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# A Squeeze Film Model of Ink Flow under a Printing Nip

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***Abstract***—this research includes a modelling for film flow, where a model was created according to literature review with depth about 2.55 µm and width about 20 µm the squeeze film analysed at the first 1 µm before entering the cell. The model was created using solid works then the model was analysed using CFD in ANSYS software using different range of flow rate to assess flow characteristics for the printing. CFD simulation was created for Newtonian fluid in ANSYS software. The results shows the increasing in the velocity will lead to decrease in the ink thickness layer, in this research the testing velocity was taken in range of (8-14) m/min.

***Keywords— Squeeze Film; Printing Nip; ink;***

## I. Introduction

There are several types of known printing process techniques. The types of printing process are letterpress printing, offset printing, gravure printing, inkjet, flexography and others. Flexography can be said as a modern form of printing process using letterpress printing technique. Letterpress printing technique itself is a printing technique that uses the relief printing process, which is a process that uses a prominent surface that has been given ink [1]. The process of letterpress uses the pressing process to the part to be printed. Flexography uses the same principle as letterpress printing, which uses a prominent part of the plate or a printing material which is then pressed on the part to be printed. What distinguishes flexography with letterpress printing is, flexography using a flexible material. Flexography is usually used for printing packaging process such as wrappers and boxes. This is because the use of flexography printing is very easy and able to use water-based inks as well.

Some advantages of flexography, among others, that it can work with high press speed, can be used for diverse materials, maintenance needs an equipment that is not too expensive, can be used for printing process in the long operation, die cutting, laminating, varnishing and printing can be done in one pass. In addition to some of the advantages of flexography printing, there are also some shortcomings of flexography printing which is the cost for making flexography printing plate low cost, takes a long time to do the process of die cutting, varnishing, laminating, and printing, and requires quite a lot of substrate material to do printing.

Printing process using flexography printing can be done through several processes such as preparation of image or object to be printed, plate making, mounting and then printing process. The process of image preparation is done by preparing the object to be printed which will then be captured by camera, computer or scanner. Preparation of this image is needed for the next stage of making plate flexography. The making of flexography plate using flexible material such as plastic material, ultra violet sensitive polymer are also called as photopolymer. The process of making the plate produces a relief in accordance with the results of the image preparation. Furthermore, from the mounting process, this process puts the plate that has been made on the cylinder located on the printing press. In the mounting process, this flexible plate is placed with mounting marks in the form of micro-sized dots to achieve a high degree of accuracy. Next is the printing process, in this process the ink is transferred by pressing by using a roller that is pressed through the plate to the substrate to produce the image on the printing object [2].

In the image transfer process, this process occurs on the printing nip. At the time of image transfer occurs, the column of ink with the size of the microscopic level is squeezed between the plate and the substrate. So the image transfer process occurs with a dot pattern that appears on the plate. This column of ink can be modelled with squeeze hydrodynamic film. By modelling the squeezed column of ink can provide

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insight into the effect of ink rheology and dot form on the creation of a printed image where the shear stresses and the viscosity of the ink effect on the image quality.
Rheology is the study of fluid flow, especially liquid fluid which has a continuous deformation condition by force or pressure influence [3]. Rheology is closely related to the viscosity of a fluid, the flow associated with the viscosity of a fluid is called shear flow. Rheology of ink on flexography printing will certainly give an explanation about the effect of the nature of the ink flow in the process of dot formation in image printing. Research on the rheology of ink can use modelling aided by squeeze film hydrodynamics. The modelling can be done on numerical data processing computing software such as solid works and ANSYS Fluent model.

## II. LITERATURE REVIEW

Research on rheology of ink has been done to understand the characteristics of the ink on flexography printing. The influence of behaviour of ink rheology was examined by B. Havlinova et al. The object of research conducted by B. Havlinova et al is the rheology behaviour of water-reducible inks with their interaction with the paper substrates [4]. From this research it is found that shear stress curve and shear rate of original ink and ink added to show pseudo-plastic behaviour and in accordance with Ostwald and Casson model.
Research conducted by B. Havlinova et al. It uses a low viscosity ink that is 0.1 - 0.25 Pa.s. Ink materials used are Idroflex B072, Idroslotter C 380, Idroflex Base SL 3320, Base Idroflex B 265, and Base Idroflex B210. For paper substrates, this study uses coated papers substrates and uncoated paper substrates. Additional deionized water is used in addition to ink solutions. Measurement from this study using Slovak standard adopted from the ISO standard is STN ISO.
The measurements of this study used several tools such as BURST-O-MATIC (bursting strength measurement), automatically operated micrometre, INSTRON 1011 (water absorbency determination), automatic analytical balance, permeameter testing (water permeance determination), and ELREPHOMAT DFC-5 smoothness evaluation). The test is done by paper condition in standard STN ISO 187 before measurement.

Another study conducted to explore flexography printing and its association with dot formation on image transfer on flexography printing was also performed by D. C. Bould et al. Their research refers to the investigation of plate deformation on flexography printing. Deformation that occurs in the flexography plate is a very important parameter in producing the printed image quality
Research conducted by D C. Bould et al. using numerical models for individual dots developed to be tested against flexography plate with various printing conditions and printed images [6]. This test is to determine the condition of deformation experienced by flexography plates. From this test it is found that two processes that cause deformation in the image are caused by dot barrelling and dot surface expansion. The results obtained are then combined with experimental research leading to ink dissemination and physical damage of the dots.
Results obtained from research D. C. Bould et al. this shows that low coverage in high lines is influenced by the effects of different pressure variations. This greatly affects the process of producing images with high resolution. This research can be concluded that, rheology of ink has a high impact on the result of image printed. For certain conditions, rheology behaviour of ink can give a certain effect on flexography printing.
Research conducted by Z.Żołek-Tryznowska and J.Izdebska on flexography printing by modelling on flexographic printing ink, which is modified with hyper-branched polymer. The research is based on the type of Urania flexographic printing ink with modification of Boltorn P500 and Boltorn P1000, both of which are hyper-branched polymers. The rheology testing of the modified flexographic printing ink is done by measuring the surface tension of flexographic printing ink [7].
Research conducted by Z.Żołek-Tryznowska and J.Izdebska shows the rheology of polymer and flexographic printing ink. The flow curve obtained from this study showed pseudo-plastic properties. The flow curve shown is the value of the shear stress to the value of the shear rate. For the modified flexographic printing ink used 3 different plastic films are PET, oPP, and PE. The effect of small amounts of hyper-branched polymers on flexographic printing ink colours is checked using optical density, gloss of the print film and total colour difference. In addition, hyper-branched polymers affect the rheological properties of flexographic printing ink.

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Maria Rentzhog and Andrew Fogden conducted research on flexography printing. Their study aims to determine the effect of ink formulation and pre-treatment of substrate on the quality of print and water-based resistance flexography on polymer-coated boards. A test was performed for the acrylic flexographic (water-based) using 3 different polymer-coated boards. The 3 different types of polymer-coated boards are PP, OPP and LDPE [8].

The influence of ink formulation on research conducted by Maria Rentzhog and Andrew Fogden, is very influential on the quality of print and also the nature of the resistance. Use of ink formulation used with additional silicone additive and emulsion polymer. It also affects the resistance and print quality is substrate pre-treatment. For this study, adhesion and print mottle conditions are in worse condition on plate with PE and OPP materials. The condition of this trait is influenced by the ink formulation and also with the corona level. Research conducted shows that ink formulation affects rheology behaviour on certain plate materials. This is certainly related to the viscosity and elasticity of the ink formulation.

Research conducted by Z. Żołek-Tryznowska et al where the results of the research were tested based on total colour difference, colour values, and density and gloss from dried ink film. For the resistance characteristics of water-based flexographic printing, the investigated resistance properties are wet /dry resistance of the printed sample. In general, this study yields the conclusion that the added branched polyglycerols affect the characteristics of printing ink. The most fundamental effects of branched polyglycerols are the condition of dry and wet resistance that is increased [9].

Srinivas K. Mirle and A. C. Zettlemoyer conducted a study that could be said to be a pioneer in flexographic printing modelling research using numerical computation based on photopolymer plates and ink hydrodynamics conditions. Photopolymer plates were carried out using 3 plates with plates A, B and C. The physical properties of these 3 plates differed by material and structural differences, resulting in different press performance [10].

Plates used by Srinivas K. Mirle and A. C. Zettlemoyer are known by the characteristics of microscopic analysis of print, glass transition, resilience, A2 hardness shoot, ink receptivity, swelling properties, Young's modulus, and surface energies. Their research focuses on the relaxation conditions of the plate based on its viscoelastic properties. For nip rollers, the tests were performed with mathematical modelling based on the use of printing, calendaring and lubrication. The model of this roller nip is intended to represent the viscoelastic deformation of the photopolymer plate and ink hydrodynamics on the nip.

For most polymers, the modulus $E_{\gamma}$ is estimated to be equivalent to E 'which is the storage modulus, these two modules constitute a benchmark for stored elastic energy. The value of E 'represents an over-wide temperature value in the Autovibron tool (DDV-III-C Automated Rheovibron). To calculate the value of $E_{\gamma}$, we use the William-Landel-Ferry time temperature transformation formula based on the time function.

Mathematical modelling would be possible if the mathematical parameters for the factor of relaxation are time function. To obtain the relaxation value of the modulus based on the function of time, the use of Prony-series equations can help the acquisition of the relaxation value of the modulus based on the time function. Computer programs are compiled and written to obtain numerical correlations from $E_{\gamma}$. The value of $E_k$ is computed simultaneously to complete the number n of the equation by using the Gauss Elimination method. The calculation of the value of the relaxation factor is closer to the empirical value. Different researches used the numerical correlations during the modelling.

The parameters governing the flexography printing process are the pressures between different roller presses, the printing speed, ink rheology, and the plate type. For the different designs of the printing nips, the pressure (P) on the nip plate is essential where the transfer ink occurs on the region between the substrate and plate. From Figure 1, we can see the plate diagram of the substrate nip. Where the modelling of the deformation of the squeezed film can be obtained according to local strain and deformation however the main advantages of this model can easily be solved but the main disadvantage is that the model is assumed as rigid body.

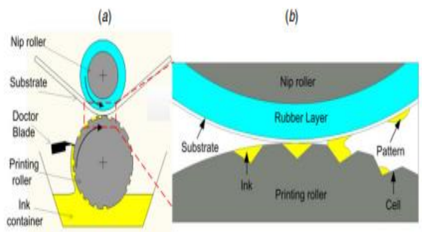


*Figure 1 contact zone Geometry [13]*

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Different researchers used this model which is called Boltzmann superposition principle to constitute equations relating to the relationship between time dependencies, strains and stress for photopolymer plates. P pressure vs. the nip length in x direction.
Software simulation was prepared by [11] to solve the equations compiled by both iteratively. With the use of the computer program it is expected to pressure distribution and ink thickness of the entrance nip and the time required for the traverse nip distance made on the basis of the initial numerical solution. The time required at nip is estimated to be 20 ms. at nip entrance, gauge pressure is assumed equal to zero. The corresponding $E_e$, $E_k$ and $\alpha_k$ data for each plate are included in the compiled computer program. Results from computer programs run by [11] can be seen in Table 2. For plate A tested, it can be seen in Figure 2.

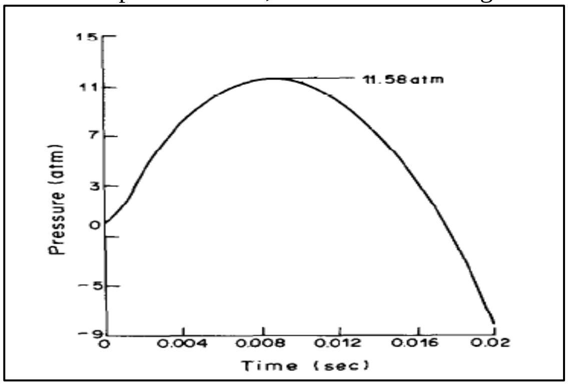


*Figure 2 Plate A, modelled nip pressure profile [11]*

The results of investigating and modelling the nip prints shows the flow of the ink can be modelled using different methods such as using numerical modelling or software package to find the relation between the flow characteristics and the nip pressure vs. the time. Also the experimental investigation can be obtained, but its required advanced technology to assess the variation in the flow characteristics in the flow channels which are in micro-scale, so in this research a software modelling was adopted using two software packages which are solid works and ANSYS, these software packages are used to simulate the flow parameters of the ink.
Modelling and analysis
The dimensions of the ink cells are very small comparing with roller dimensions, where the depth of the cell 2.55 $\mu m$ with width 20$\mu m$, so the model was created in SOLIDWORKS for the contact region between the ink and the substrate as shown in figure (3) but it's taken from the inlet the first edge of the cell, then another layer was added at the top of the cell to specify the boundaries of the fluid domain as shown in figure (4)

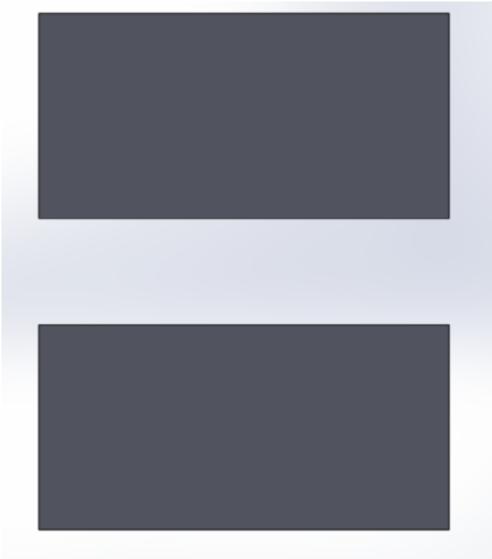

*Figure 3: Geometry of the two plates where the ink will squeeze between them*

This model was imported to ANSYS software as shown in figure (4), where the ink layer was modelled as fill was added in ANSYS as shown below in green colour; however the zero boundary conditions of the inlet and the outlet will be defined on this flow channel only the speed of the upper plate will be changed.

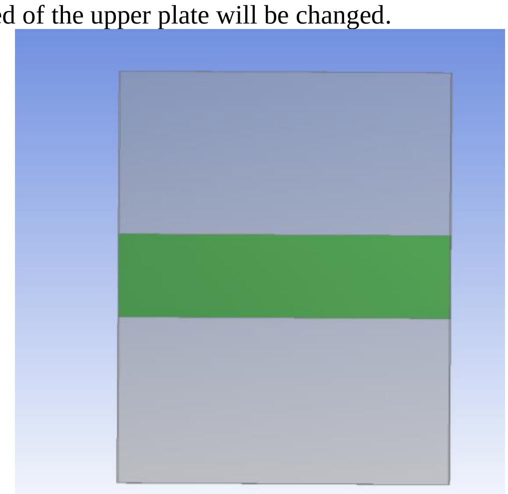

*Figure 4importing the channel geometry to ANSYS software*

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Vbbripress.org


The mesh was created for the cell geometry and the fluid domain as shown in figure (5) where the size of the elements meshing was defined as fine to increase the number of nodes are included in the analysis.

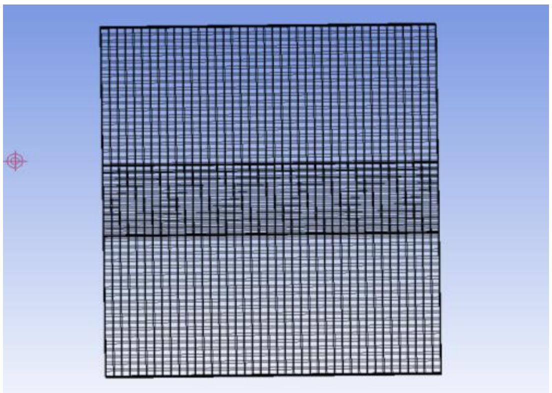


*Figure 5 creating the mesh*

The velocity of the ink depends directly on the printing speed so, the velocity of the speed will be assumed initially in this study at the upper surface where the lower is rigid fixed 10m/min [13], and the main properties of the film are: the young modulus 3.611 N/mm2, and the poisons ratio is 0.43 regarding [14]. The density of the film was assumed and the viscosity of the ink was taken as assuming the ink is water base. The model was created as non-Newtonian model, where in fluent workspace the model was selected to be viscous, then using k-epsilon model was used:. This model was selected for the squeeze film because the ink is considered as non-Newtonian fluid as mentioned by [15]. After defining the fluid as -Newtonian, K-$\varepsilon$ model was used.

The boundary condition was defined at the inlet and the outlet of the film, where the velocity was assumed initially 10 m/min according to literature review [13] e then the velocity was changed in the range of (8-14 m/min) to assess the effect of changing the velocity on the characteristics of the ink squeezing. Regarding the outlet it was assumed as outlet pressure discharged to atmosphere, in other words zero gauge pressure.

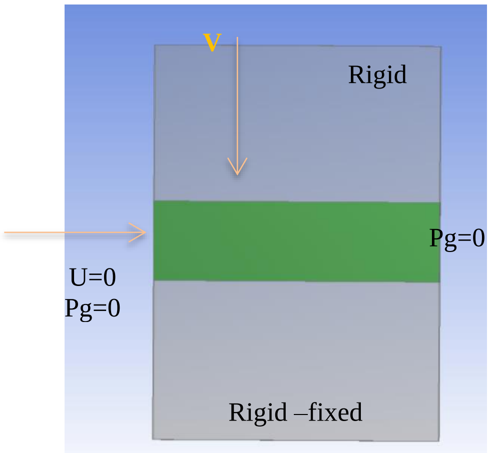
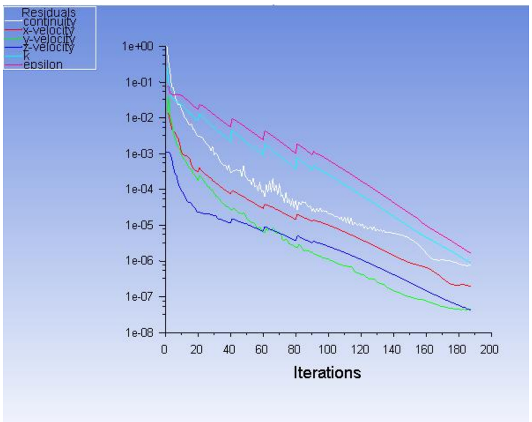
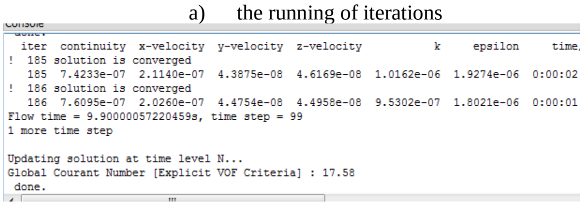



*Figure 6: the boundary conditions*

To solve the equations of the flow equations were solved by running the calculations, where the step time was assumed initially 0.01 sec, the following figure shows the iterations for the momentum and quantity conservation. As shown the solution achieved the convergence results after 190 iterations, where each iteration is repeated 100 times according to the time setup (0.01 sec).




a) the running of iterations



```
  iter  continuity  x-velocity  y-velocity  z-velocity           k     epsilon     time,
!  185 solution is converged
   185  7.4233e-07  2.1140e-07  4.3875e-08  4.6169e-08  1.0162e-06  1.9274e-06  0:00:02
!  186 solution is converged
   186  7.6095e-07  2.0260e-07  4.4754e-08  4.4958e-08  9.5302e-07  1.8021e-06  0:00:01
Flow time = 9.90000057220459s, time step = 99
1 more time step

Updating solution at time level N...
Global Courant Number [Explicit VOF Criteria] : 17.58
 done.
```

b) results convergence results

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*Figure 7: running calculations in ANSYS software where this mark (!) in ansys software shows the results is converged.*

The results for the velocity distribution when the inlet velocity is 10m/min or 0.166 m/s are shown below, where the velocity as shown is increased at the middle of the film thickness because the middle layers are the farthest layers from the wall, where velocity at the wall is zero and gradually increases up to the middle of the film.

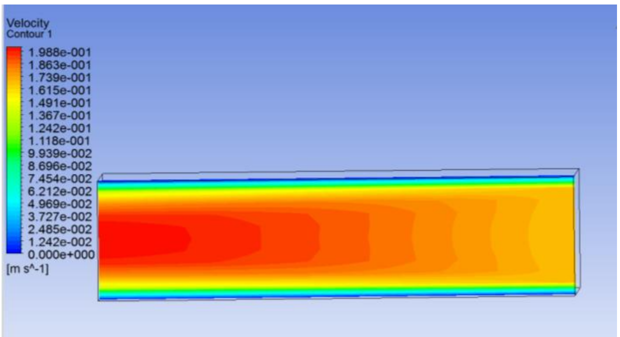


*Figure8: the velocity distribution when the velocity is 10 m/min.*

The velocity gradient or the strain rate is an important property can be used to determine the viscosity of the fluid where the slope of the relation of shear stress with the velocity gradient is the dynamics viscosity.

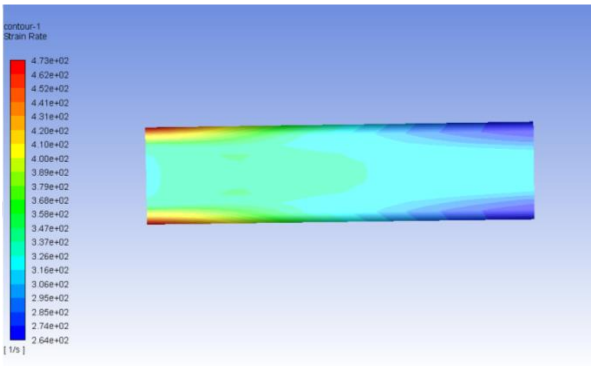


*Figure 10: the velocity gradient distribution when the velocity is 10 m/min.*

The shear stress in x-direction is shown in the following figure where the shear stress increases after certain distance from the inlet especially at the cell inlet. The negative sign of the shear stress means the friction in the opposite direction of the flow where the minimum value at the inlet.

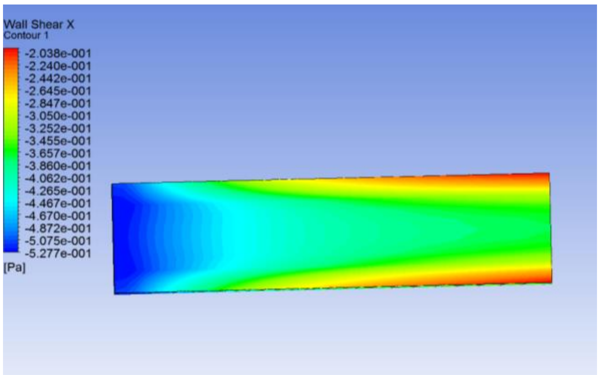


*Figure 11: the pressure distribution when the velocity is 10 m/min.*

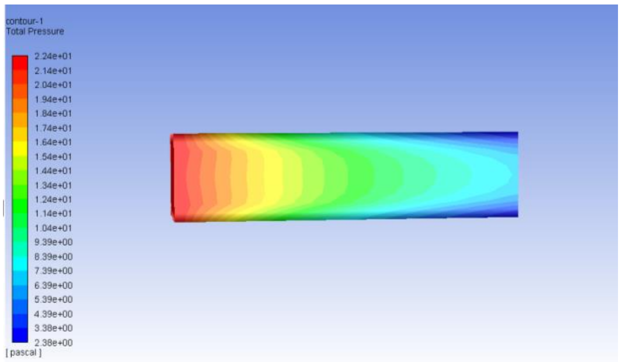


*Figure 12: the pressure distribution when the velocity is 10 m/min.*

The thickness of the film was estimated by exporting XY-data for the x-velocity derivative in y-direction, where the thickness was taken at the zero derivatives, which mans at the thickness of boundary layer.

The following figure shows the thickness of ink layer along the film when the velocity is 8m/min, where the thickness increases to maximum value about 0.18 $\mu$m according to reduction in pressure.

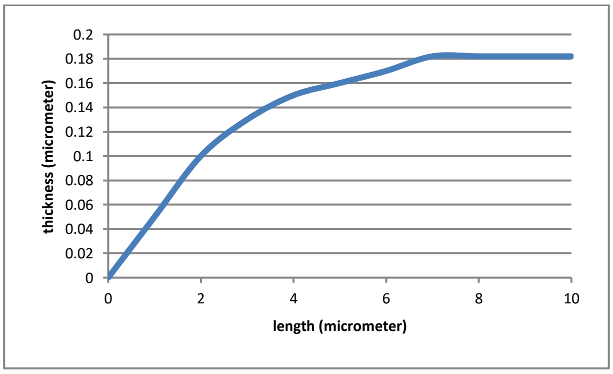


*Figure13: thickness of ink layer when the velocity is 8 m/min.*

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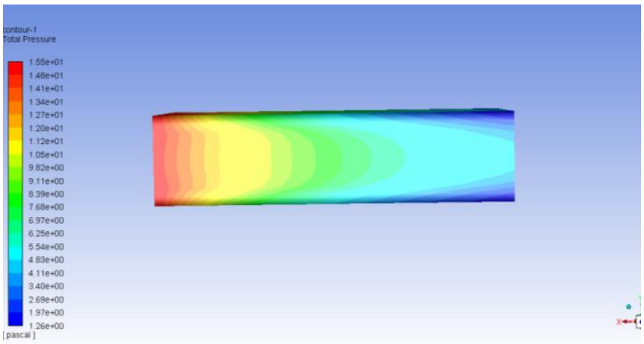
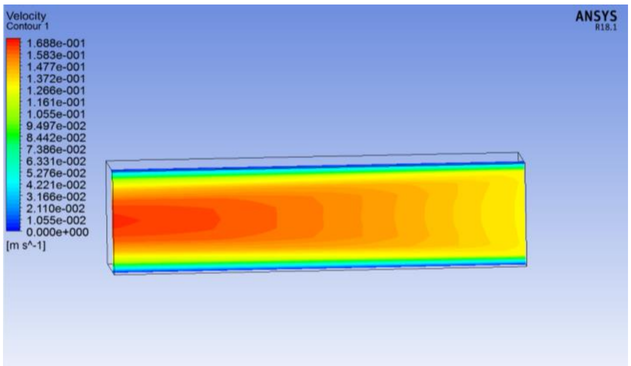
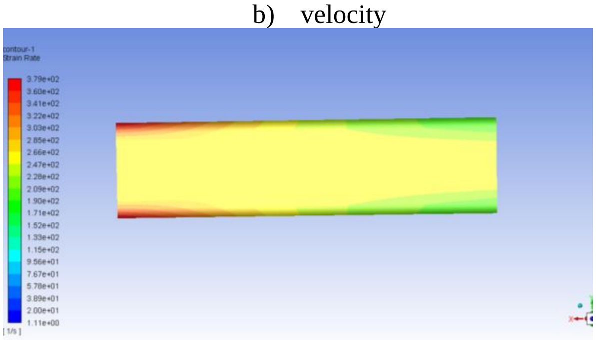
The following figure shows the simulation results for the velocity 8m/min where figure (14) shows the pressure distribution where the pressure increases with decreasing the velocity. The velocity distribution is shown in figure (14)b , also the strain rate is shown in figure (14) C , as shown the strain rate reduces with decreasing the velocity , where the decreasing of velocity will lead to decrease in the strain rate then the shear stress which is a function of strain rate.




a) pressure




b) velocity




c) strain rate

*Figure 14: the simulation results @ velocity =10m/min*

With increasing the speed up to 10m/s the ink thickness layer about 0.162 $\mu$m.

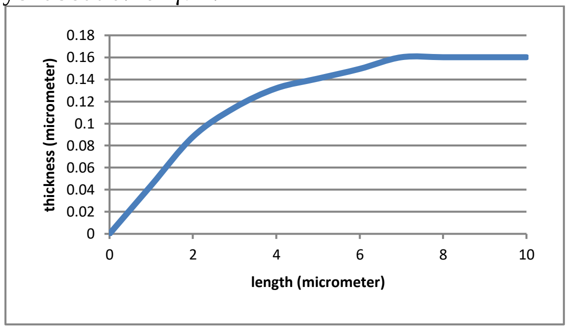
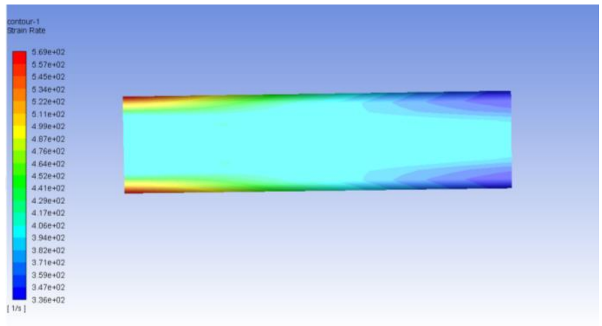
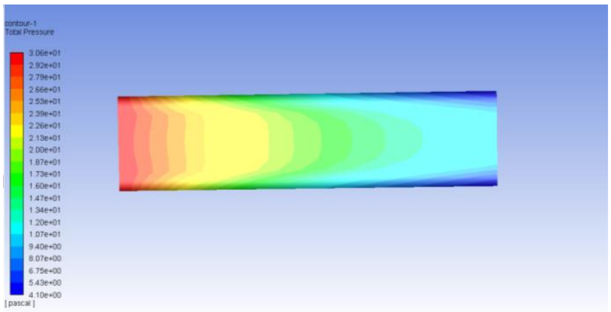



*Figure 15: thickness of ink layer when the velocity is 8 m/min.*

The simulation results when the speed was increased up to 12 m/min are shown in the following figure, where the maximum strain rate increases at the inlet, in other hand the pressure decreases with increasing the velocity




a) wall strain rate




b) the pressure

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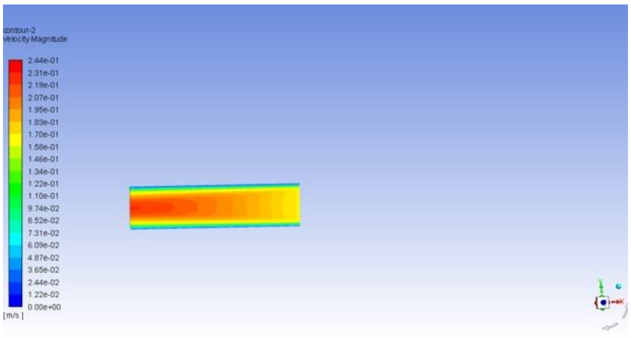


c) velocity

*Figure 16: the simulation results @ velocity =12m/min*

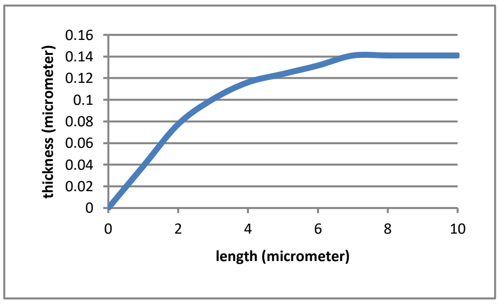
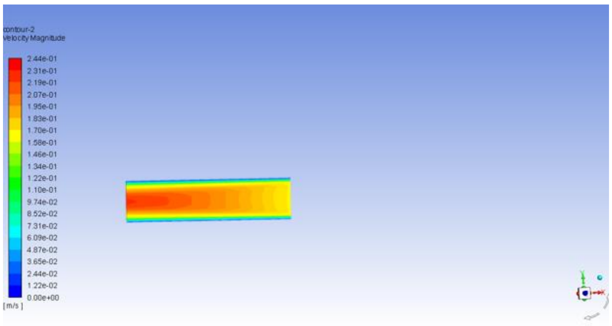



*Figure 17: thickness of ink layer when the velocity is 12m/min.*

The results of simulation when the velocity was increased up to 14 b was doesn't significant comparing with results of 12m/min as shown below



a) velocity

*Figure 18: the simulation results @ velocity =14m/min*

The results of simulation for the ink thickness with the length was similar to 12m/s. Comparing between the different velocities the thickness of the film increases with increasing the velocity which means more ink will be consumed during printing process.

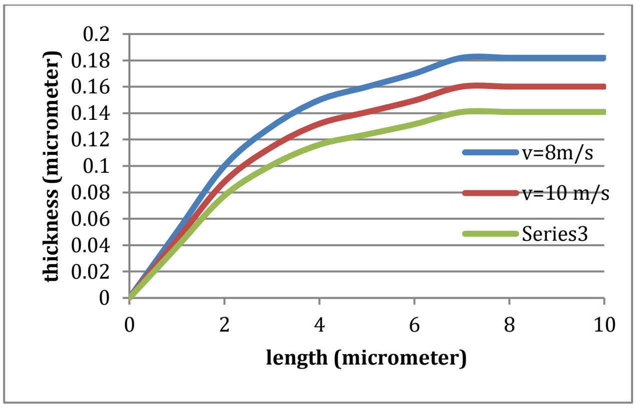



*Figure 19: comparing the thickness of ink layer*

The maximum ink thickness vs. the velocity was formulized as shown in the following figure

.

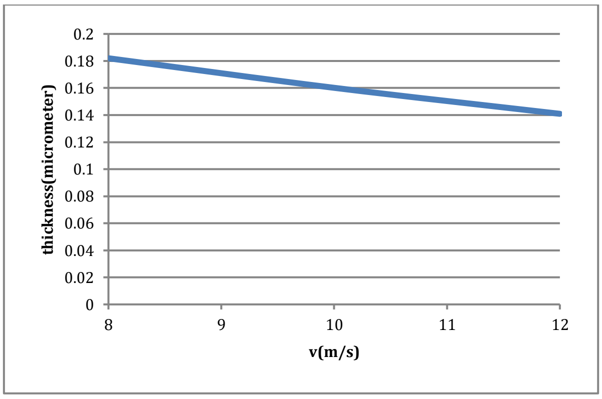



*Figure 20: the maximum thickness of ink layer vs. Speed.*

The shear stress vs. the strain rate was plotted as shown in the following figure by taken the values of shear stress at the where the maximum shear stress increases with increasing the velocity however for the non-Newtonian fluid the shear stress is formulated as high order equation where the shear stress proportion to the strain rate .

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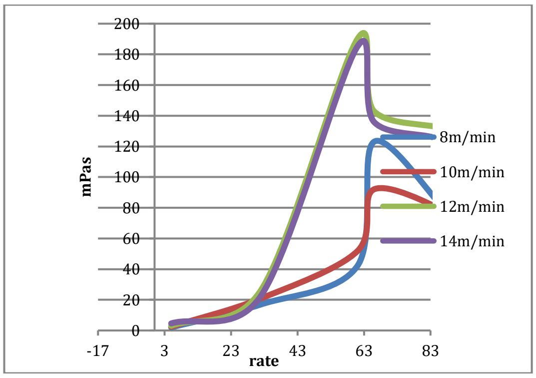


*Figure 22: the strain rate vs. the shear stress*

## III. Conclusions

In this project a modelling for the film flow where a solid works model was created for the squeeze film then the model was exported to any software. The model was solved using CFD simulation. The Newtonian k-epsilon model was used to solve the equations of flow, where the mesh size was refined to get the smallest mesh size with high accuracy. The results show the increasing in the velocity of flow increases the thickness of ink layer by increasing the shear stress on the wall. Also increasing the velocity of the flow leads to a decrease in the layer thickness and decreases the pressure

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