Chapter 1

Introduction

1.1 Motivation

Rollers are commonly used in the converting of bulk materials to finished products. A long rotating cylinder over which there is a material flow is considered a roller. Rollers are frequently found in the paper, metal, glass and plastic industry where there is the need to process and transport high volumes of thin sheets of materials. Rollers have been used in applications ranging from crushing rock and thinning steel sheets to the calendering of sheet stock and delicate printing applications. Often the long sheets of material are called webs. The functions of rollers can be split into two broad categories, transport and processing. Transport rollers move the web in a controlled fashion between the processing rollers. The are used to set the speed and position of the moving web. They add no value to the product and, ideally are minimized.

Process rollers create value, and are used to convert the bulk web material in successive steps to the finished product. The number of steps and the exact nature of the steps vary with both the raw material and the desired finished product. Heated rollers are often used to both soften the web and set the web to a certain temperature for the next finishing operation. Web temperature is especially critical in plastic processing due to the

low glass transition temperatures of plastics. There is a balance that must be kept between softening the plastics and avoiding a catastrophic tear in the web.

The energy used by heated rollers in the state of Wisconsin and the U.S. in general is substantial. Rollers are used in the converting process in the forest product, printing and plastics industry to convert raw feed stock to a finished product. In 1985, paper drying was estimated to consume 3.95×10^{14} kJ of energy. The printing industry has also become increasingly important to the Wisconsin economy, with companies like Quad/Graphics alone printing more than 100 million magazines a month. In addition, the plastics used in this study; polyester, polyethylene, polypropylene and polyvinyl chloride (PVC) in all of their forms account for 70% of the U.S. polymer production. Product temperature is a vitally important parameter in the processes of all three industries, and improvement in its control will offer substantial energy efficiency gains.

Figure 1.1.1 shows a web passing over a rotating roller as would be encountered in a typical processing application.

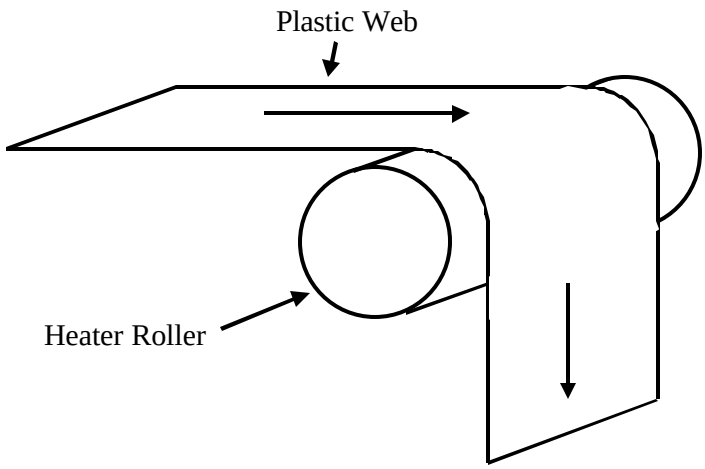

Figure 1.1.1: Web-Roller Schematic

Rollers have been traditionally heated using steam or hot oil. The fluid is passed into the roll by a rotating union through the bearing on each side of the roll. The fluid then heats the inside of the hollow roll through convection. The heat is then conducted through the roll, heats the outside face of the roll, and eventually heats the plastic. Due to the various thermal resistances in the system, the hot fluid must be supplied at higher temperature than needed in the actual process.

There are several inadequacies in using internally heated rollers. From a process viewpoint, the temperature of an internally heated roller is inherently difficult to regulate. Internally heated rollers have a long thermal time constant, which is the primary obstacle to tight control of temperature. Internally heated rollers are also mechanical difficult to maintain. Both the boiler used to produce the heat and the actual roller shell are essentially high temperature pressure vessels, and require extensive design and safety analysis. The

rotary unions needed to pass the hot fluid to the spinning roller are also prone to failure and can be the cause of messy and environmentally dangerous leaks.

Three new roller-heating techniques have been developed that overcome most of the above limitations:

Induction heating uses technology commonly used to melt metal in foundries. Reversing magnetic fields are induced in the ferromagnetic core of the roller, generating heat in the roller through hystereses loses.

A second technique uses a thin layer of a electrically semi-conductive material applied to the surface of a hollow steel core. The finite electrical resistance of the coating depends on the thickness and chemical constitution of the applied coating. A voltage is applied across the ends of the conductive layer, and the flowing current generates heat through ohmic dissipation in the conductive layer.

The third technology uses cartridge resistance heaters embedded in the steel core. Generally they run axially the whole face length of the roller and may number 8 - 12 in the typical roller. They are arranged in a regular radial pattern to promote even heat distribution. The heat generation is again due to ohmic heat dissipation. The electric power is supplied to the cartridges through electrical slip rings.

Electrically heated rollers have higher installation cost than internally heated rolls, as the roll cost includes both the energy source used to generate heat (AC power supply) and the required control system. The energy cost may also be higher as they must use electricity and cannot use waste heat from other manufacturing steps. Demand energy charges may apply and can be substantial. However the electrically heated roller advantages of quick startup time and ability to be regulated closely may drastically increase production rate and product quality.

Generally the heater (or cooler) rollers are controlled using the surface temperature of the roller as a feedback to the control loop. An alternative technique would be to use a power regulation method, where a specified power was delivered to the web. With a specified power, the roller surface temperature would be allowed to float to the necessary temperature to drive the power to the web. A simple feedback control law is often used with a Proportional/Integral/Derivative (P.I.D.) controller to regulate the heat supply to the roller based on whether the roller is above or below the desired temperature. Typically a non-contact infrared sensor is calibrated to give a correct measurement based on the emisivity of the roll covering. The sensor signal is then used in the feedback loop of the P.I.D. controller.

The relation between the roll temperature and the web outlet temperature as it leaves the web is complex and is the motivation for the present study. The thermal capacity of the web moving over the roller is important, as is the wrap angle of the web on the roller and the surface characteristics of the roller. The most elusive parameter in controlling the rate of heat

transfer between the roller and the web is the thermal contact resistance between the surfaces of the web and roller in contact.

The shortcomings of traditional web heating have been even more apparent with plastics processing. Thin plastic webs have low heat capacity and can be easily overheated and undesirably stretched. Much processing is done at close to transition temperatures where temperature control is critical. Given the high radiation trasmisivity of most plastics, the temperature is difficult to measure using an infrared pyrometer, and the quality of the signal in the feedback loop is low.

This study examines the effect of contact resistance on the heating of plastics, specifically polyester, embossed polyethylene polypropylene and PVC. A physically static, thermally transient method is developed to measure contact resistance in chapter 2, and the results for the above plastics are shown in chapter 3. The development of a finite difference thermal model of the roller and web system is in chapter 4. Chapter 5 discusses the test methods used and the results found in dynamic rolls test at American Roller Company's Research and Development Facility.

1.2 Contact Resistance Fundamentals

Contact resistance is defined by the ratio of the heat transfer through a joint of two materials in contact to the driving temperature potential across the joint. The thermal contact resistance between a roller surface and a web is defined as:

$$R''_{tc} = \frac{T_{roll,surface} - T_{web,surface}}{q''} \tag{1.2.1}$$

The contact resistance is due to the microscopic qualities of the surfaces where the roller and plastic meet. All real surfaces are microscopically rough, and when two surfaces are brought into contact there will always be imperfect mating. A measure of the degree of contact is the ratio of the actual to the nominal contact area, and can be anywhere from 0.02 for relatively hard materials to approaching 1 for softer, ductile materials. The surface characteristics of the roughest surface generally determine the actual area of contact.

The actual heat transfer between the two solids is due to multiple processes. Conduction through the contact spots is usually the most significant, but there is also radiation exchange between the two surfaces as well as convection currents through the air gaps in the joint. Convection currents can only occur in the presence of an interstitial material such as air or other gas. The heat exchange processes in a simplified model of a real joint is shown in figure 1.2.1. below.

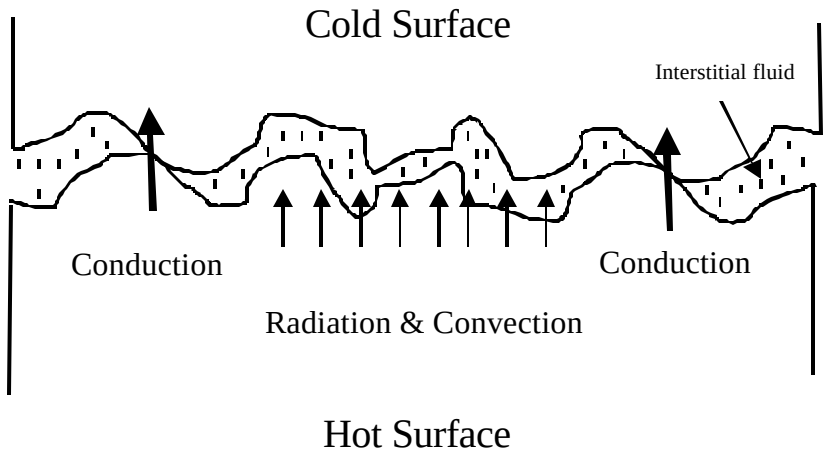

Figure 1.2.1: Heat Transfer Processes in a Typical Joint.

Increasing pressure, smoother surfaces, and higher thermal diffusivity interstitial fluids increase the heat flow and decrease the contact resistance. Contact resistance can have a major effect on the effectiveness of heater rollers. The contact resistance is also due to the air entertainment on high-speed webs. Air entertainment is a thin layer of air that is compressed between the web at high web velocities. The resistance will vary with different web material and roll finishes, different interface pressures and different web speeds.

Attempts have been made to predict contact resistance from first principals, with mixed success for metal joints. Predicting the contact resistance of a joint requires predicting the microscopic deformation of the surfaces in contact on a statistical basis, including any plastic or inelastic deformation. The thermal and pressure dependence of the modulus of elasticity, thermal conductivity and other factors must also be predicted, complicating the derivation. Given the high property sensitivity of plastic webs to both pressure and temperature, an analytical solution was not feasible.

1.3 Literature Review

TAPPI (Technical Association of Pulp and Paper Industries) and others have extensively studied web – roller processes. Much research has been on the production of paper and associated forest products. Paper drying, usually done on large cast iron drums called Yankee dryers, has been the most extensively studied process. A summary of studies, authors and their results is shown below in table 1.3.1.

Author	Paper Grade	Pressure [kPa]	Thermal Contact Conductance [W/m^2-K]	Contact Resistance [m^2-K/W]
Sundberg & Osterburg (1966)	Unbleached Sulfite	---	400-4500	0.00022-0.0025
Kerekes (1980)	Newsprint	---	875-1610	0.00062-0.0011
Byrd (1982)	Linerboard	13.8	191-1806	0.00055-0.005
Seyed-Yagobi,Ng & Fletcher (1991)	Bleached	0-300	90-450	0.0022-0.011

Table 1.3.1: Summary of Published Contact Conductance Data. Adapted from Seyed-Yagoobi, 1992a

The range of contact resistance's for drying different grades of paper products ranged from 0.00022 m^2-K/W to 0.011 m^2-K/W. Considerable scatter can be found in the contact resistance data, with some studies being performed on actual production roll systems (Kerekes), and the rest using physically static contact resistance measurement techniques. Static contact resistance techniques use an apparatus to force the paper in contact with a machined sample at a specified pressure. The heat flux and the temperature drop across the joint is measured, determining the contact resistance between the paper and machined surface. It should be noted that laboratory studies with steady state techniques could not measure the effect of air entrainment into the roller web interface.

Joint interface resistances have not been widely published, especially for plastic webs. In addition, the studies that have been done have been at much higher pressures than normally encountered on unnipped rolls. Madhusudana (1996) gives an extensive review and both Kerekes (1980) and Seyed-Yagoobi et al. (1996) give condensed reviews of contact resistance methods, all without reference to plastic contact resistance studies.

Most authors have used physically static methods to measure the contact resistance of paper to metal interfaces. Kerekes (1980) alone has published an expression for contact resistance based on dynamic measurements.

1.4 Scope of Study

The present study has two direct purposes, developing an accurate, physically static method to measure the contact resistance between plastics and rollers, as well as determining the viability of using static contact resistance tests in a dynamic roller application. The study is limited to examining the effect of contact resistance on the heat transfer between both smooth (polyester and polypropylene) and rough (embossed polyethylene) plastics and heated rollers. Both stationary and dynamic web tests are used to measure the thermal contact resistance, and finite difference techniques are used to examine the effect of contact resistance on web roller systems.