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

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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 ^{0}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. The 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]

$$\frac{\partial U}{\partial t} = \alpha \left[\left(\frac{\partial^2 U}{\partial x^2} \right)_{yz} + \left(\frac{\partial^2 U}{\partial y^2} \right)_{xz} + \left(\frac{\partial^2 U}{\partial z^2} \right)_{xy} \right] + \frac{q_v}{c_p \rho} \quad (1)$$

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

$$\frac{\partial U}{\partial t} = \alpha \frac{\partial^2 U}{\partial x^2} \quad (2)$$

Where U is the heat, t is the time, c_p is the specific heat and ρ is the density of the material, α 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

$U(x,0) = u_0, U(0,t) = u_1, U(d,t) = u_2$

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

$$U(x,t) = A_1 e^{-\lambda^2 \alpha t}\left(A_2 \sin \lambda x + A_3 \cos \lambda x\right) \tag{3}$$

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

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

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.

Table 1. Design and process parameters [1–5]

Parameters	Rolling calender	Adopted value
Composition	Soft nip	one hard roll and one soft roll
Roll material (Hard Roll)	Steel cylinders having covering of chilled cast iron	Steel cylinder having covering of chilled cast Iron $E_1 = 140\ kN/mm^2$ $\nu_1 = 0.28$
Roll Material (Soft Roll)	Steel cylinders having covering of cotton, wool or polymer	Steel cylinders having covering of compressed long fiber cotton. Bulk modulus and Poison's Ratio $E_2 = 2.41\ kN/mm^2$ $\nu_2 = 0.48$
Nip width	$5 - 15\ mm$	$.0042\ m$
Diameter of roll	$450 - 1000 mm$	$300mm, 700mm$
Thickness of N6 polymer fabric		$.0001m$
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		$0.115 \times 10^{-6}\ m^2/sec$

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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 to $200\ ^0C$, soft roll temperature u_1 is taken as $40\ ^0C$ and the initial fabric temperature u_0 is taken as $30\ ^0C$.

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 (^{0}C) 100/40**	**Contact Roll Temperatures (^{0}C) 150/40**	**Contact Roll Temperatures (^{0}C) 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

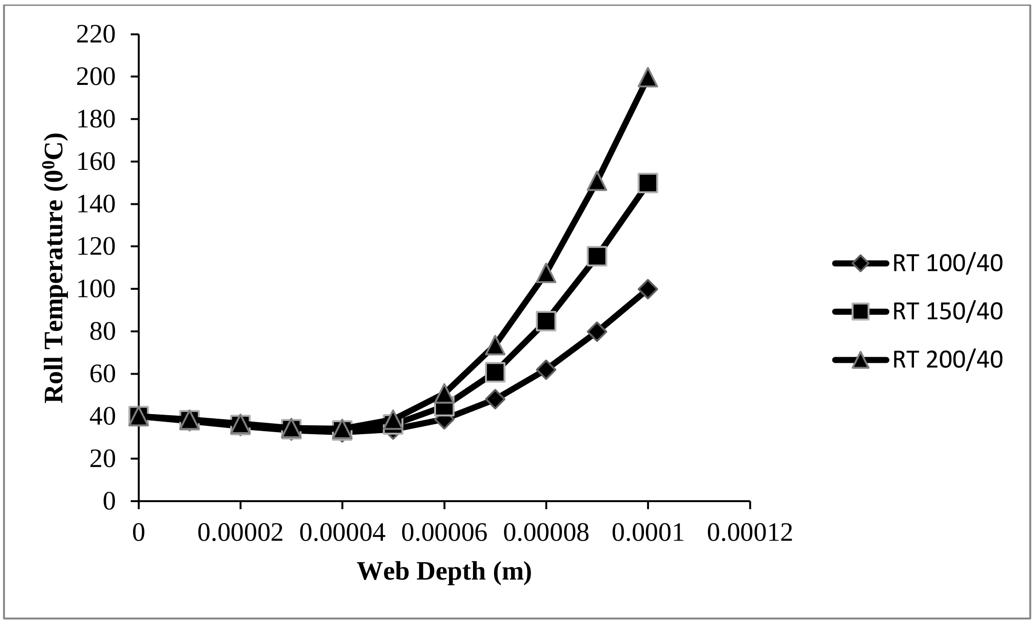

Fig.1. Impact of temperature of roll on fabric temperature at different depths

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 (^{0}C) 100/40**	**Contact Roll Temperature (^{0}C) 150/40**	**Contact Roll Temperature (^{0}C) 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

0.0045	39.413	45.296	51.180
0.005	41.098	48.035	54.972

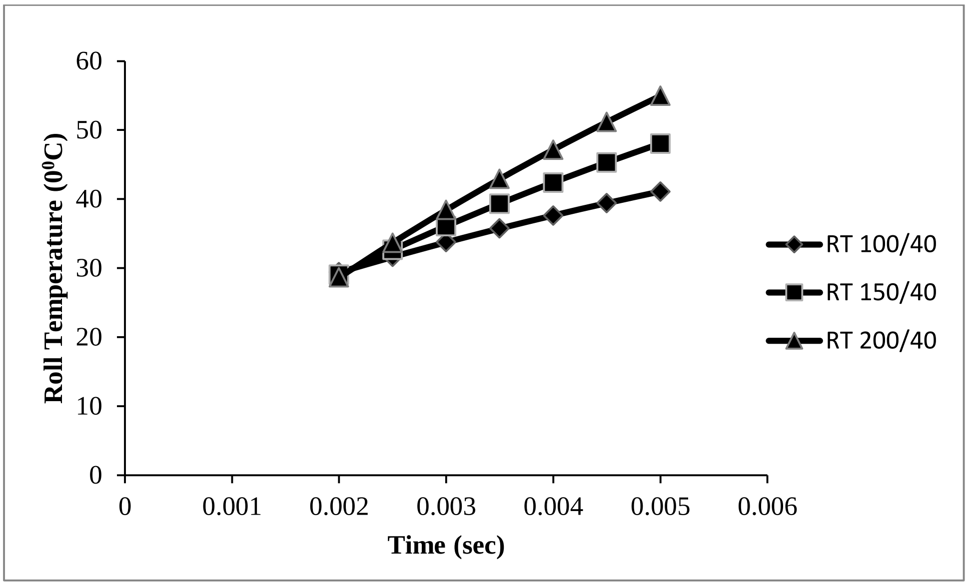

Fig.2. Impact of bonding time at mid part of the fabric $0.00005m$

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.

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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_0 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

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$$\frac{\partial^2 u}{\partial x^2} = 0 \qquad [2a]$$

with $u = u_1$ at $x = 0$ and $u = u_2$ at $x = d$.

Also, v satisfies

$$\frac{\partial v}{\partial t} = \alpha \frac{\partial^2 v}{\partial x^2} \qquad [3a]$$

with $v = 0$ at $x = 0$ & $x = d$ and $v = u_0 - u$ at $t = 0$.

from equation [2a], we have

$$u = u_1 + \frac{(u_2 - u_1)}{d} x \qquad [4a]$$

using boundary conditions on v , we get

$$v = \sum_{n=1}^{\infty} C_n e^{-n^2\pi^2\alpha t/d^2} \left[\sin \frac{n\pi}{d} x \right] \qquad [5a]$$

Using initial conditions and $v = u_0 - u$ at $t = 0$ in equation [5a], we have

$$u_0 - u = \sum_{n=1}^{\infty} C_n \left[\sin \frac{n\pi}{d} x \right] \qquad [6a]$$

$$u_0 - \left\{ u_1 + \frac{(u_2 - u_1)}{d} x \right\} = \psi(x) \qquad [7a]$$

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

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

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

$$B_n = \frac{2}{n\pi} \left(u_2 \cos n\pi - u_1 \right) + \frac{2}{d} \int_0^d u_0 \sin \frac{n\pi x'}{d} dx' \qquad [10a]$$

Therefore, equation [5a] becomes

$$v = \sum_{n=1}^{\infty} B_n e^{-n^2\pi^2\alpha t/d^2} \left[\sin \frac{n\pi}{d} x \right] \qquad [11a]$$

Substituting the values of u and v from equation [4a] and [11a] in equation [1a], we get

$$U(x,t) = u_1 + \frac{(u_2 - u_1)}{d} x + \sum_{n=1}^{\infty} B_n e^{-n^2\pi^2\alpha t/d^2} \left[\sin \frac{n\pi}{d} x \right] \qquad [12a]$$

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Now, substituting the value of B_n from equation [10a] in equation [12a], we have

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

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

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