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IJIE

http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Relationship Between Heat and Troughs During a Transport Process of Heating the Pet Films

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DOI: https://doi.org/10.30880/ijie.2023.15.05.014
Received 9 June 2023; Accepted 18 June 2023; Available online 19 October 2023

Abstract. Understanding the troughs caused during a heat treatment process is important for ensuring process stability and product quality in roll-to-roll (R2R) productions methodology. The purpose of this study is to confirm the relationship between heat and troughs during a transport process of heating where heat is applied over a wide range of area. The temperature and tension applied to the web during the heated transport process were measured in the experimental analysis. Results showed that the web were stretched in the web transport direction during the heat transfer process. However, troughs did not occur because the experiment was conducted below the glass transition temperature. The comparison between the web temperature obtained in the experimental analysis with the one-dimensional thermal conduction simulation for the temperature distribution of the web are also conducted in this paper. This simulation was performed using a non-Fourier model that can be used on microscales. Simulation results show that when the temperature is gradually raised, the amount of thermal conduction is reduced during transportation of the web. The thermal conduction of ballistic phonon is smaller than that of the diffuse phonon when compared at same distance. Even though there were differences between the experimental values and the simulation results, this is because it ignores the heat transfer and radiant heat transfer.

Keywords: Web handling, R2R, PET films, heat transfer, wrinkles

1. Introduction

Sheet of flexible material long enough such as paper, plastic film, and metal foils that are familiar to us are called the web and are indispensable to our daily lives. The main products using the web as a substrate are optical films, photovoltaic cells, flexible devices, and so on. Until now, research and development of displays and the like, has progressed, but in the future, mass production of devices with high affinity with humans is expected in the medical field. Figure 1 shows the roll to roll (R2R) processing [1]. Multiple processes in R2R are composed of continuously performed while tensioning, supporting, and transporting the web using many rollers, and winding it into a roll. It can be mass-produced in a shorter time than the conventional continuous flexible medium production process and has the feature of being able to handle various sizes, large and small. However, R2R has many defects, where so far, stable production process has not yet been established. One of the main problems is the troughs that cause wrinkles on the surface of the web due to the stress acting perpendicular to the transport direction of the web. Since the web has elasticity, some wrinkles are restored, but when troughs are concentrated, the elastic modulus of the web is exceeded and wrinkles occur, making it impossible to restore. This will result in the loss of the product value. According to

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Hashimoto [2-4], one of the causes of troughs is the generation of compressive force due to the rollers not being parallel to each other. The frictional force is generated between the web and the rollers, and the web is pulled in the transport direction and compressed in the vertical direction. It has also been reported that the heat is causing shrinkage and troughing of the web during heat treatment [5-8]. The heat treatment is performed in the process of drying the ink or organic solvent applied to the web surface by printing technology. The current mainstream of heat chamber is a hot air system that uses convection heat transfer. These are forced convection in the chamber using blowers. On the other hand, there are also radiant heat transfer using the infrared ray (IR) systems. This uses natural convection, so problems such as floating dust or wind patterns do not occur. Due to that, a hybrid IR chamber that combines them is drawing attention. It can help shorten the drying process time, and can be used in a clean room, where the running cost is low. Furthermore, uneven heating can be expected to be reduced. Feng [9] obtained the relationship between heat and compressive force because troughs are generated near the heat source by applying local heat to the web. However, although the above-mentioned research confirmed the relationship between heat and compressive force by heating locally, the effect of heating to the web over a wide range of areas has not been clarified. Therefore, the purpose of this study is to confirm the troughs generation conditions of the web where heat was applied over a wide range of areas, where the changes in troughs and tension generated during heat transfer were measured. In addition, to confirm the temperature distribution of the web during heat transfer, a one-dimensional heat conduction of the web was also simulated in this paper.

2. Experimental Equipment and Method

2.1 Experimental Equipment

Figure 2 shows the heat transfer equipment used in this study. This equipment consists of three rubber rollers and two steel rollers that support the web in loops for transporting representation. The heat chamber schematically shown in figure 3 was fixed on the base and set between the upper rollers. Ribbon heaters for radiant heat transfer and a heat insulating material are installed in the heat chamber. Thermocouples were set at the inlet, outlet, and center of the heat chamber to obtain the temperature. A thermo camera was used to measure the temperature distribution in the heat chamber. In addition, to keep the temperature at the center of the heat chamber constant, the temperature of the heat source was monitored and changed using a digital temperature controller.

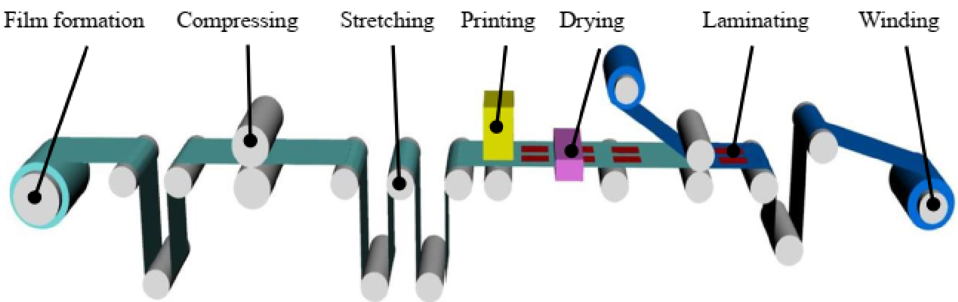

Fig. 1 - R2R processing

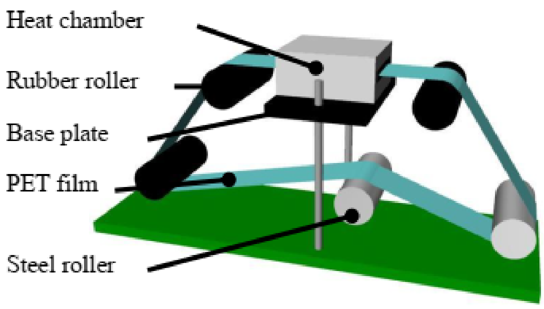

Fig. 2 - Outline of heat transfer experiment. This equipment is composed of three rubber and two steel rollers that supported the web by five rollers and looped for transportation. The heat chamber was fixed on the base and set between the upper rollers

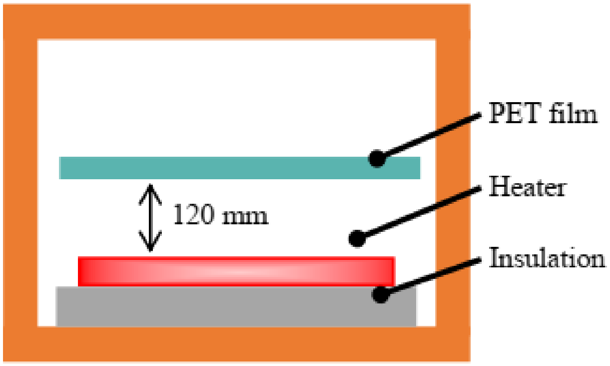

Fig. 3 - Cross section of heat chamber. Between the heater and PET film is 120mm. The body is covered with polycarbonate plates

2.2 Experimental Method

Table 1 shows the experimental conditions conducted in this paper. First, the webs were bonded together, and the initial tension was applied using a tension control roller. Second, the transport speed was set, and the web was transported while increasing the temperature in the heat chamber. The temperature and tension in the heat chamber at that time were then measured. Finally, the device stopped when a trough occurred. The measurement started after the central temperature reached 30℃, and the maximum temperature of the heater was set to 60℃.

3. Simulation Method

Common thermal conduction is expressed by Fourier's equation (1).

$$\frac{\partial T}{\partial t} = k_F \frac{\partial^2 T}{\partial x^2} \tag{1}$$

where, k_F [W/cm·K] is the thermal diffusivity, T [℃] is the temperature, x [cm] is the distance from the heat source, and t [sec] is the time. However, equation (1) cannot express the temperature change that shows a nonlocal reaction [10, 11]. Due to usage of thin film material PET film, it is necessary to transform the equation into a form that can be used on the micro-scale and nano-scale that shows nonlocal reactions. Therefore, in this paper, we adopted the Ballistic Diffusion Model reported by Lebon [12]. The method is dominated by two types of phonons, ballistic phonons that transfer heat while moving straight, and diffusion phonons that are derived from ballistic phonons [13, 14]. The heat conduction equation of the diffuse phonon in the stationary state is derived from equation (1) and is expressed by equation (2) [15, 16].

$$\left(\tau \frac{\partial^2}{\partial t^2} + \frac{\partial}{\partial t}\right) T = k_F \frac{\partial^2 T}{\partial x^2} \tag{2}$$

where τ [sec] represents the heat flux relaxation time. Similarly, the ballistic phonon is expressed by equation (3) [17, 18].

$$\left(\tau \frac{\partial^2}{\partial t^2} + \frac{\partial}{\partial t}\right) T(x,t) = \left(k_b \frac{\partial^3}{\partial t \partial x^2} k_{\mathrm{F}} \frac{\partial^2}{\partial x^2}\right) T(x,t) \tag{3}$$

where k_b [W/cm·K] represents the ballistic thermal diffusivity. The heat conduction of the non-transport web was simulated using equations (2) and (3). Table 2 shows the simulation conditions. In this experiment, the temperature at the center the heat chamber rises during heat transfer. The experimental temperature in the center of the heat chamber was adopted for the simulation temperature T. Figure 4 shows the simulation model. The simulation model was set at 5 cm intervals. The state of temperature change at each position was obtained by thermal conduction simulations.

4. Experimental Results and Discussion

4.1 Heat Transfer Experiment

Figure 5 shows the temperature in the heat chamber. From figure 5 (a), the low temperature was obtained near the inlet and the outlet. It is considered that this is because the outside air flowed in with the film during transportation and the temperature rise in the chamber was prevented. Therefore, it is necessary to design the chamber inlet and outlet to be narrower to prevent the inflow of the outside air. However, as can be seen from figure 5 (b), the temperature was lower compared to the ones without the thermal camera. Since this was open on one side, there was heat exchanged with the outside air. Next, figure 6 shows the change in tension applied to the web during transportation. From the figure, it can be seen that the decrease in tension during transportation is because of heat. It can be said that from figure 5 and figure 6, the tension is temperature-dependent because the tension decreases as the temperature rises. It is considered that this is because the web was stretched in the transport direction by heating while applying tension. Then the web was stretched, the width was shortened, where it was not possible to withstand the stress. In addition, troughs did not occur, because the experiment was conducted below the glass transition temperature. Therefore, heating above the glass transition temperature is the cause of trough generation.

Table 1 - Experimental conditions

Web material			PET
Heating type			Ribbon heater
Thickness	t_W	[μm]	25
Width	W	[mm]	300
Transport speed	V	[m/s]	0.01
Initial tension	F	[N/m]	200
Inside temperature	T	[°C]	30 ~ 60

Table 2 - Simulation conditions

Represents the heat flux relaxation time	τ	[sec]	0.5
Thermal diffusivity	k_F	[W/cm·K]	1.67
Ballistic thermal diffusivity	k_b	[W/cm·K]	1.5
Initial temperature	T_0	[°C]	26
Heating temperature	T_h	[°C]	26 ~ 45

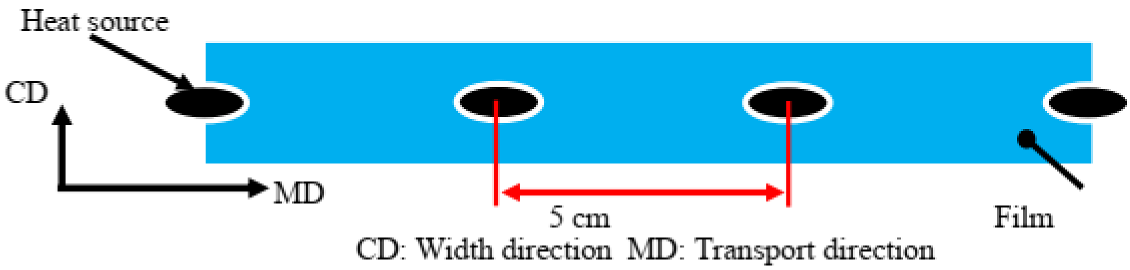

Fig. 4 - Simulation model. Measurement points set at 5 cm intervals on the film, and state of temperature change at each position was obtained by thermal conduction simulations

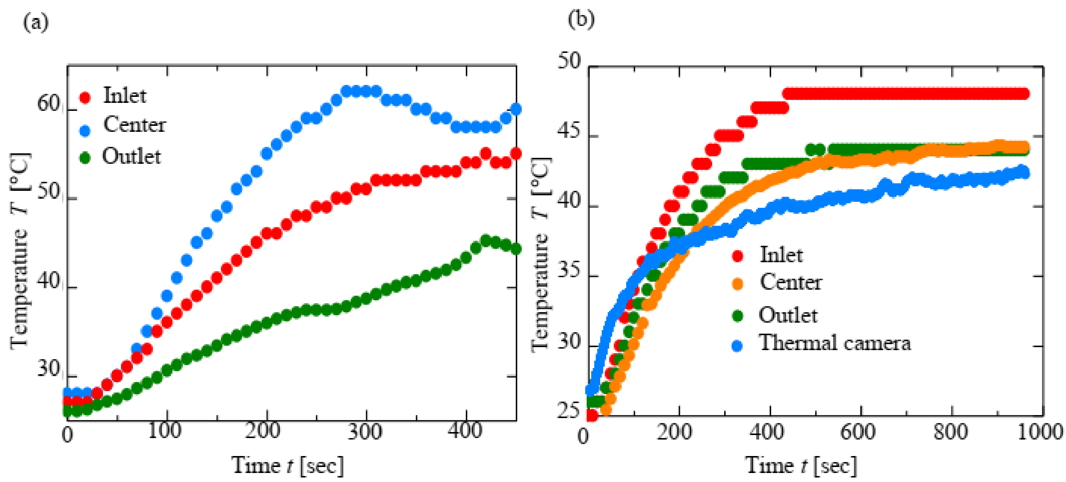

Fig. 5 - Temperature change in heat chamber (a) measurements with thermocouple without thermal camera; (b) measurements with thermocouple and thermal camera

4.2 One Dimension Thermal Conduction

Figure 7 shows the temperature profile at each distance from the heat source. From figure 7, at the distance of 5 cm from the heat source, the temperature rises sharply immediately after heating and the inclination decreases with the passage of time. As a result, it was possible that a compressive force due to heat was generated immediately after heating, and the stress rising rate decreases over time. Moreover, the ballistic phonon is smaller than that of the diffused phonon at the same distance. We considered that this is because the ballistic phonons move straight and cause more collisions than the diffused phonons. In this experiment, there was a difference between the experimental values and the analysis results. The difference is believed due to the neglected heat transfer affected by far infrared rays.

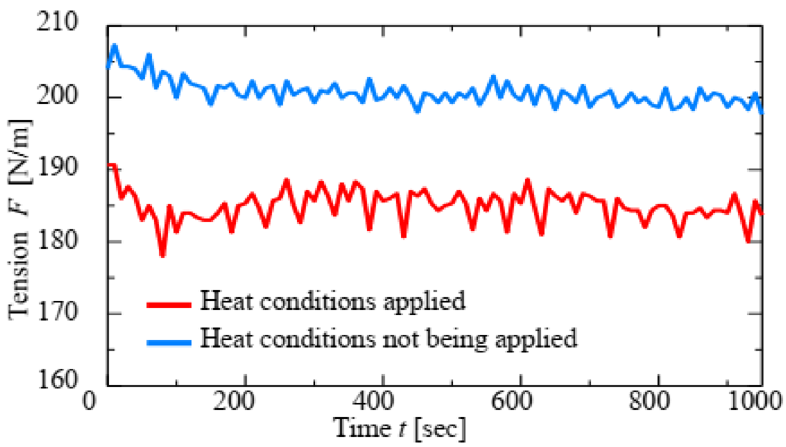

Fig. 6 - Tension applied to the web during heat transfer

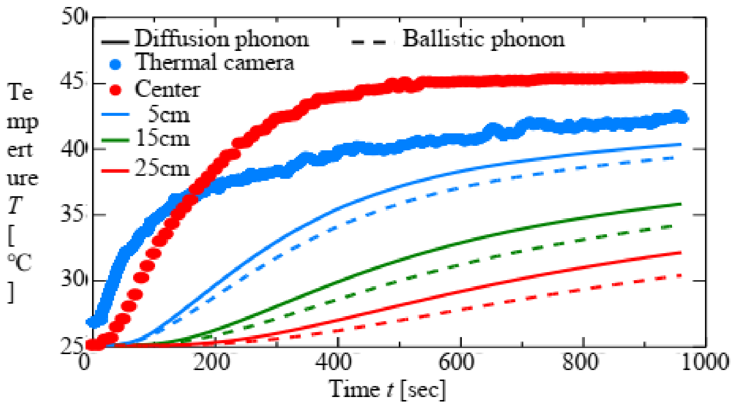

Fig. 7 - Transition of temperature change at each distance

5. Conclusions

The purpose of this work is to confirm the troughs generation conditions of the web where heat was applied heat over a wide range of area, and the changes in troughs and tension generated during heat transfer were measured. In addition, in order to confirm the temperature distribution of the web during heat transfer, we simulated the one-dimensional heat conduction of the web. As a result, the following findings were obtained.

1. The web was stretched in the transport direction by heating while applying tension.
2. A compressive force due to heat was generated immediately after heating, and the stress rising rate decreases over time.
3. The thermal conduction of ballistic phonon is smaller than that of the diffuse phonon at same distance from the heat source. We considered that this is because the ballistic phonons move straight and cause more collisions than the diffuse phonons.
4. There was a difference between the experimental values and the analysis results. This is because in this paper, the temperature distribution of the web using only the ballistic diffusion model were simulated, hence the heat transfer and radiative heat transfer were ingnoerd, which should be taken into considered in order to close the gaps between those values.

Acknowledgement

The authors fully acknowledged the Tokai University, LINTEC Corporation7-7-3 Tsuji and Universiti Malaysia Sarawak for supporting this work.

References

[1] David R, Timothy W and Dilwyn J 2020 *The Web Handling Handbook* (USA: DEStech Publications, Inc.) pp 1-23
[2] Hashimoto H 2007 Prediction Model of Paper-Web Wrinkling and Some Numerical Calculation Examples with Experimental Verifications *J. Microsyst. Technol.* **13** 933-41
[3] Hashimoto H, Ibi Y, Kiribe S and Kondou C 2007 Prediction of Slippage Onset Condition between Web and Steel Roller *J. Microsyst. Technol.* **13** 965-71
[4] Hashimoto H 2015 *Theory and Application of Web Handling* (Japan: Converting Technical Institute) pp 90-102
[5] Guo Y, Batra S, Chen Y, Wang E and Cakmak M 2016 Roll to Roll Electric Field "Z" Alignment of Nanoparticles from Polymer Solutions for Manufacturing Multifunctional Capacitor Films *ACS Appl. Mater. Inter*. **8** 18471-80
[6] Frederik C 2009 All Solution Roll-to-Roll Processed Polymer Solar Cells Free from Indium-Tin-Oxide and Vacuum Coating Steps *Org. Electron.* **10** 761-68
[7] Frederik C 2010 Upscaling of Polymer Solar Cell Fabrication using Full Roll-to-Roll Processing *Nanoscale* **2** 873-86
[8] Kouko J, Retulainen E and Kekko P 2013 Influence of Heating on Tensile and Relaxation Behavior of Wet Paper *Proc. ICWH* **6** 297-316
[9] Feng D and Raman A 2019 Thermomechanics of Axially Moving Webs in Roll-to-Roll Manufacturing Processes *Int. J. Heat Mass Transf.* **129** 1317-27
[10] Kaminski W 1990 Hyperbolic Heat Conduction Equation for Materials with a Nonhomogeneous Inner Structure *ASME J. Heat Transfer* **112** 555-60
[11] Mitra K, Kumar S, Vedevarz A and Moallemi M.K 1995 Experimental Evidence of Hyperbolic Heat Conduction in Processed Meat *ASME J. Heat Transfer* **117** 568-73
[12] Lebon G, Machrafi H, Gremela M and Dubois Ch 2011 An Extended Thermodynamic Model of Transient Heat Conduction at Sub-Continuum Scales *Proc. R. Soc. A* **467** 3241-56
[13] Zhokovsky K, Oskolkow D and Gubina N 2018 Some Exact Solutions to Non-Fourier Heat Equations with Substantial Derivative *Axioms* **7** 1-18
[14] Zhukovsky K and Oskolkov D 2020 Modelling of Heat Transport and Exact Analytical Solutions in Thin Films with Account for Constant Non-Relativistic Motion *Int. J. Heat Mass Transf.* **150** 1-15
[15] Cattaneo C 1958 Sur une Forme de l'equation de la Chaleur Eliminant le Paradoxe d'une Propagation Instantanee *C R Acad. Sci. Paris.* **247** 431-33
[16] Vernotte P 1958 Les Paradoxes de la Theorie Continue de l'equation de la Chaleur *C R Acad. Sci. Paris.* **246** 3154-55
[17] Guyer R A and Krumhansl J A 1966 Solution of the Linearized Phonon Boltzmann Equation *Phys. Rev.* **148** 766-78
[18] Guyer R A and Krumhansl J A 1966 Thermal Conductivity, Second Sound, and Phonon Hydrodynamic Phenomena in Nonmetallic Crystals *Phys. Rev.* **148** 778-88