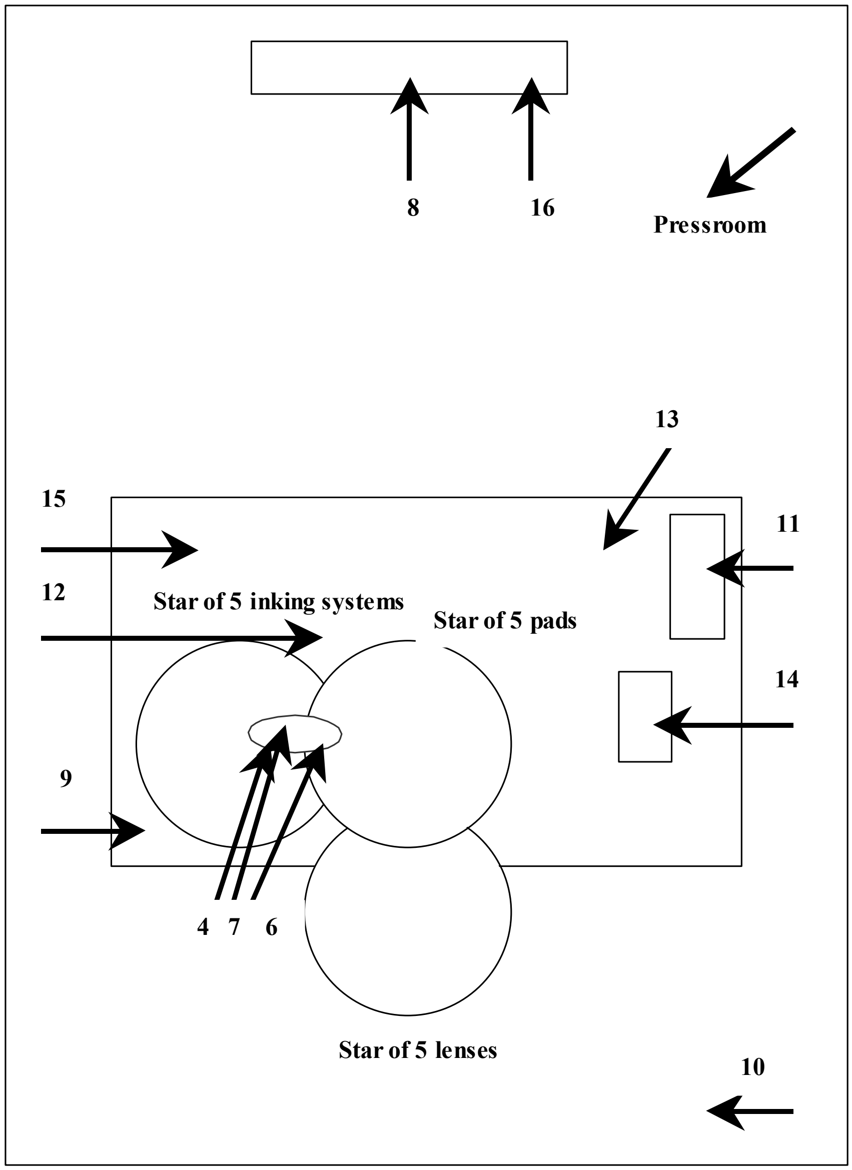

Figure 1. Schematic representation of the rotary pad press and thermocouple locations

To aid thermal audit of the press the remote infrared camera was used to facilitate temperature measurement of the moving parts from a distance of about 2 m at 5 minutes interval during the whole period (almost 3 hours) of the trial. An additional external lens (telephoto lens x2 TH71-343) was used in order to increase the resolution of the thermal imaging camera.

Figures 2 to 6 illustrate the temperature variations measured during the entire trial including the cooling stage. Clearly the temperature fluctuations are very different for different parts (see Table 2) of the press varying from 23°C (14) to 26.6°C (15). The air temperature variation in the press room is significant. It displays about 5.77ºC change varying from 18.01°C (4) to 23.78°C (8) during the trial (see Table 3).

Temperature\Thermocouple No	4	6	7	9	11	13	14	15
Min, °C	24.28	24.29	23.87	25.57	24.27	25.16	23.02	26.18
Max, °C	24.38	24.53	23.94	25.83	24.47	25.85	23.32	26.61
Mean, °C	24.32	24.40	23.90	25.70	24.34	25.60	23.16	26.42
Stdev, °C	0.02	0.06	0.02	0.04	0.04	0.12	0.06	0.09
Difference, °C	0.1	0.24	0.07	0.26	0.2	0.69	0.3	0.43

Table 2. Summary of the press part temperature

Temperature\Thermocouple No	4	6	7	8	10	12	16
Min, °C	18.01	18.11	18.12	21.72	19.02	21.98	20.65
Max, °C	20.73	20.75	20.76	23.78	21.45	22.87	22.61
Mean, °C	19.55	19.61	19.61	23.02	19.95	22.46	21.9
Stdev, °C	0.59	0.55	0.56	0.51	0.49	0.18	0.50
Difference, °C	2.72	2.64	2.64	2.06	2.43	0.89	1.96

Table 3. Summary of the air temperature

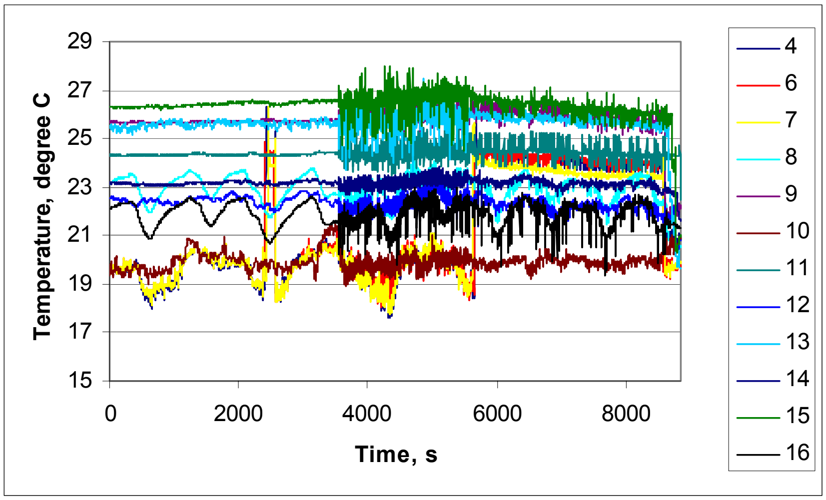

Figure 2. Temperature fluctuations at 12 thermocouple locations during the trial

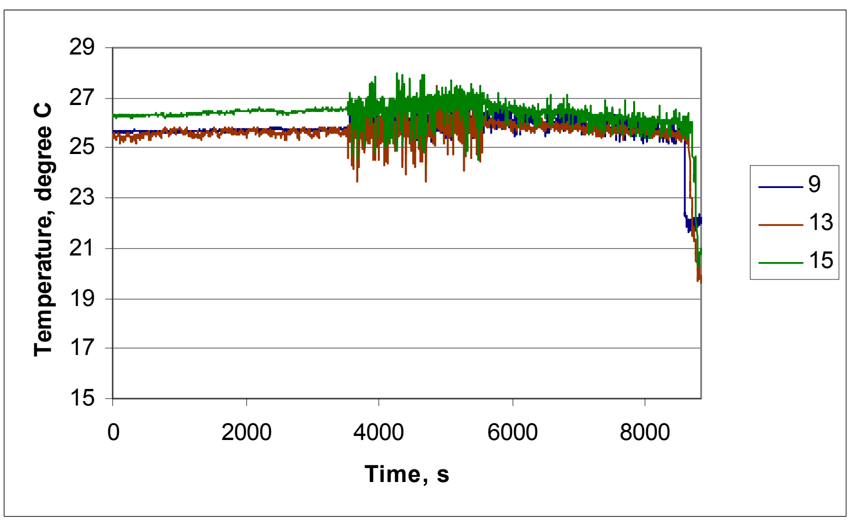

Figure 3. Printer bed temperature fluctuations during the entire trial

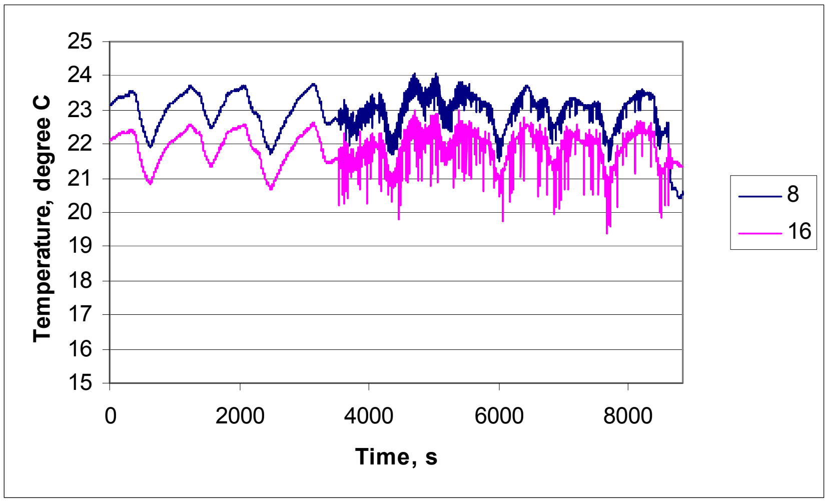

Figure 4. Laminar flow temperature fluctuations during the trial

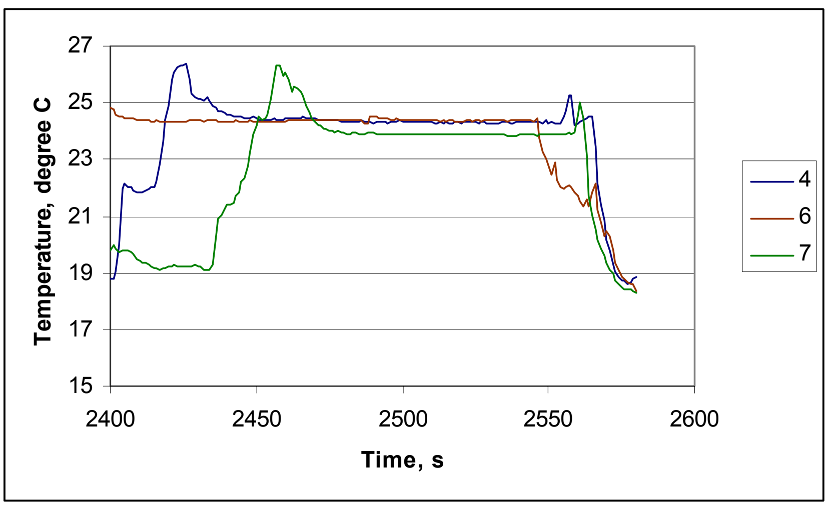

Figure 5. Doctor blade, cliché plate and ink cup temperature fluctuations during two minutes stoppage

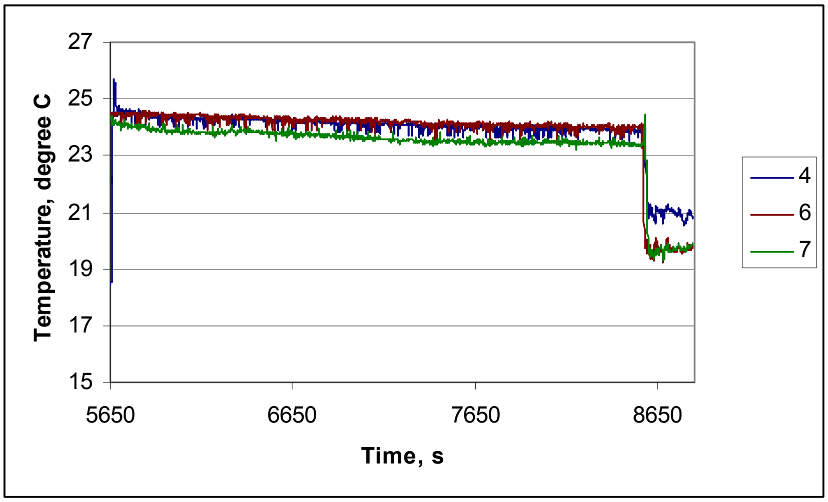

Figure 6. Doctor blade, cliché plate and ink cup body temperature fluctuations during press cooling down

Regarding the temperature traces shown in Figures 2-4 and 6 the data is unaffected until approximately, 3500 seconds (58 minutes) into the trial. Thereafter, all the traces are overlaid with a high frequency noise component, however the nominal level is still evident. The data, Figures 2-4 and 6, is consistent with some kind of device being switched on at that moment in time, and, that it is more likely to be a mains bourne interference problem.

Figure 3 illustrates the printer bed temperature and their fluctuations. It displays about 0.3ºC change at the front of the printer bed (right hand side), about 0.4ºC at the left hand side of the printer bed (rear) and about 0.7ºC at the right hand side of the printer bed (rear). Generally the temperature remains stable and uniform over the course of the trial.

Figure 4 illustrates the temperature fluctuations in the laminar flow stream. These display two very similar curves that follow two distinctive patterns of temperature change: warming up and cooling down. At first the heating is rapid, almost linear, having a high temperature gradient. Then the heating slows down and the gradient is much lower, once again the temperature change curve in this period of time is almost linear. Finally, the temperature falls, at first rapidly and then levelling off. The temperature variation across the laminar flow stream is about 1.2ºC being slightly higher at the centre. It displays about 2.6ºC change at the centre and about 2.0ºC at the right hand side. Generally the centre of the laminar flow has a slightly higher temperature at all times. The fluctuations are cyclic arising as a consequence of the thermostatic control that switches in and out to maintain a near uniform stream temperature.

Figure 2 shows temperature fluctuations of the press room air at two locations (above the floor and above the printing carousel, 10 and 12) during the trial. The temperature of the air above the floor fluctuates around the mean value of 20ºC during the entire interval of monitoring. The mean temperature of the air above the printing carousel is about 22.5ºC. This difference is attributed to the large electric motor in the base of the press that generates heat.

Figures 5 and 6 illustrate the temperature variations measured by the thermocouples 4, 6 and 7 during a two minute stoppage when they were placed in contact with the press component and the details during the cooling down phase respectively where again they were in contact with the press. The minimum air temperature of 18ºC was observed for the thermocouples 4, 6 and 7, Figure 2, while they were suspended near the front face (operator side) of the press base during the periods 0 to 2400s and 2550s to 5650s. With regard to Figures 5 and 6, the temperature at all three locations show similar trend, decreasing slightly after the press was stopped. The temperature of the ink cup body is slightly lower than the temperature of the doctor blade and the cliché plate at all times. It is most likely to be associated with the heat generated by friction between the doctor blade and the cliché plate.

The temperature at all thermocouple locations on the press remains relatively constant during the course of a print run. Insignificant heating of the whole press is observed. This is most likely to be associated with sufficient performance of the air conditioners and air circulation in the pressroom. The temperature and fluctuations are slightly different for different parts of the press. This reflects local heating by the large electric motor and the friction of the doctor blade during printing. Also the laminar air flow shows good thermostatic control at all times.

The temperature monitored by means of the thermal imaging camera was converted to a digital signal, which is displayed as a thermal image in colour (Micron Instrument Company, 2002), Figure 7. As shown in Figure 7, a white box is included to enable reference to the measurement position (see Figure 1). Each thermal image was automatically saved on a compact memory card for later processing and analysis.

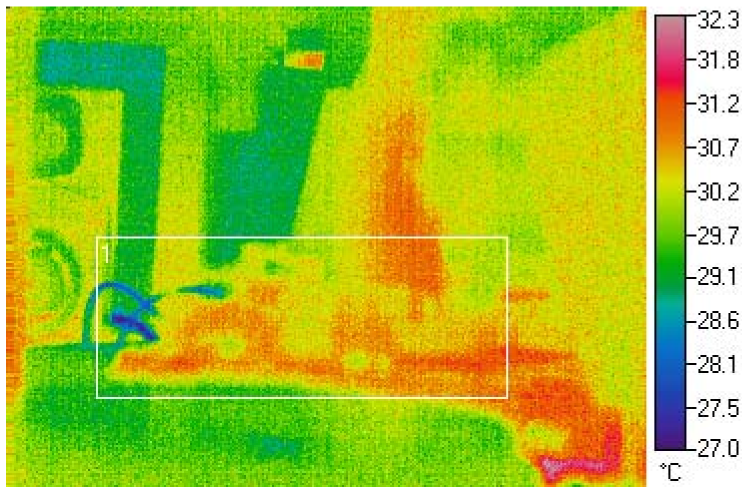

Figure 7. Typical thermal image of the press

Only one region was used in thermal imaging data interpretation: the printing carousel area (see the white box on Figures 7). Distinctive darker cables are evident on the left hand side of the printing carousel area and serve as a convenient reference feature. The area does not have distinctive hotspots and can be used as an indicator of trends, as it is not affected by the movement of the carousel table and the cliché plates. This area is also close to perpendicular to the camera and hence does not require significant corrections to compensate for the viewing angle. Thus, this area will be used to analyse the thermal trends and the distribution within the printing carousel area.

The difficulty associated with reflected radiation and the presence of several surfaces was minimised as far as possible through the use of a telephoto lens that narrowed the field of view while retaining a good depth of field.

There were 153 thermal images taken during the trial. The size of a thermal image was 152 kB. Every image consisted of 240x320 pixels. The temperature range –20 °C to 100 °C was used for all temperature measurements. All thermal images were converted into excel spreadsheets containing temperature values of a blackbody source for every pixel. The areas of interest such as the printing carousel were extracted from the excel spreadsheet and processed using graphic software, see Figure 8.

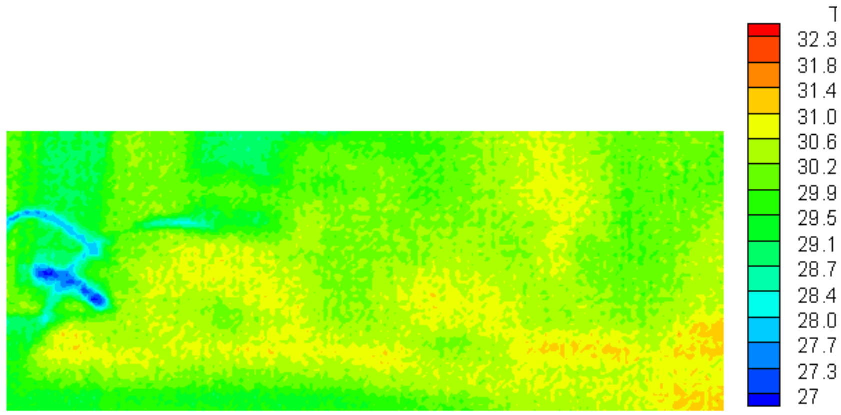

Figure 8. Typical thermal image of the printing star area

The results are itemized in Tables 4 and 5 and showed that the temperature variation of the press was very small. For example, the temperature variation across the printing carousel area is about 5.1 °C during printing and is exactly the same during cooling one hour later. During the trial, the average temperature of the printing carousel area showed a trend to increase from 30 °C to 30.16 °C after more than one hour printing.

Temperature\Image No	127	128	129	130	131
Mean, °C	30.3	29.8	29.8	30.3	30.6
Min, °C	26.8	26.3	26.1	27.	26.8
Max, °C	31.6	31.3	31.4	32.1	32.2

Table 4. Summary of the printing star area temperatures during printing

Temperature\Image No	143	144	145	146	147	148	149
Mean, °C	30.5	30.0	29.9	30.5	29.9	29.8	29.9
Min, °C	26.8	26.5	26.6	27.3	26.6	26.4	26.5
Max, °C	32.3	31.7	31.6	32.4	31.6	31.7	31.6

Table 5. Summary of the printing star area temperatures during cooling

The overall result from this measurement shows that generally the excursions of the temperature were small and are not likely to have a significant effect on the print quality.

Colour

The aim of this part of the investigation was to understand the natural colour fluctuations that occur within the pad printing process (Field, 1999). The inks were applied to the lenses using five printing stations on the pad press.

Traditionally single lenses are removed from each colour unit during printing and used for quality control checks. However, to evaluate the affect of process parameters it is first necessary to investigate the consistency of the printing process. A total of thirty two lenses printed sequentially were collected once steady conditions had been achieved, with no alterations being made to the press. Additional multiple sample sets of lenses were collected during investigation into the thermal balance of the press.

The quality of printed colour was measured using a reflectance/transmittance spectrophotometer ColorQuest XE. Universal Software was used to collect, analyse and display colour data. $L^* a^* b^*$ values of printed lenses were measured by the spectrophotometer, compared to the standard colour and ΔE values were calculated between the standard colour and each of the lenses (British Standards, 1988). Three different graphs were plotted showing the variability of ΔE (Figures 9,10 and 11).

Figure 9 shows the variability of ΔE within 32 sequential lenses with standard deviation being 0.12 and ΔE average being 1.32 with respect to the standard. However the ΔE variation within the 32 samples is very small, experiencing about 0.5 indicating that the process is stable. Most of the points (27 out of 32) lie above the limit of 1.2. This is not acceptable and indicates that the process is printing out of specification. There are a number of reasons for this, the most likely being the possibility that the viscosity of the ink lies outside the correct operating band. This is known to affect wet ink transfer and, hence, the colour of the printed image.

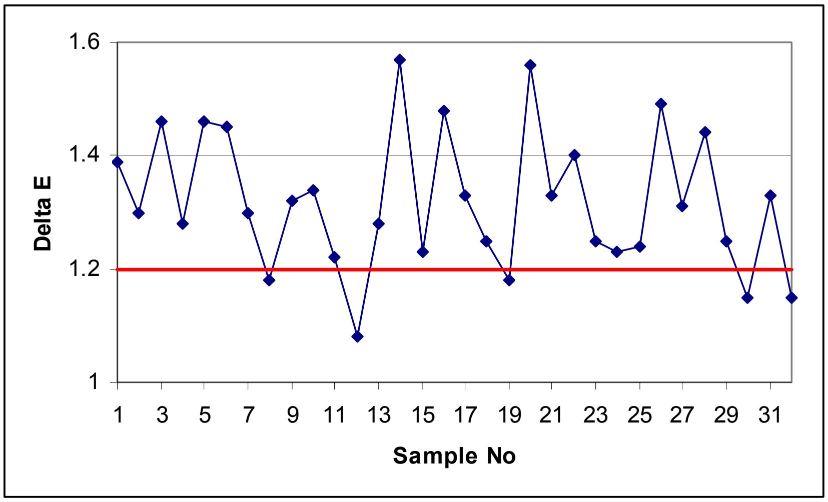

Figure 9. ΔE values for thirty two consecutive lenses

As shown in Figure 9 there is a variation of approximately 0.5 in ΔE levels. Fourier analysis of the ΔE values was used to highlight whether these variations were random or could be attributed to cyclical variations. The results showed that the fluctuations did not appear to follow any dominant frequency.

Figure 10 shows ΔE variation within the first ten minutes of printing for ten sets of lenses. Although the standard deviation is very small indicating early stabilisation of the process, the ΔE values lies above the acceptable limit at all times.

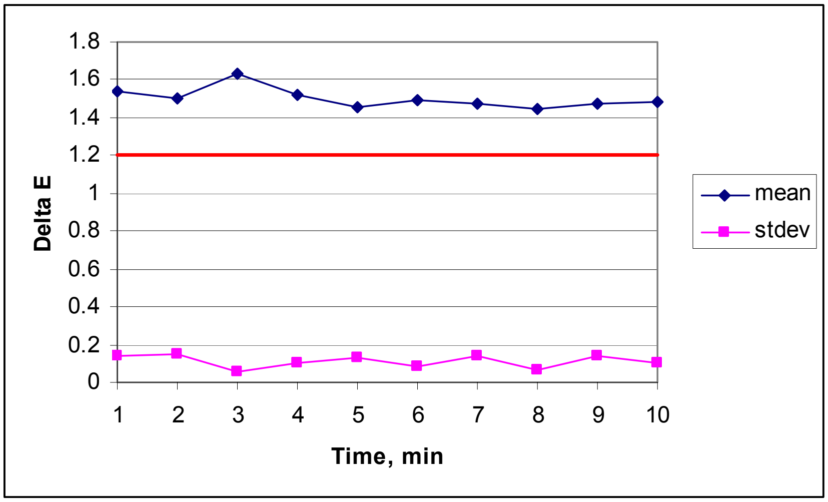

Figure 10. ΔE variation and standard deviation for ten sets of lenses collected every minute

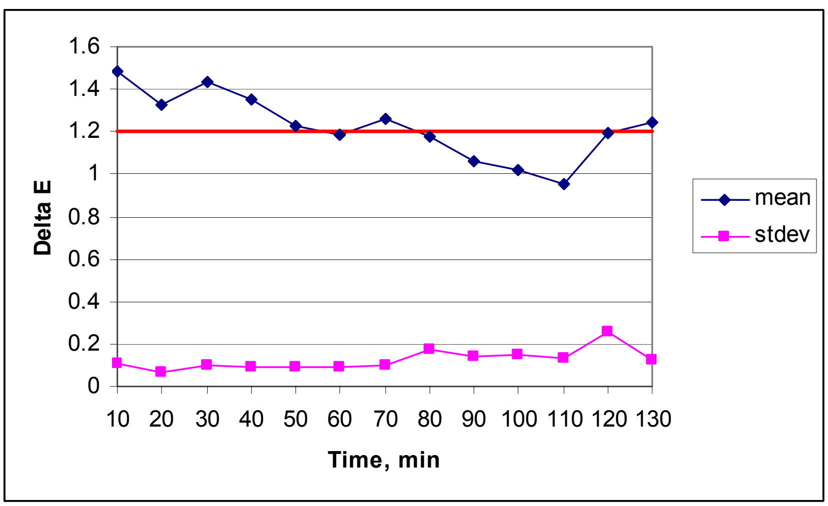

Figure 11. ΔE and standard deviation for thirteen sets of lenses collected every ten minutes

Figure 11 illustrates ΔE variation for lenses collected every ten minutes during the entire trial. The ΔE showed a trend to decrease from 1.44 down to 0.96 during printing for 100 min. It then increased from 0.96 to 1.24 during the final 20 minutes of the trial. Again the standard deviation remains small confirming the process stability.

Viscosity

Knowledge of ink viscosity is important since it is a key parameter in the pad printing process (Thompson, 1998). Viscosity changes take place at various stages within the pad printing cycle. The two main stages include the ink deposition onto the etch plate where it will be subjected to very high shear stresses during doctoring and during the transfer stage where it will be subjected to compressive and tensile stress.

The objective of the laboratory trial was to measure viscosity variation with time for a single ink colour. The first viscosity measurement was taken straight after mixing the two components and allowing the trapped air to escape. Then the ink was placed in the water bath at 24°C. The temperature was controlled by altering the hot plate temperature and was kept at 24°C ±1°C. It took about 13 minutes to perform one measurement. Six more ink samples were measured every 15-20 minutes during the entire trial (about 2 hours). Six T type thermocouples were used to monitor temperatures: three in the water bath, and three in the ink jar.

A cone on plate rheometer was used to establish ink characteristics at different shear rates. For this test, a cone with 35 mm radius and 0.5 degree taper was selected. The speed of the cone and the torque necessary to turn it were measured electronically, recorded and used in viscosity calculations. Figure 12 illustrates the relationship between viscosity and shear rate for seven ink samples. Clearly the ink viscosity decreases as the shear rate increases and so they shear thin. During the trials, the ink viscosity showed a trend to increase: from 13.9 Pas to 17.9 Pas during 1 hour and a half at the shear rate of 120 /s; from 10.7 Pas to 14.4 Pas at the shear rate of 720 /s and from 10.0 Pas to 13.5 Pas at the shear rate of 1680 /s, Figures 12-13. The increase in viscosity was most likely to be associated with solvent evaporation (the ink was kept in an open jar during the trial) and polymerization. As the temperature was relatively low it is likely that the solvent evaporation rate was also low and had a less significant effect on viscosity increase and, hence, polymerisation may have a more significant impact and this require further investigation.

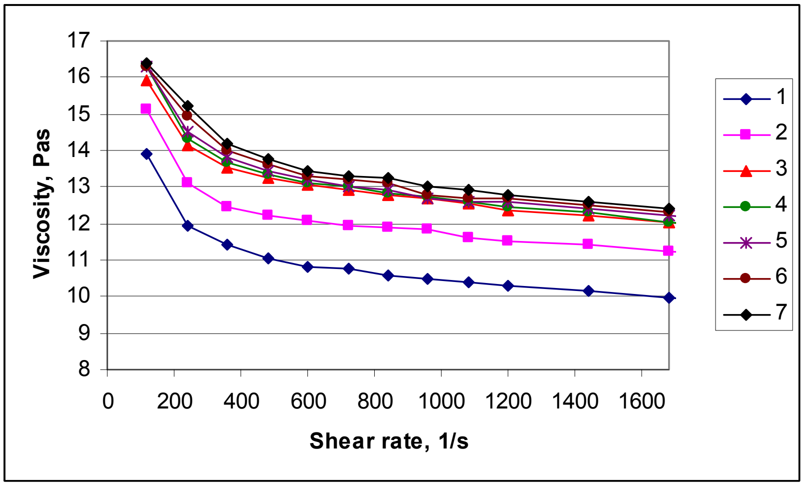

Figure 12. The relationship between ink viscosity and shear rate for seven ink samples

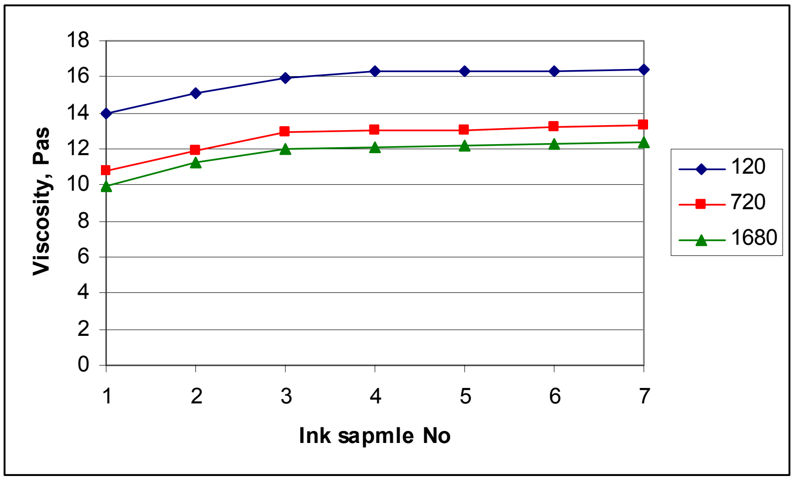

Figure 13. Viscosity changes during the trial for three shear rates

Conclusions

The following conclusions can be drawn from this investigation:

The main finding from thermocouple readings is that the temperature at all thermocouple locations on the press remains relatively constant during the course of a print run. Insignificant heating of the whole press is observed. This is most likely to be associated with sufficient performance of the air conditioners and air circulation in the pressroom.

The temperature and fluctuations are slightly different for different parts of the press. This reflects local heating by the large electric motor and the friction of the doctor blade during printing.

The analysis of thermal images confirmed that the temperature variation of the press is very small. The difference between the ink cup body temperature and the cliché plate or the doctor blade temperature is about 0.6 °C.

The main finding from colour measurements is that the process is stable. However, the process is printing out of specification over most of the trial duration. There are a number of reasons for this, the most likely being the possibility that the viscosity of the ink lies outside the correct operating band. This is known to affect wet ink transfer and, hence, the colour of the printed image.

The increase in viscosity was associated with solvent evaporation and polymerization. As the temperature was relatively low, the solvent evaporation rate was also low and had a less significant effect on viscosity increase. The impact of polymerisation rate on viscosity change requires further investigation.

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