Dynamic measurement of ink film thickness, pressure and temperature in rolling contacts

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Abstract

The understanding of the dynamics of the nip contact in printing and coating applications is key to the transfer mechanisms. This paper describes a series of experimental trials that have been carried out to obtain the physical characteristics within this contact region. A full-scale printing unit has been instrumented to allow the dynamic measurement of pressure through the nip region on both a solid copper and at the rubber-steel interface of a covered roller. Measurements were made using a dry contact, a Newtonian fluid (oil) and a non-Newtonian fluid (ink). In addition, the fluid film thickness each side of the contact has been measured using non-contact methods providing data on the film thickness and the splitting ratios. The system used incorporated both capacitance and inductive probes, which eliminated the influence of vibration or eccentricity. Finally, the build up of temperature in the contact and rubber layer has been evaluated. The results provide data for assessing the stresses on and within the rollers and comparisons for numerical models. They also give an insight into the mechanisms within the nip contact.

Introduction

The measurement and analysis of the fluid characteristics with a roller system is critical to the understanding of the process dynamics. It is this system that controls the flow within the system and the ultimate print quality. This study focuses on obtaining reliable quantifiable data relating to the pressure profiles and temperature deviations in the nip contact and the film splitting.

Numerous papers have been produced on the theoretical modelling of the pressure profile through a nip contact for both hard [1] to [3] and soft elastohydrodynamic lubrication cases [4] to [7]. However, limited experimental data is available from which the applicability of these models can be assessed. In the printing field trials have generally been carried out on laboratory equipment such as tackmeters and inkometers [8]. This paper presents a set of comprehensive trials carried out to measure the pressure profile using miniature pressure transducers on a production scale press.

The non-contact analysis of film thickness in a high-speed rotational system provides a difficult and experimentally exacting problem. Numerous techniques have been employed in differing applications including the use of light reflectance, the dielectric of the fluid [9], x-ray fluorescence, infrared [10] and image processing techniques. However, these techniques have predominantly focussed on static situations and struggle to adapt to either rotation or vibration of the system. Both of these are important in printing applications, a suitable method was incorporate some of these techniques to produce a combined inductive and capacitance system. The capacitance system measures the change in dielectric as the film thickness changes and the inductive probe the distance to the measurement surface.

This paper discusses the experimental apparatus used to accurately measure the performance of the fluid within the roller train. This is followed by a presentation, analysis and discussion of the results from which conclusions on the roller systems can be made.

Experimental apparatus and programme

A single stand of a Baker Perkins G12 web offset print unit was installed and instrumented. A schematic of the top half of the roll configuration to the plate is shown in Figure 1. This allowed the detailed investigation of press parameters to be carried out in a controlled manner. The investigation aims were to evaluate dynamically the nip contact in terms of pressure, film thickness and temperature. Different fluid options were to be used in the trials to aid the understanding of this process. The press was run in three configurations being dry, with a Newtonian fluid (oil) and with a non-Newtonian fluid (ink).

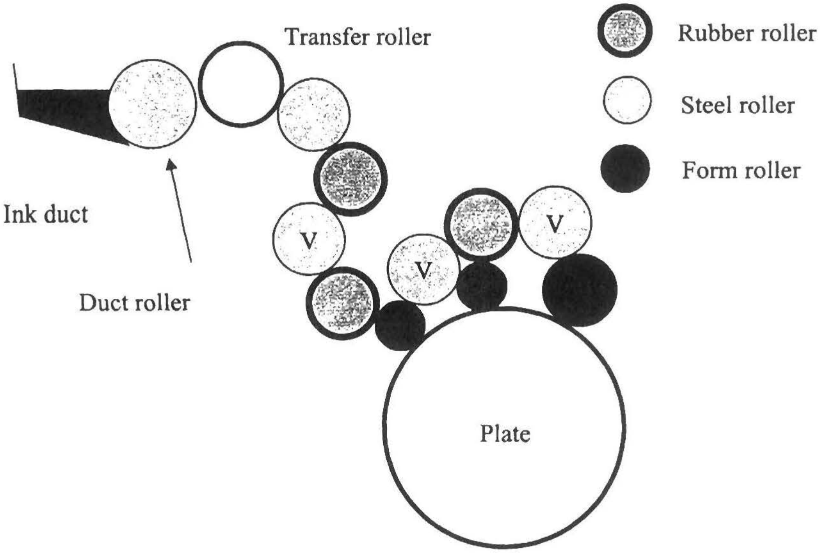

Figure 1 Schematic of G12 press top half roller configuration

The ink supply system consisted of a segmented ink keys and it was adapted to for manual control of the key position. This allowed the ink film thickness on duct roller to be accurately controlled. This was calibrated prior to operation and the gap set to 0.03 mm and 0.05 mm. These were similar to production settings. Throughout the programme the duct roll speed remained constant. The press unit was not installed with paper handling facilities as this would minimise the experimental cost and facilitated extended trials. However, the fluid used (ink or oil) had to be removed from the system to represent a printing system. After various trials this was achieved by the use of a squeegee blade running against the plate cylinder and doctoring off the fluid.

Four types of instrumentation were required to measure roll speed, pressure, film thickness and temperature. Each of these will be discussed in turn. The roll speed was assessed using a slotted disc (20 slots) mounted on the roll shafts and using an inductive proximity meter to count the slots as the roll rotated. Measurements were averaged over 5 seconds allowing a resolution of 0.01 rev/s to be resolved.

Pressure measurements were carried out on both the surface of a copper roller and the rubber-core interface of the covered rollers. Piezo-resistive pressure sensors were used to measure the pressure with a nominal diameter of 3 mm. These were mounted in the copper roll flush with the surface. A mounting was used to ensure the transducer was flush, with a silicone sealant holding the sensor in the holder, Figure 2. Temperature compensation was used to minimise the influence of changing temperature. The signals were removed from the roller using slip rings mounted at the end of the roll, data capture was effected automatically using a high frequency data acquisition system. The use of slip rings allowed measurement through the rotation of the roll but due to practical considerations is applicable only to test facilities and not production presses.

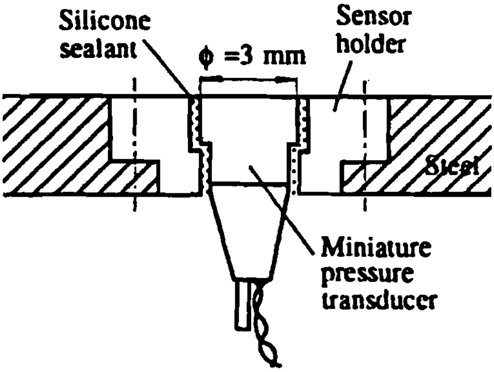

Figure 2 Pressure sensor arrangement

The pressures at the rubber-core interface were measured using similar sensors. An existing roller was recovered and the sensor added before the coating process. The only change in the sensor was its ability to withstand the increased temperature it would experience during curing (150^{0}C). The signals were again removed using a slip ring arrangement.

The film thickness was measured on the copper rollers using capacitance and inductive probes. These are mounted adjacent to each other, Figure 3. The capacitance probes measures the film thickness as the dielectric in the gap will change. The advantage of this is the signal is relatively insensitive to shear rate and temperature changes, making a robust system. However, any relative motion between the sensor and target surface (roll) will affect the capacitance, hence giving a false reading. By using an inductive probe in parallel to measure the distance to the roller surface this effect can be eliminated. The system can then remove the effect of vibration or eccentricity in the roller motion and provide an accurate reliable film thickness measurement. For this application it is critical that the dielectric constant of the fluid is determined before hand. This is carried out using a known volume of ink and parallel plate capacitor theory. Analysis indicated a wide range of capacitance of the fluids used from 2.5 for the oil, 3.39 for magenta, 3.62 for cyan, 3.90 for yellow and 5.43 for black.

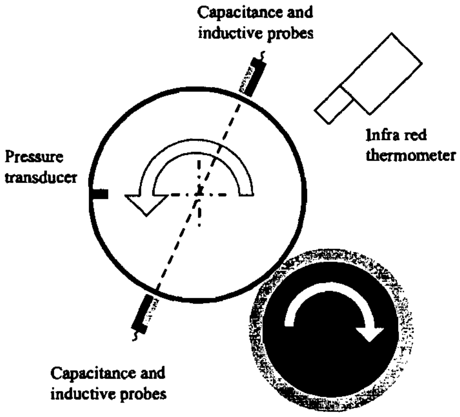

Figure 3 Capacitance and inductive probe arrangement

The sensor pairs were mounted either side of the nip contact to evaluate the film thickness. The operational distance for the sensors was set to 0.25 mm from the roller surface. It was not possible to measure on the rubber roll, as the rubber is not conductive. The possibility of altering the rubber properties was evaluated but this would change the material properties to such an extent (by hardening) that they would not be representative.

The temperatures in the rubber roll were measured on the same roll as used for the pressure measurement. During the recovering a K-type thermocouple was mounted at the rubber core interface and in the middle of the rubber layer. The temperature signals were then removed using the slip ring. The ink temperature on the surface of the rollers were measured using an infra red thermometer. This allowed for cross correlation with the thermocouple readings and to help establish the fluid viscosity on the rollers.

The experimental programme focused on the nip contact, evaluation of the film splitting and the thermal behaviour of the rollers. The trials were divided into three sections as follows:

- Dry trial
- Low speed wet trials
- High speed wet trials

The dry trials evaluated the effect of speed and engagement on the pressure and temperature build up in the system. These were followed by a number of wet trials evaluating speed, engagement and the film thickness for Newtonian and non-Newtonian fluids. Finally, the speed of the rollers was increased to represent typical printing conditions. The experimental settings for the wet trials are summarised in Table 1. At the higher speeds the film thickness probes were not used due to problems of capacitance probe contamination and ink misting.

Fluid	Speed range ms^{-1}	Roller engagement h_0 mm	Duct gap h_d mm
Ink and oil (low speed test)	0.2 to 1.0	0.1, 0.2, 0.3	0.03, 0.05
Ink (high speed test)	1.7 to 3.0	0.2	0.03, 0.05

Table 1 Experimental programme

Results and discussion

The results will be divided into sections relating to the each of the different instrumentation used. The objective of the work was to provide experimental data to give an understanding of the mechanisms taking place in the roller train and also to provide data from which numerical models could be compared.

The pressure through the nip was measured both on the surface of the copper roll and at the rubber-core interface on the covered roller. These measurements were made at a number of engagements, speeds and supply fluid film thickness, Table 1. Typical results for the dry contact are shown in Figure 4 for both the surface of copper roll and at the rubber-core interface. These results show the pressure change through the nip. The copper surface pressure profiles are not Hertzian in form with a sharper increase at the inlet producing a skewed pressure distribution. Analysis of the pressure on the surface of the copper roll indicates a small sub ambient pressure at the inlet with an increased sub-ambient at the outlet. This feature is not fully understood but could be due to the bulging of the rubber (a Poisson's ratio of approximately 0.5) and non-uniform surface strains on the surface of the rubber in the contact. The pressures measured at the rubber core interface are significantly lower (approximately 30%) than those at the copper surface, with the contact width being increased significantly. In these contacts, the pressure distribution is symmetrical with no sub-ambient component. These profiles support the explanation of the non-uniform surface strain contributing to the sub-ambient component of the pressure profile on the copper roll surface. Increases in the press speed were shown to narrow the contact width, a result of the increased dynamic loading of the rubber, for further explanation refer to [11].

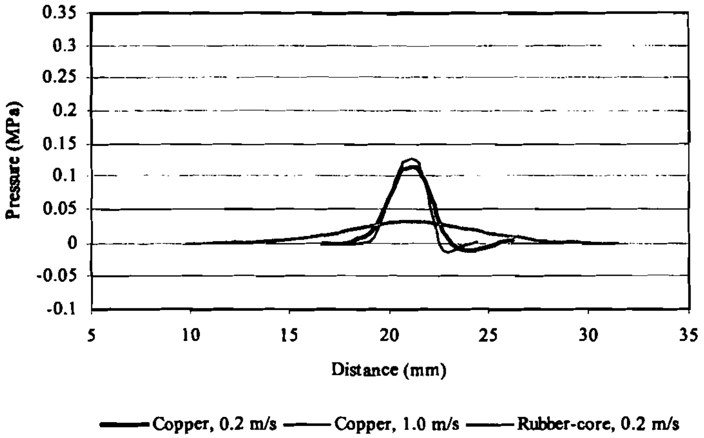

Figure 4 Pressure profiles through the nip contact for a dry contact

The pressure profiles for the wet contact are significantly altered from the dry condition, Figure 5, with the sub ambient region at the nip exit being significantly larger. This sub-ambient region also increases with the quantity of fluid supplied (supply rate) and the speed of the rollers. In addition, the maximum pressure through the contact also increases as the speed and the supply rate is increased. It should be noted that for these measurements in all cases the nip is operating in a starved condition.

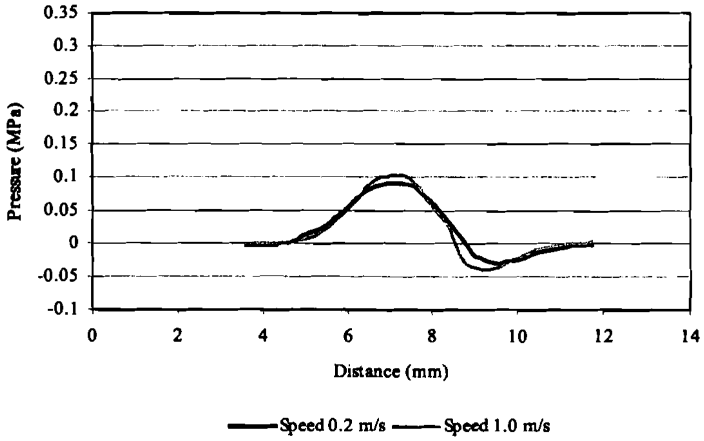

Figure 5 Pressure profiles through the nip contact for a wet contact (oil), h_d 0.03

Changing the fluid to ink causes a further change in the profiles of the pressure distribution, Figure 6. The form is still similar though the maximum pressure, contact width and sub-ambient values are increased. The resultant increase in the sub-ambient is a direct result of the differing rheological properties between the two fluids. Again, as the speed of the press and the flow rate into the nip contact increase, so the magnitude of the sub-ambient also increases.

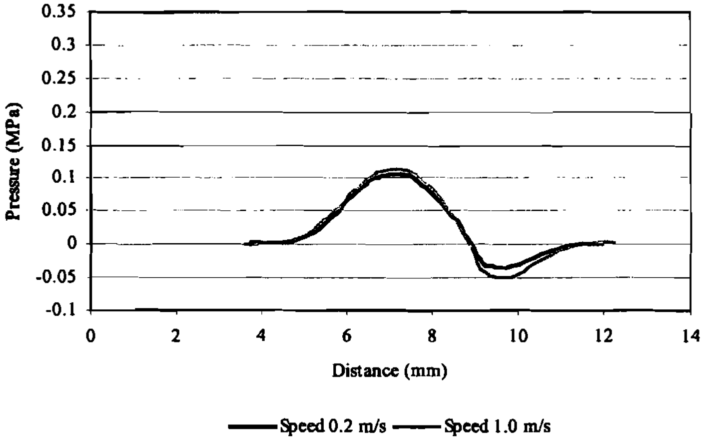

Figure 6 Pressure profiles through the nip contact for a wet contact (ink), h_d 0.03

Similar trends, to those reported above, with respect to the influence of flow rate and roller speed on the pressure profile were found when the engagement of the nip contact was increased from 0.1mm to 0.2 mm and 0.3 mm. However, the overall size and magnitude of the pressure distribution altered, as shown in Figure 7. This shows that as the engagement is increased both the contact width and maximum pressure within the nip region are also increased. By referring to the contact width it can be seen that the increase in width with respect to engagement is non-linear with the contact increasing from approximately 4 mm to 6 mm and then to 7 mm for the three engagements respectively. In addition, the maximum pressure through the nip contact is also significantly increased with the engagement, in this instance from 0.125 MPa through to 0.325 MPa. The sub-ambient pressure detected at the nip entry region become more significant with the increasing engagement as larger surface strains are induced on the rubber surface.

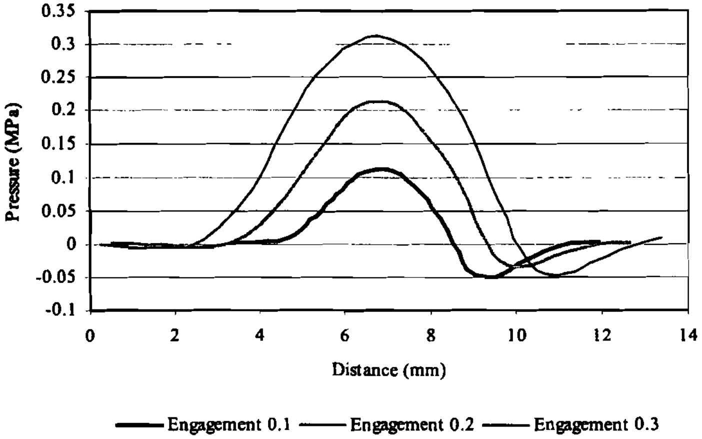

Figure 7 Pressure profiles through the nip contact for a wet contact (ink) for different roller engagements (h_d 0.03 mm, 1.0 ms^{-1})

As the speed was increased further the most significant feature is the increase in the sub-ambient at the nip exit, Figure 8, with the maximum pressure also increasing. In addition, the results indicate that the contact width narrows slightly with increasing press speed.

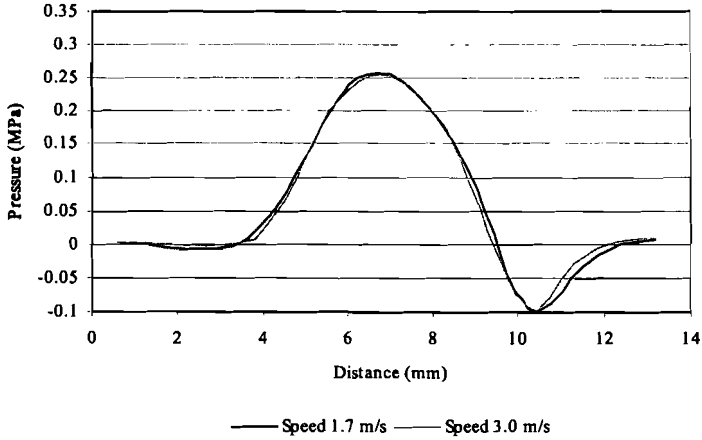

Figure 8 Pressure profiles through the nip contact for a wet contact (ink) for different roller speeds (h_d 0.03 mm, h_0 0.2 mm)

The fluid film thickness was monitored during the trial with measurements made on the inlet and outlet side of the copper roll, Figure 3. Using this arrangement, under steady state conditions, the data could provide information on the film splitting at the nip contact. Measurements were made for both the Newtonian and non-Newtonian fluids, with typical results shown in Figure 9. These show larger film thickness on the inlet as would be expected. There are no consistent significant changes in the film thickness with respect to press speed, indicating the transfer system (i.e. the transfer roll) is operating in a manner to supply a constant volume of ink into the supply train. The quantity of ink in the system was larger for the ink, indicating that the rheology was having a significant impact on the flow into the roller train from the ink duct, for further details see [12]. The larger film thickness would also account for the difference noted earlier in the maximum pressure measured in the nip contact.

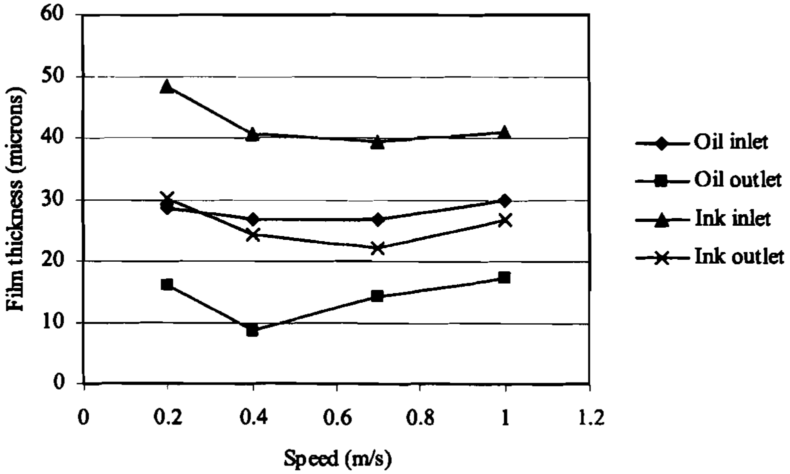

Figure 9 Film thickness measurements (h_0 0.1 mm, h_d 0.05mm)

The transfer ratio are calculated as the percentage of fluid left on the roller after the nip contact and these values are summarised in Table 2, with the measurements at different speeds being averaged. This shows that more of the oil is transferred than the ink. Also, the response to increasing the supply rate to the system is affected by the fluid, with more fluid being transferred for the oil while for the ink less is transferred to the next roll. These results highlight the importance of understanding and controlling the fluid rheology when a repeatable and consistent printed product is required.

Engagement (mm)	Supply	Oil transfer ratio	Ink transfer ratio
0.1	High	0.45	0.65
0.1	Low	0.46	0.61
0.2	High	0.50	0.64
0.2	Low	0.59	0.60
0.3	High	0.30	0.75
0.3	Low	0.38	0.58

Table 2 Transfer ratio's for ink splitting

During the trials the temperature of the rubber was monitored as the speed of the rollers increased for both low and high ink supply levels. Typical ink results are presented in Figure 10 for the ink during the low speed test and again for the ink at the higher speed trial in Figure 11. These show the increase in speed for each throughout the trial run and the slight variation in roller speed. At all times the copper roll operated at a faster speed than the rubber covered roll and this agrees with published data [13]. The speed differentials became increasing apparent when either the roller engagement was increased, the change from the dry to wet contact or increasing the roller speed.

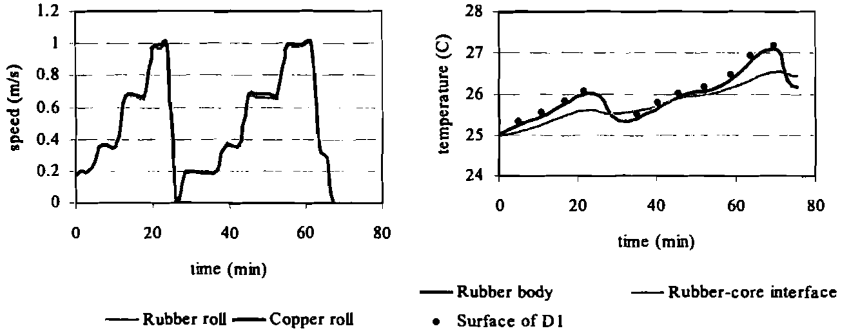

Figure 10 Surface speed and temperature variation for ink during low speed tests, h_0 0.2 mm

The effect of speed on the amount of slippage can be is a consequence of the interfacial friction between the rolls, which has been shown to have an influence on the slip. The increase in roller speed will increase the interfacial stress, which in turn increases the slippage. The changes are occurring at speeds that could be expected predicted analytically. The change in speed affected by the dry to wet contact transition can also be explained using the interfacial friction.

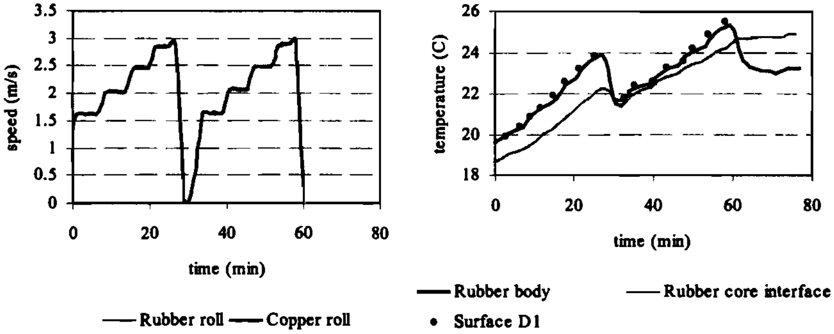

Figure 11 Surface speed and temperature variation for ink during high speed tests, h_0 0.2 mm

The results clearly show an increase in temperature as the speed of the rollers are increased with the reduction in the middle of the test occurring while the press is stationary. In addition, the temperature in the middle of the rubber layer increased at a greater rate than that at the core-rubber interface. There was also an increase in the rate of temperature change with the greater engagements. These increases in temperature can be attributed to the deformation of the rubber through the nip contacts, as there are no external heat sources. The build up of temperature will be dependent on the rate and magnitude of deformation (i.e. the speed and roller engagement). The higher temperatures in the middle of the rubber layer supports this explanation that the deformation as the cause of the temperature source and that the low conductivity of rubber result in the heat being generated at a faster rate than it can be removed. These results indicate that temperature build up in the rubber rollers is a significant factor in printing press.

Conclusions

The experimental programme utilising an instrumented commercial web offset printing press has been completed successfully. The programme evaluated nip pressures, film thickness on the copper rollers and the build up of temperature in the rubber coating on rollers. The findings can be summarised as

- At the nip exit large difference between the Newtonian and non-Newtonian (ink) fluids were detected, with greater sub-ambient pressures due to the fluid rheology for the non-Newtonian fluid.
- At the rubber-core interface the pressure was approximately 30% of that in the nip contact.
- Fluid flow through the system was higher for the Newtonian fluid.
- A small amount of micro-slippage was detected between the rollers.
- Hysteresis in the rubber lead to a build up in temperature in rollers, which was removed by the fluid, heating up the fluid at the same time.

This work has also provided information to support the development of finite and boundary element numerical models for the evaluation of nip contacts [14], [7].

Acknowledgements

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