Study of Heat Conduction inside Rolling Calender Nip for Different Roll Temperatures

Neelam Gupta¹ and Neel Kanth²

¹Research Scholar, Department of Mathematics, Jaypee University of Information Technology, Waknaghat, Solan (H.P.), India
²Assistant Professor, Department of Mathematics, Jaypee University of Information Technology, Waknaghat, Solan (H.P.), India

Corresponding Author: Neel Kanth
Email ID: shah.neelam28@yahoo.in, neelkanth28@gmail.com

Abstract

Calendering is a smoothening process at the final stage in textile industry, where fabric passes through the nips formed by two or more rolls in contact. The material used for making of rolls varies for different types of calenders. Depending on the quality of fabric required these rolls are hard or soft and can be heated to certain temperature, using induction process, hot water passage or heated oil passage inside the rolls. In rolling calendering process, fabric is pressed between two or more rolls, where nip is formed by the combination of alternate hard and soft rolls. In this paper effect of roll temperature and bonding time on fabric temperature has been discussed using single nip rolling calender, when fabric is inside the calender nip formed by hard and soft rolls having different temperatures using one dimensional unsteady state heat conduction equation.

Keywords: Rolling calender, heat transfer, bonding time, thermal conductivity, specific heat, density, diffusivity

1. Introduction

Calendering is widely used to enhance the smoothness and gloss of nonwoven fabrics. In this process web is passed through the nip formed by two rolls pressed against each other at high pressure and temperature [1,2]. These rolls may or may not be heated internally to get the desired temperature. Calendering machine is composed of 2-10 rolls, depending upon the type of calender. The fabric runs through these rolls at a desired speed in accordance with the quality required. Design parameter of calendering rolls and type is of great importance [3]. These rolls are hard or soft depending on the type of calenders. In hard nip calendering all the rolls are hard while in soft nip calendering there are
alternate hard and soft rolls. Hard rolls are made of steel, having covering of chilled cast iron while soft rolls are having covering of soft materials like nylon, rubber and other polymers are used depending upon the quality of fabric required [3–5]. The major difference between the hard nip and soft nip calender is the time of the contact between fabric and rolls [6]. Rolling calender is having combination of alternating hard and soft rolls. Hard rolls are heated externally up to 210 °C, through percolation of hot oil, water, steam or by induction heating. Heat is also developed due to friction between hard and soft roll [4,5]. Heated rolls in contact may or may not have the same temperature. 

Surface properties of fabric changes after calendering. It becomes thin, smooth, glossy and papery [1,2]. We can design a rolling calender accordingly to the fabric required [3]. Fabric properties are changed due to bonding of fibers. Bonding is obtained due to heat conduction and pressure inside the calender nip [7,8]. Heat is transferred by conduction to the fibers in contact with the heated roll inside the nip. The time for which heat is conducted from heated rolls in thickness direction of fabric inside the nip is very short, due to which it is always in unsteady state. Heat transfer occurring between the fabric and heated rolls inside calender nip is governed by the thermal conductivity of the web and its contact resistance with the surface. Heat conduction is also influenced by the specific heat and thermal diffusivity of the material [9,10]. With increase in temperature of rolls or lowering speed of rolls up to a particular limit, the strength of fabric improves, as more heat is conducted to the fibers in contact with the roll [3,5]. Temperature has the most prominent effect on gloss and smoothness. High temperature creates better web surface quality, consistency and smoothness [7,11].

In the present study, heat conduction from calender rolls to N6 fiber is considered, when fiber passes through single nip rolling calender which helps to predict the temperature inside the rolls at different depths.

2. Heat conduction model for rolling calender

Heat conduction model describes how temperature is being distributed in the calendering process [10]. Three dimensional heat conduction model is described as [12]

\[
\frac{\partial U}{\partial t} = \alpha \left[ \frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} + \frac{\partial^2 U}{\partial z^2} \right] + \frac{q}{c_p \rho}
\]

Equation (1) in one dimensional form and after dropping the heat generation term \( q = 0 \) (which is true for any system under investigation) can be written as

\[
\frac{\partial U}{\partial t} = \alpha \frac{\partial^2 U}{\partial x^2}
\]

Where \( U \) is the heat, \( t \) is the time, \( c_p \) is the specific heat and \( \rho \) is the density of the material, \( \alpha \) is the thermal diffusivity.

The initial and boundary conditions for heat conduction from rolls of calender to the fabric of thickness \( d \) inside the nip of rolling calender are

\[
U(x,0) = u_0, \quad U(0,t) = u_1, \quad U(d,t) = u_2,
\]

Where \( u_1 \) and \( u_2 \) are the roll temperatures, \( u_0 \) is the initial temperature of the fabric entering the rolling calender.
3. Solution of heat conduction model

General solution of equation (2) using Separation of variables method [12] is

\[ U(x,t) = A_1 e^{-\lambda x} \left( A_2 \sin \lambda x + A_3 \cos \lambda x \right) \] (3)

depending on the initial and boundary conditions, constants \(A_1, A_2\) and \(A_3\) can be found [12]. After applying initial and boundary conditions, the above solution changes to

\[ U(x,t) = u_1 + \frac{(u_2 - u_1)}{d} x + \left[ e^{-\frac{x^2}{\alpha t}} \sin \frac{\pi x}{d} \left( 2 \frac{x}{\pi} (-u_2 + u_1) + \left( \frac{4u_1}{\pi} \right) \right) + e^{-\frac{x^2}{\alpha t}} \sin \frac{2\pi x}{d} \left( \frac{1}{\pi} (u_2 - u_1) \right) \right] \] (4)

The complete procedure of finding the solution is shown in appendix A.

Equation (4) is used for calculating amount of heat transfer to fabric in thickness direction for the given bonding time. The bonding time can be calculated using nip mechanics models [3,10]. The simulation of the model is done using the reference values for a single nip rolling calender as given below in table 1.

| Parameters                        | Rolling calender                  | Adopted value                      |
|-----------------------------------|-----------------------------------|------------------------------------|
| Composition                       | Soft nip                          | one hard roll and one soft roll    |
| Roll material (Hard Roll)         | Steel cylinders having covering   | Steel cylinder having covering      |
|                                   | of chilled cast iron              | of chilled cast Iron               |
|                                   |                                   | \( E_1 = 140 \text{ kN/mm}^2 \)    |
|                                   |                                   | \( \nu_1 = 0.28 \)                 |
| Roll Material (Soft Roll)         | Steel cylinders having covering   | Steel cylinders having covering    |
|                                   | of cotton, wool or polymer        | of compressed long fiber cotton.    |
|                                   |                                   | Bulk modulus and Poison’s Ratio    |
|                                   |                                   | \( E_2 = 2.41 \text{ kN/mm}^2 \)   |
|                                   |                                   | \( \nu_2 = 0.48 \)                 |
| Nip width                         | 5 – 15 mm                         | 0.0042 m                           |
| Diameter of roll                  | 450 – 1000mm                      | 300mm, 700mm                       |
| Thickness of N6 polymer fabric    | 0.001 m                           |                                    |
| Density of fiber                  | 1140 kg/m\(^3\)                  |                                    |
| Thermal conductivity of fiber     | 0.21 W/m.K                       |                                    |
| Specific heat of fiber            | 1600 J/kg.K                      |                                    |
| Speed of fabric                   | 5 – 12 m/min                      | 10 m/min                           |
| Bonding time                      | 0.001 – 0.006 sec                 | 0.003 sec                          |
| Diffusivity                       | \( 0.115 \times 10^{-6} m^2/sec \) |                                    |
4. Results and discussion

Using above mathematical model, temperature profile in thickness direction of fabric, effect of bonding time on heat conducted from rolls to fabric and effect of roll temperature on average fabric temperature has been investigated inside the calender nip. Hard roll temperature \( u_2 \) is taken in the range from 100 \(^\circ\) C to 200 \(^\circ\) C, soft roll temperature \( u_1 \) is taken as 40 \(^\circ\) C and the initial fabric temperature \( u_s \) is taken as 30 \(^\circ\) C.

4.1. Impact of roll temperature on fabric temperature at different depths

The impact of roll temperature on fabric temperature has been calculated at different depths of fabric from equation (4) as shown in Fig.1. The calculated temperatures at different depth of the fabric are shown in Table 2.

It shows that temperature at the mid part of the fabric also increases with increase in temperature of the roll. The side of the fabric is more heated which is in touch with the roll and having the greater temperature as compared to the other roll. It also shows that with increase in temperature of roll, average temperature of the fabric increases when the fabric is inside the nip having different roll temperature.

Table 2. Temperature of the roll at different depths of fabric temperature

| Web Depth (m) | Contact Roll Temperatures \(^\circ\)C | Contact Roll Temperatures \(^\circ\)C | Contact Roll Temperatures \(^\circ\)C |
|---------------|-------------------------------------|-------------------------------------|-------------------------------------|
|               | 100/40                              | 150/40                              | 200/40                              |
| 0             | 40                                   | 40                                  | 40                                  |
| 0.00001       | 37.679                               | 38.079                              | 38.478                              |
| 0.00002       | 35.355                               | 35.923                              | 36.491                              |
| 0.00003       | 33.336                               | 33.892                              | 34.448                              |
| 0.00004       | 32.405                               | 33.259                              | 34.114                              |
| 0.00005       | 33.745                               | 36.087                              | 38.429                              |
| 0.00006       | 38.628                               | 44.672                              | 50.716                              |
| 0.00007       | 47.981                               | 60.749                              | 73.516                              |
| 0.00008       | 61.983                               | 84.750                              | 107.517                             |
| 0.00009       | 79.853                               | 115.408                             | 150.963                             |
| 0.0001        | 99.927                               | 149.878                             | 199.828                             |
| Average Roll Temperature | 49.172 | 61.154 | 73.136 |
4.2. Impact of bonding time

The heat transfer in a rolling nip depends upon the bonding time of the fabric. The impact of bonding time has been found on the temperature of the roll at the mid part of the fabric in thickness direction, using equation (4) as shown in Fig. 2. The temperatures at different bonding time of the fabric are shown in Table 3.

It shows that with increase in bonding time, temperature of the fabric at the mid part also increases. Average roll temperature increases with increase in bonding time which is possible by lowering the speed of roll. With the help of this, the desired gloss and smoothness of fabric can be attained.

Table 3. Temperature at mid depth of fabric at different bonding time

| Bonding time (sec) | Contact Roll Temperature (°C) | Contact Roll Temperature (°C) | Contact Roll Temperature (°C) |
|-------------------|-------------------------------|-------------------------------|-------------------------------|
|                   | 100/40                        | 150/40                        | 200/40                        |
| 0.002             | 29.396                        | 29.020                        | 28.645                        |
| 0.0025            | 31.632                        | 32.654                        | 33.675                        |
| 0.003             | 33.745                        | 36.087                        | 38.429                        |
| 0.0035            | 35.742                        | 39.332                        | 42.922                        |
| 0.004             | 37.629                        | 42.399                        | 47.168                        |
5. Validity of the model

The results obtained from heat transfer model in the present paper has been validated for the data given by [7] and [11]. The predicted temperatures in this analysis show a good agreement with the temperature measured on a calender stack as given in [7].

6. Conclusion

There are many temperature measuring instruments which can tell the temperature on the surface of rolls but not possible to predict the temperature inside the rolls using these instruments. The model described in the present investigation helps in predicting the temperature inside the roll at different depths which is not possible in conventional methods. This model is applicable for all types of calenders such as machine calender, soft calender, supercalenders and rolling calender in which rolls are at different temperatures. While the centre of the web remains unheated, a steep temperature gradient is maintained by the web at the outer surface in contact of the roll, the only part of the web which is heated is the outer third. Therefore the side of the fabric is more heated which is in touch with the roll and having the greater temperature as compared to the other roll. Average roll temperature increases with increase in bonding time which is possible by lowering the speed of roll. With the help of this, the desired gloss and smoothness of fabric can be attained. If calendering speed is exceeded beyond a certain limit, desired gloss and smoothness of roll may not be attained because there will be no change in temperature at the mid part.
References

[1] Bhat, G S, Jangala, P K and Spruiell, J E (2004). Thermal bonding of polypropylene nonwovens: effect of bonding variables on the structure and properties of the fabrics. *Journal of Applied Polymer Science*. 92 3593–3600

[2] Fedorova, N, Verenich, S and Pourdeyhimi, B (2007). Strength optimization of thermally bonded spunbond nonwovens. *Journal of Engineered Fibers and Fabrics*. 2 38–48

[3] Gupta, N and Kanth, N (2018). Analysis of Nip Mechanics Model for Rolling Calender Used in Textile Industry. *Journal of the Serbian Society for Computational Mechanics*. 12 39–52

[4] Çinçik, E and Günaydin, E (2017). The influence of calendering parameters on performance properties of needle-punched nonwoven cleaning materials including r-PET fiber. *The Journal of the Textile Institute*. 108 216–225

[5] Kanth, N, Ray, A K and Dang, R (2016). Effect of design and process parameters on nip width of soft calendering. *International Journal for Computational Methods in Engineering Science and Mechanics*. 17 247–252

[6] Litvinov, V and Farnood, R (2010). Modeling of the compression of coated papers in a soft rolling nip. *Journal of materials science*. 45 216–226

[7] Kerekes, R J (1979). Heat transfer in calendering. *Transactions PPMC*. 5 TR66–76

[8] Hestmo, R H and Lamvik, M (2002). Heat transfer during calendering of paper. *Journal of pulp and paper science*. 28 128–135

[9] Belgacem, M N and Pizzi, A (2016). *Lignocellulosic Fibers and Wood Handbook: Renewable Materials for Today’s Environment*. John Wiley & Sons, First edition, 493-527

[10] Gupta, N and Kanth, N (2019). Study of heat flow in a rod using homotopy analysis method and homotopy perturbation method. *AIP Conference Proceedings*. AIP Publishing. 2061 020013 1-8

[11] Keller, S (1994). Heat transfer in a calender nip. *Journal of pulp and paper science*. 20 J33–37

[12] Carslaw, H S and Jaeger, J C (1959). *Conduction of Heat in Solids: Oxford Science Publications*. Oxford, England, Second edition, 13-133

Appendix A

Solution of one dimensional unsteady state heat equation

\[
\frac{\partial U}{\partial t} = \alpha \frac{\partial^2 U}{\partial x^2}
\]

under the initial and boundary conditions

I.C. : \( U(x,0) = u_0 \)

B.C. 1: \( U(0,t) = u_1 \)

B.C. 2: \( U(d,t) = u_2 \)

where \( u_o \) is the initial temperature of fabric coming out from dryer section, \( u_1 \) and \( u_2 \) are the temperature of two rolls of the nip.

Let \( U(x,t) = u + v \) \[1a\]

where \( u \) satisfies
\[
\frac{\partial^2 u}{\partial x^2} = 0 \tag{2a}
\]

with \( u = u_1 \) at \( x = 0 \) and \( u = u_2 \) at \( x = d \).

Also, \( v \) satisfies
\[
\frac{\partial v}{\partial t} = \alpha \frac{\partial^2 v}{\partial x^2} \tag{3a}
\]

with \( v = 0 \) at \( x = 0 \) & \( x = d \) and \( v = u_0 - u \) at \( t = 0 \).

From equation \[2a\], we have
\[
u = u_1 + \frac{(u_2 - u_1)}{d} x \tag{4a}
\]

using boundary conditions on \( v \), we get
\[
v = \sum_{n=1}^{\infty} C_n e^{-n^2 \pi^2 \alpha t/d^2} \left[ \frac{\sin \left( \frac{n \pi} {d} x \right)}{x} \right] \tag{5a}
\]

Using initial conditions and \( v = u_0 - u \) at \( t = 0 \) in equation \[5a\], we have
\[
u = u_0 - \left[ u_1 + \frac{(u_2 - u_1)}{d} x \right] = \psi (x) \tag{6a}
\]

From which it is noted that the constant \( C_n \) is the Fourier coefficient of a Fourier sin series.

\[
C_n = B_v = \frac{2}{d} \int_0^d \psi (x') \sin \frac{n \pi x'}{d} dx' \tag{8a}
\]

\[
B_v = \frac{2}{d} \int_0^d \left[ \left( u_0 - \left( u_1 + \frac{(u_2 - u_1)}{d} x \right) \right)^2 \right] \sin \frac{n \pi x'}{d} dx' \tag{9a}
\]

\[
B_v = \frac{2}{n \pi} \left( u_1 \cos \frac{n \pi}{d} - u_1 \right) + \frac{2}{d} \int_0^d u_0 \sin \frac{n \pi x'}{d} dx' \tag{10a}
\]

Therefore, equation \[5a\] becomes
\[
v = \sum_{n=1}^{\infty} B_n e^{-n^2 \pi^2 \alpha t/d^2} \left[ \frac{\sin \left( \frac{n \pi} {d} x \right)}{x} \right] \tag{11a}
\]

Substituting the values of \( u \) and \( v \) from equation \[4a\] and \[11a\] in equation \[1a\], we get
\[
U (x,t) = u_1 + \frac{(u_2 - u_1)}{d} x + \sum_{n=1}^{\infty} B_n e^{-n^2 \pi^2 \alpha t/d^2} \left[ \frac{\sin \left( \frac{n \pi} {d} x \right)}{x} \right] \tag{12a}
\]
Now, substituting the value of $B_n$ from equation [10a] in equation [12a], we have

$$U(x,t) = u_i + \left( \frac{u_2 - u_1}{d} \right) x + \sum_{n=1}^\infty e^{\frac{-n\pi^2 t}{d^2}} \sin \frac{n\pi x}{d} \left[ \frac{2}{n\pi} \left( u_2 \cos n\pi - u_1 \right) + \frac{2}{d} \int_0^d u_0 \sin \frac{n\pi x'}{d} \, dx' \right] \quad [13a]$$

$$U(x,t) = u_i + \left( \frac{u_2 - u_1}{d} \right) x + \sum_{n=1}^\infty e^{\frac{-n\pi^2 t}{d^2}} \sin \frac{n\pi x}{d} \left[ \frac{2}{n\pi} \left( u_2 (-1)^n - u_1 \right) + \frac{2}{d} \int_0^d u_0 \sin \frac{n\pi x'}{d} \, dx' \right] \quad [14a]$$

$$U(x,t) = u_i + \left( \frac{u_2 - u_1}{d} \right) x + \left[ e^{\frac{-\pi^2 t}{d^2}} \sin \frac{\pi x}{d} \left( \frac{2}{\pi} \left( -u_1 - u_1 \right) + \left\{ \frac{4u_0}{\pi} \right\} \right) + e^{\frac{-4\pi^2 t}{d^2}} \sin \frac{2\pi x}{d} \left\{ \frac{1}{\pi} (u_2 - u_1) \right\} + \ldots \right] \quad [15a]$$