

Christian Kohlert
Tamara Chistyakova

Innovations in Film Manufacture

Exemplified by Calender Technology



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Opening Remarks

Christian Kohlert

This book was developed by specialists in plastics technology, especially calendering technology, and is based on around 20 years of professional experience and scientific collaborations with international universities and research institutions. Results are presented based on around 20 doctoral theses and 200 diploma and master's theses, which were supervised by the authors.

The aim of this book is not a general presentation of the calendering process, as this is already sufficiently contained in the books by Kopsch and Kohlert. It is also not intended to convey knowledge that can be easily researched on the internet. Instead, the aim is to present innovations and practical experiences in plastics processing—using the example of the calendering process—that can also be used in other plastics technologies, such as extrusion, injection moulding, or coating. All calculation methods presented are applicable to other plastic technologies, or can be transferred to them.

The images used in the book are taken from the authors' working lives, unless otherwise stated in the image caption or at the end of the section. We recommend that anyone interested in re-using the images contact the authors' collective at info@kohlert-consulting.de.

The book was written by Prof. Dr. Christian Kohlert and Prof. Dr. Tamara Chistyakova, with the participation of Helmut Welbers, Dr. Andrey Polosin, Dr. Michael Kohlert and Prof. Dr. Frank Kleinert.



Prof. Dr. Christian Kohlert



Prof. Dr. Tamara Chistyakova



Helmut Welbers



Dr. Andrey Polosin



Dr. Michael Kohlert



Prof. Dr. Frank Kleinert

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1

Introduction

Christian Kohlert

Via AI you will find the following definition of “calendering”, and this underlines the importance of our focus on innovations and similar evaluations in this book:



Calendering is a process in the plastics and rubber industry in which materials, especially plastics or rubber, are processed into thin layers or films by rolling. This process is primarily used for the production of flat materials such as films, panels, and sheets.

Calendering involves four main steps:

1. **Heating:** The raw material (plastic or rubber) is heated to a high temperature to soften it and make it malleable.
2. **Rolling:** The heated material is passed through a series of rollers that are coordinated to maintain the correct pressure and temperature. As it passes through the rollers, the material is formed into a thinner layer.
3. **Cooling:** The thin layer or film is cooled to achieve the desired strength and thickness.
4. **Slitting:** The cooled material is slit to the desired dimensions.

Calendering can also be used to bond different materials together, for example to produce a composite of two or more plastic or rubber layers. The process parameters, such as temperature, pressure, and roll speed must be carefully controlled to achieve the desired material properties and dimensions.

Calendered products are used in a variety of applications, such as the packaging, automotive, construction, and electrical industries. Calendered plastic films play a major role as homopolymer films, as multilayer films, or as mixed films in the packaging

industry, as well as in technical and agricultural applications, and they are an integral part of polymer value chains.

Of course, the type of film, material, and property profile, as well as new innovations, play a major role in the optimization processes, which in turn affect the price–property ratio. Many innovations have been incorporated into polymer production processes in recent years, especially sensors (driven by advances in microelectronics) and in data processing, and these can generally be used in any polymer film manufacturing process.

As shown in Figure 1.1, every film manufacturer faces market tensions, and needs to find a system that is optimal for them. Raw material suppliers are concentrating on the production of cheaper raw materials and have a better market position; customers are becoming more demanding regarding quality and property profiles; and new competitors from outside Europe are striving to enter the market, and in so doing, substitute products with their own polymer bases.

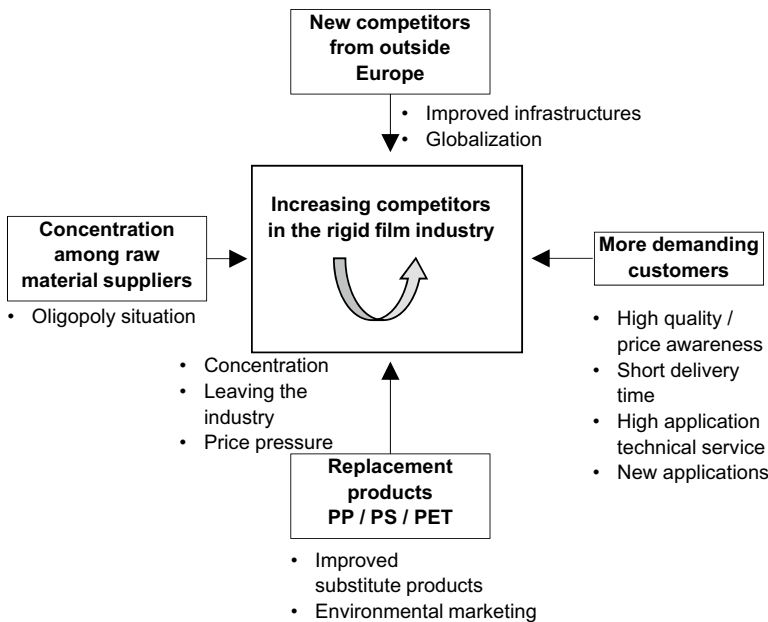


Figure 1.1 Market tensions in the production of polymer films

Polymer films are usually produced using three manufacturing processes (Figure 1.2). Of these, the calendering process is the most productive process in terms of tonnage, thickness tolerance, and quick changeover times (see Figure 1.3). The basics of calendering are covered in the books by Kopsch and Kohlert [1, 2]. Extrusion has its advantages in terms of the investment amount, the number of workers, and the colour

change. Spreading and laminating several films can be used for finishing after any film production process.

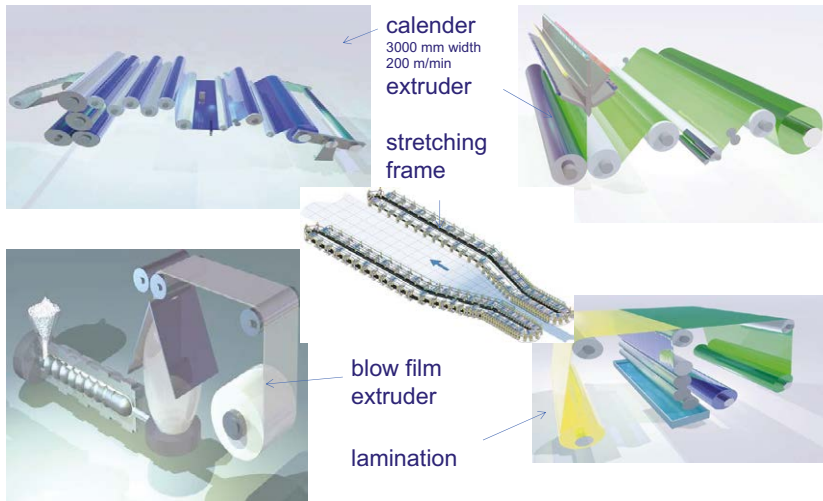


Figure 1.2 Manufacturing process for polymeric films and their finishing (Source: [3])

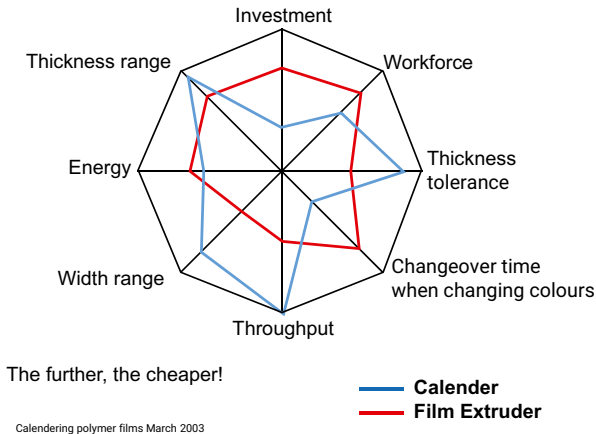


Figure 1.3
Comparison of calendering and extrusion

The calendering process is characterized by material storage and preparation, dosing and mixing, the fluxing process in an extruder or co-kneader, the actual calendering process by molding between several rollers, the after-treatment for the final adjustment of the film thickness and film shrinkage, as well as the temperature control for cooling and the winding up.

For customer requests, a winder or format cutter is usually used for final packaging (Figure 1.4).

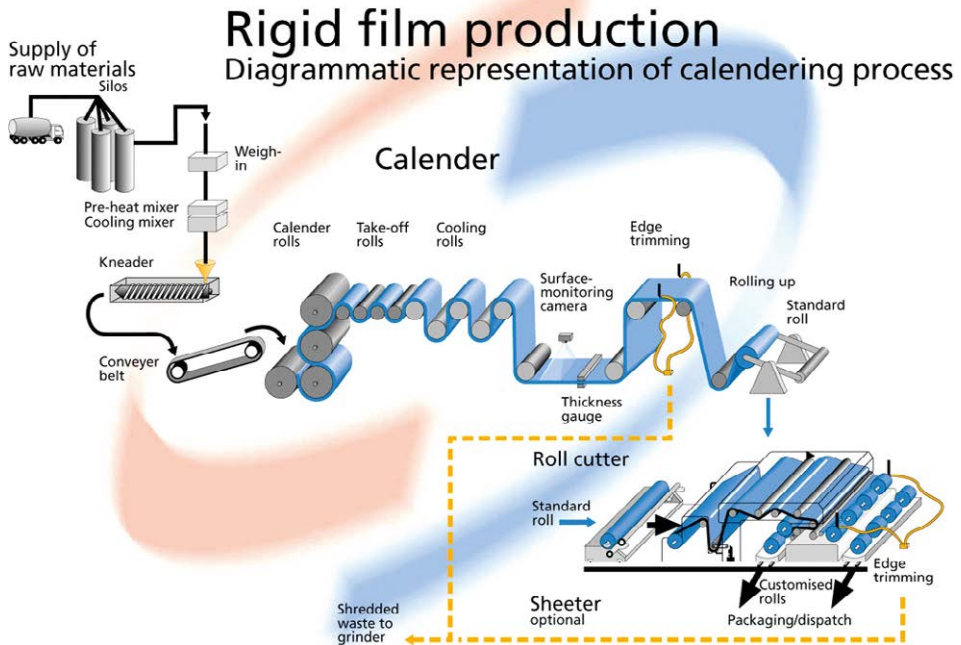


Figure 1.4 Schematics of a calender line (Source: [3])

The extrusion process is usually characterized by processing granules, i.e. prefabricated material particles and not direct raw materials. Especially with PET and PA granules, the material must be pre-dried so that no air bubbles or air cracks occur in the finished film, due to the hydrophilic nature of the material. The melting and shaping then takes place in one or more (up to seven) extruders via so-called wide slot dies, and the emerging film is then cooled with a cooling roller. The film is then cooled and assembled, as in calendering (Figure 1.5).

The finishing options include longitudinal stretching in the post-calender unit (MDO) and transverse stretching in a wide stretching frame (TDO). The state of the art uses thickness measuring systems, camera systems for surface defects, as well as in-line measurements of colour, gloss, and haze.

Film thicknesses between 20 and 1600 μm and widths of up to 2.2 m are achieved, and up to 6.2 m when stretched. By stretching and using a suitable T-guide, shrinkage values of up to 80% can be achieved.

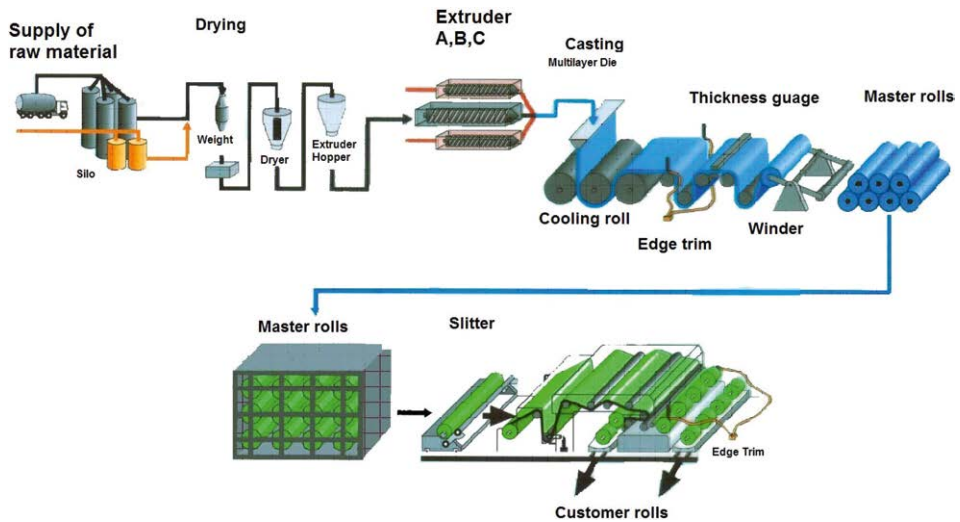


Figure 1.5 Schematic of a film extrusion line (Source: [3])

When extruding blown film, the prefabricated granules are formed into a multilayer film in the range of several μm per layer, possibly with pre-drying, using several extruders of different sizes in a mixing nozzle and expanded by several air bubbles. This allows the desired film thickness and width, as well as the corresponding shrinkage, to be achieved (Figure 1.6).

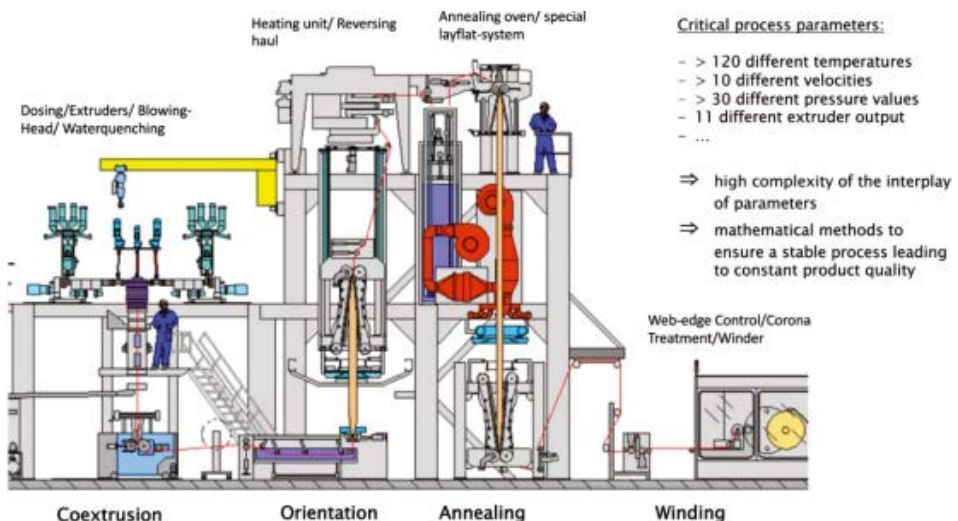


Figure 1.6 Schematics of a blown film extrusion line (Source: [4])

References for Chapter 1

- [1] Kopsch, H.: *Calender Technology*, Carl Hanser Verlag, 1978
- [2] Kohlert, C. et al.: *Kalandrieren von Polymeren*, Deutscher Verlag für Grundstoffindustrie, Leipzig, 1992
- [3] Company material, Klöckner Pentaplast GmbH & Co. KG, Montabaur
- [4] Company material, Maria Soell GmbH

2

Production of Calendered Films

2.1 Calendering

Christian Kohlert

Calendering is the process of forming polymeric masses in the nips of a calender. During calendering, the processing material passes only once through each nip, whereas during rolling, the material passes through the nip several times until the desired homogenization is achieved.

The aim of the calendering process is to achieve a uniform thickness distribution for a homogeneous polymer mixture at high film speeds in the longitudinal and transverse directions. In addition to the film thickness, also important are color consistency, uniform shrinkage, and strength values, as well as the avoidance of film defects such as black dots, specks, wrinkles, etc.

In practice, 4- and 5-roll L-shaped calenders with film guides from bottom to top have become established for hard PVC, as this makes it easier to manage the cleanliness of the rolls. For soft PVC, 4-roll calenders in F and Z shapes are used because of better suction of the vapors created by the plasticizers. Common calender designs in current use are shown in Figure 2.1 and Figure 2.2.

design		general areas of application
	2-roll-calender; I-shape	floor coverings, vinyl asbestos tiles, satin finishing of IT panels, rough rubber plates, sole plates
	3-roll-calender; I-shape	floor coverings, rubber plates, friction
	4-roll-calender; I-shape	rigid-PVC-film, rubber plates, covering fabrics and cord threads stripes on one and both sides, friction
	4-roll-calender; F-shape	soft-PVC-film, rubber plates, covering fabrics and cord threads stripes on one and both sides, friction, duplicate
design		general areas of application
	4-roll-calender; F-shape with rear breast roller	soft-PVC-film, rubber plates, covering fabrics and cord threads stripes on one and both sides, friction, duplicate
	4-roll-calender; L-shape	rigid-PVC-film
	5-roll-calender; L-shape	rigid-PVC-film
	4-roll-calender; Z-shape	soft-PVC-film, rubber plates, covering fabrics and cord threads stripes on one and both sides, friction, duplicate
	4-roll-calender; S-shape	rigid and soft-PVC-film, rubber plates, covering fabrics and cord threads stripes on one and both sides, friction, duplicate
Special design		general areas of application
	2-roll-calender; horizontal-shape	rough rubber plates, floor covering
	2-roll-calender; inclined-shape	rough rubber plates, linoleum
	3-roll-calender; inclined-shape	rubber plates, covering fabrics on one sides, friction
	3-roll-calender; A-shape	pre-film for rigid PVC pressed sheet
	3-roll-calender; triangular-shape	rubber plates, covering fabrics on one sides, friction
	4-roll-calender; Z-shape with raised front roller	rubber plates, covering fabrics and cord threads stripes on one and both sides, friction, duplicate
	4-roll-calender; I-shape with inclined top roller	rubber plates, covering fabrics and cord threads stripes on one and both sides, friction, duplicate

Figure 2.1 Calender designs (Source: [1])

Figure 2.2 shows the most important parts of a calender, namely the rollers, roller bearings, stands, and post-calender unit. In the early days of calender technology, bottle neck-drilled rolls were used, with heating taking place by electrical electrolytes in chambers filled with water. Although this was an inexpensive technology, it required long changeover times for the roll temperatures and resulted in a temperature gradient from the centre of the roll to the edge of the roll. With the desire to reduce change-over times, peripherally drilled rollers were used (Figure 2.3). Here, externally heated oil or water in the printing circuit made it possible to achieve the necessary surface temperatures more quickly for different recipes and film thicknesses. The disadvantage of filling with oil is the contamination when changing the rollers and the oil costs.

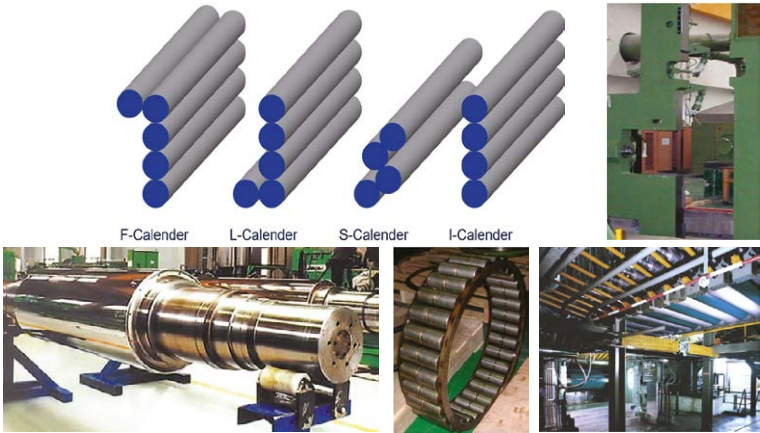


Figure 2.2 Calender designs (Source: [2])

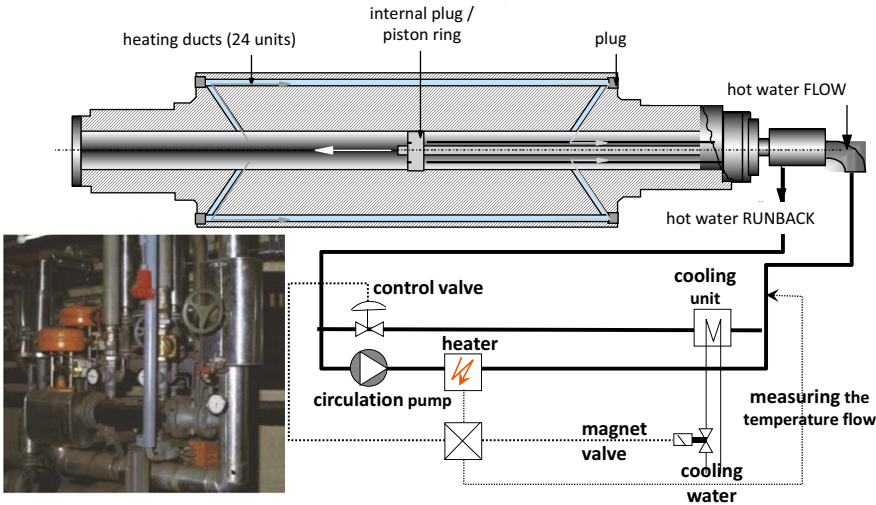


Figure 2.3 Roller structure (Source: [2])

Using the example of a 4-roll L-calender, the thickness reduction and increase in width between the individual rolls are shown in Figure 2.4. The higher the viscosity and the narrower the roll gap, the greater the increase in width. This must be taken account of by adjusting the input width of the material in the first gap.

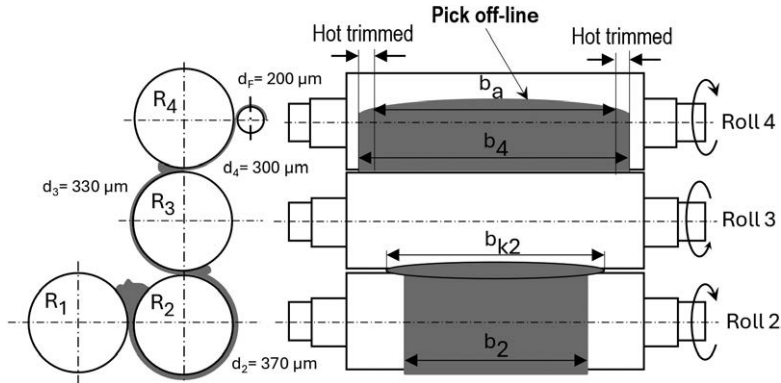


Figure 2.4 Thickness reduction and increase in width on the calender (Source: [2])

Calendering paper and plastics are an old technology that appears not to have evolved significantly in recent decades. However, when you take a closer look, you notice endless technical progress in machines and technology. The word “calendering” could come from the Greek word for “cylinder”, and was first mentioned in 1798 in the context of a smoothing calender for textile surfaces (cf. [1]). There are also references to the naming from the word deficiency of textile technology [3].

Figure 2.5 shows the first patented calender for rubberizing fabrics, with a roll width of 1830 mm and roll diameters of 457 and 305 mm, as described in US Patent No. 16. The development of calenders in the 20th century was primarily influenced by the German mechanical engineering company Berstorff. The first cambered rolls were created at this time, in which the roll diameter was larger in the middle of the roll than at the edge to absorb a large part of the roll deflection. Electromotive roller adjustments and tilt adjustment options for the central rollers followed for the purpose of faster changes and corrections of film diameter inequalities across the film width. To better control the three to five calender rolls, the gearbox had already been switched to individual drives. In the 1940s, the Luvitherm process was patented to achieve special strength through subsequent heating of the film leaving the calender.

With the first hydrodynamic analyses of the flow processes in the roll gap by Alexandre Ardichvili, for example, the theoretical understanding of the effects of a calender gap began. In the 1950s, peripherally drilled rolls provided a better temperature profile on the surface of the calender rolls, and pre-tensioning and roll bending as counter-deflection allowed further improvements in the uniformity of the films in terms of thickness and shrinkage tolerance. Around 1960, people began to switch to continuous pre-plasticization for higher throughput and to use larger roller widths (up to

2000 mm) and higher speeds in new buildings. At that time, it was already possible to achieve calendering speeds of 60 m/min for hard PVC and up to 150 m/min for soft PVC. Figure 2.6 shows a modern calender line starting from fluxing to reel slitting.

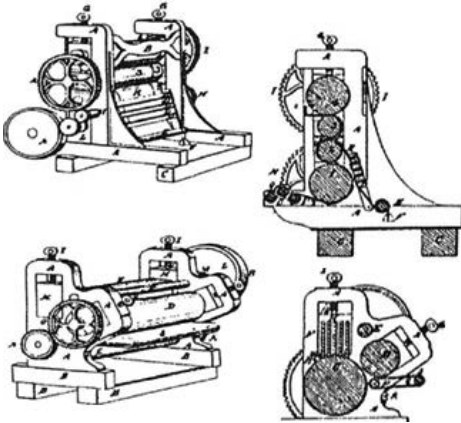


Figure 2.5
First patented calender variants
(Source: [1])

In the 1970s, the first calculation models for throughput and pressure (for example, by J. S. Chong) succeeded in bringing the roll shapes (camber or crowning) so close to reality that 80–90% of the roll deflection due to material pressure could be compensated for (Figure 2.7).

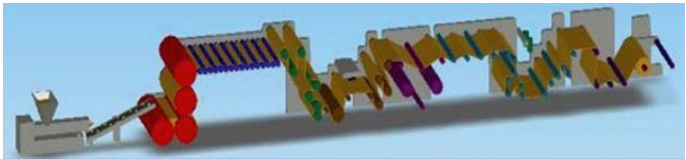


Figure 2.6 Modern 4-roll L-calender line (Source: [2])

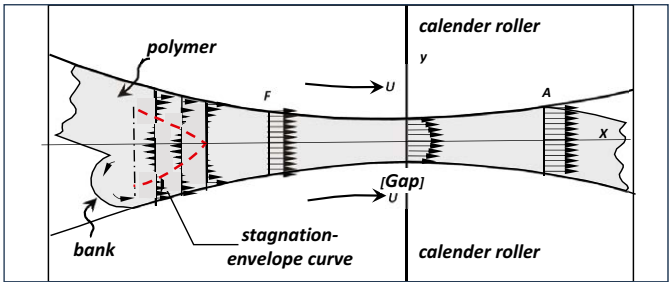


Figure 2.7 Speed distribution in the roller gap (Source: [1])

Figure 2.8 shows the basic equations for calculating the bending under camber, roll bending, and axis crossing. The first calculation models for roll deflection and com-

pensation were based on this (Figure 2.9). Initial process optimizations (for example by Ernst-Otto Reher and Vladimir Krasovski) made it possible to achieve accuracies in the μm range for PVC rigid films.

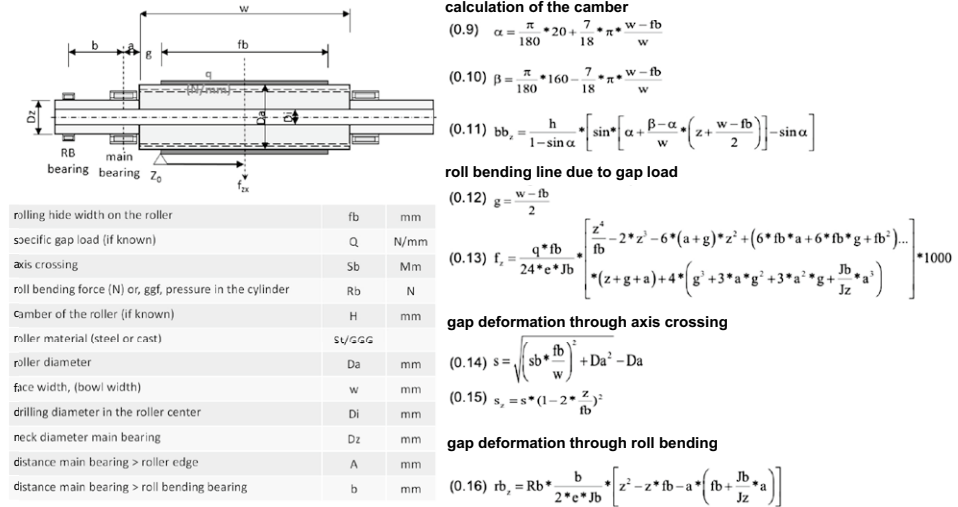


Figure 2.8 Roll calculation (Source: [2])

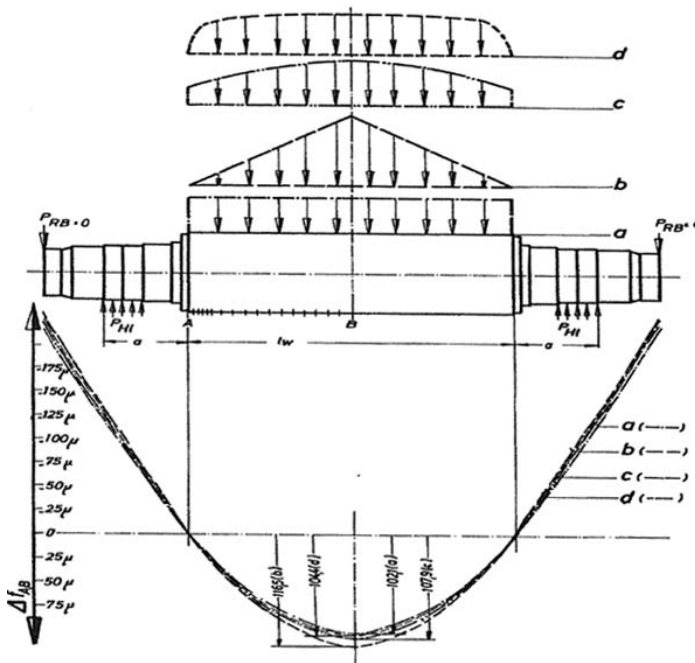


Figure 2.9 First calculation models for throughput and pressure (Source: [1])

In Figure 2.10 are shown different flow patterns depending on the friction. This also required a development of measurement technology in which these accuracies could also be practically assessed using radiometric thickness measuring systems. In the 1980s, the calender was supplemented with wedge-shaped internals (after Heinrich Collin and Christian Kohlert [4]), which were intended to improve the mixing process in the calender gaps. The first major automations and controls of temperatures and speeds led to increased system analyses of the influencing parameters and their connections in relation to film qualities (after Klaus Hartmann).

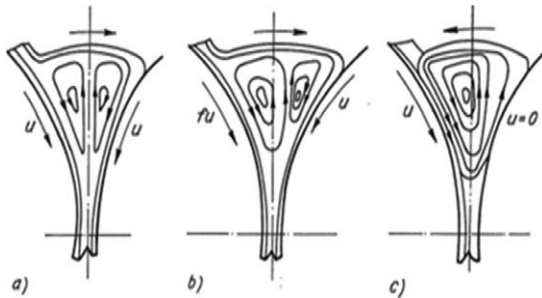


Figure 2.10

Quantitative image of the flow of a Newtonian fluid in the gap, with (a) $f = 1$, (b) $f = 1.3$, and (c) $f = \infty$ (Source: [1])

With the advent of microcomputer technology, in-line measurement technology was placed at the forefront of developments, especially in the 1990s. As a result, the quality of the film features could be measured at the point of creation, and influenced by the calender operator. This is how the defect inspection systems for evaluating surface quality, shrinkage measuring systems using polarized light, level measuring systems using ultrasound or light speed measurement, as well as in-line color and gloss devices were created.

The transition to modern techniques around the turn of the century was characterized by further strong development of in-line measurement technology, as well as automation solutions from dosing to winding technology. A modern calender line from the company Klöckner Pentaplast is shown schematically in Figure 2.11.

Film properties that need to be considered during calendering are the thickness distribution in the longitudinal (MDO) and transverse directions (TDO), the shrinkage in MDO and TDO, surface defects (black specks, gels, fibres, holes, etc.), surface roughness (glossy or matt), barriers against water vapor and gas, thermoformability, printability, color fastness, and mechanical and thermal film properties.

Calendering technology is divided into the section material storage, dosing, hot and cold mixers, fluxing, calendering, pick-off rolls, take-off-rolls, cooling rolls, measurement technology, winding and packaging using slitters or sheet cutters.

Today there are complex calender lines for film thicknesses from 25–1200 μm , with roll speeds of up to 200 m/min and roll widths of up to 3500 mm. Shrinkage values of 0–60% are possible in MDO.

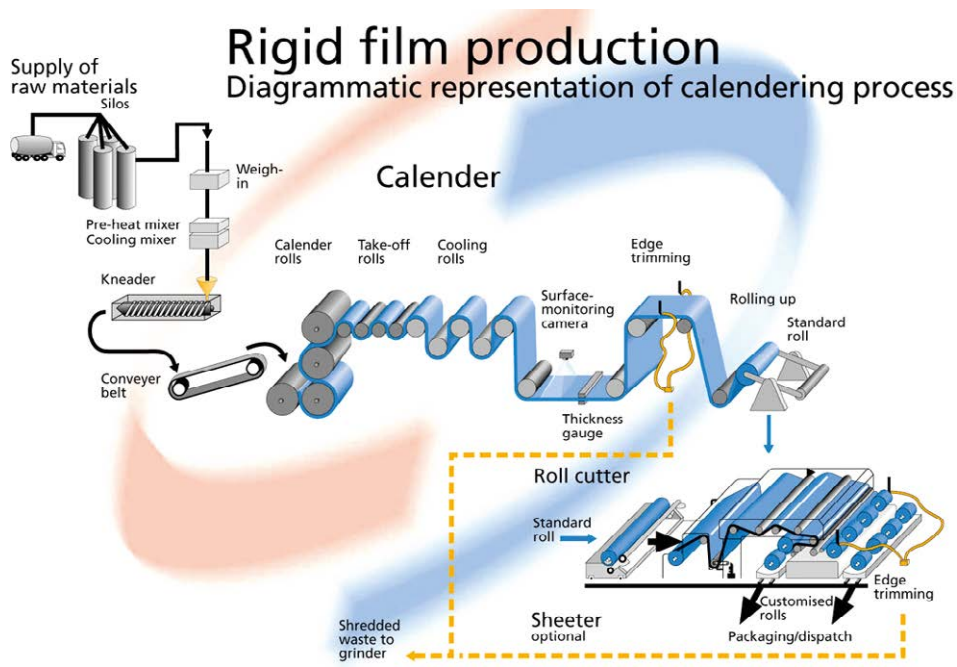


Figure 2.11 Modern rigid-PVC calender (Source: [2])

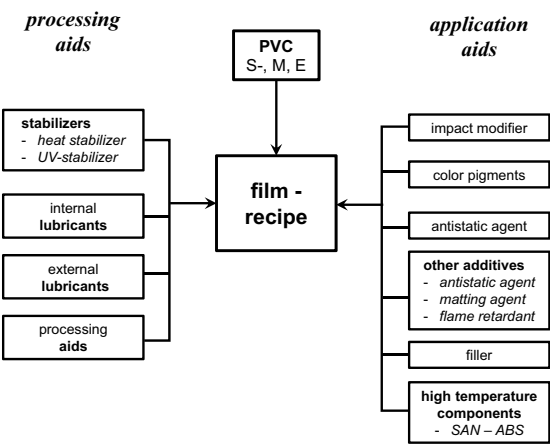


Figure 2.12
Film recipe for PVC rigid films
(Source: [2])

For the main product of a plastic calenders, a basic recipe (for PVC rigid films) is shown in Figure 2.12. It is assumed that around 80% of the recipe consists of PVC and around 10% each is made up of processing aids and application aids.

The processing aids include stabilizers, internal and external lubricants to reduce temperature peaks and reduce the adhesive effect on the calender rolls, as well as calendering aids to influence the viscosity of the polymeric mass to be processed. The ap-

plication aids include impact modifiers to influence film strength, color pigments, and antistatic agents to prevent electrical charging, as well as other additives and fillers for special applications or reducing recipe costs.

This allows throughputs of up to 4 t/h to be achieved. This is possible through automated dosing of the individual components, computer-aided control, process monitoring with control programs such as WinCC, trend analyses, and statistical process control. In-line and off-line quality control as well as energy efficiency measures complement this modern technology. Certifications according to ISO 9001 (quality), GMP, ISO 14001 (environment), ISO 50001 (energy), and hygiene are now standard in calendering companies.

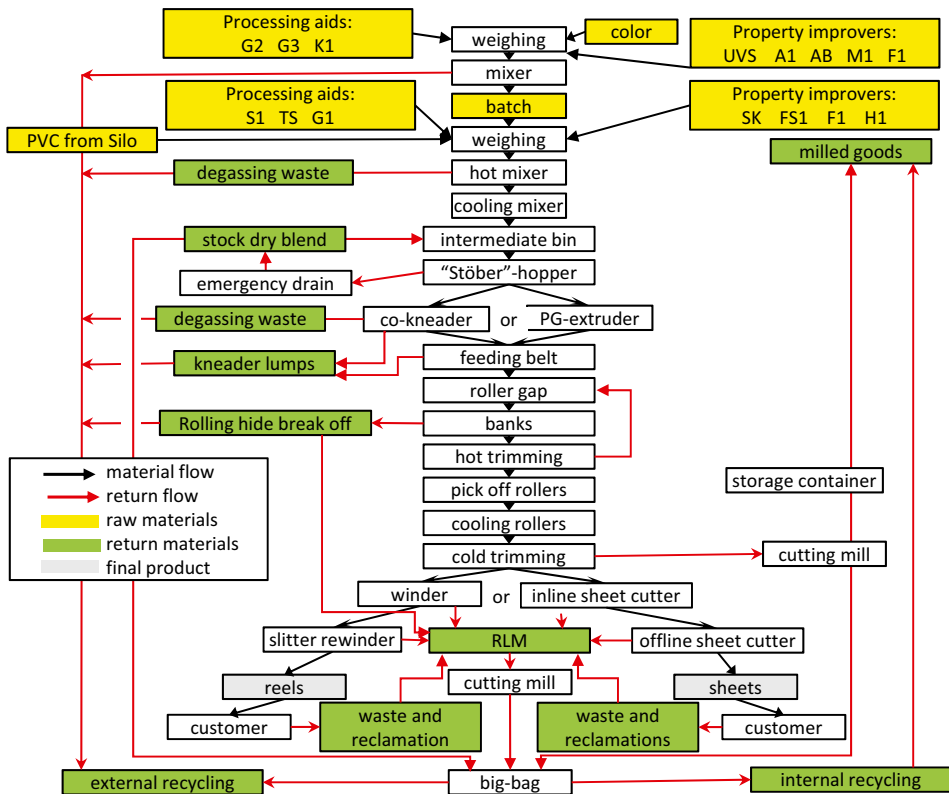


Figure 2.13 Material flow diagram in a calender line (Source: [2])

The material flow diagram of a calender line is shown in Figure 2.13. Many returns to the output flows can be seen as internal recycling. In modern calendering systems, an average yield of 85% is obtained directly from the raw material to the film for the customers. Around 15% is returned to the cycle or stored in big bags as granulated material for later further processing. Material that can no longer be processed is created through combustion or pollution, and is usually sold as down-recycling material in the range of 0.1–0.3%.

Figure 2.14 and Figure 2.15 show the status of measurement technology and data linkage at Klöckner Pentaplast. The aim of the development of measurement technology in recent years has been to capture the desired values in-line, since the operator can intervene immediately in the event of deviations from the target value. A later laboratory assessment result in ever larger unusable shortages if deviations are identified. Modern calender lines now have traversing in-line thickness measuring systems with shrinkage measuring systems, line cameras for surface evaluation, as well as color and gloss measuring systems if the film quality requires this (Figure 2.14). The results of these measuring systems are displayed directly on the calender to provide the operator with information about the film qualities, and are collected in data systems and used as trend analyses. Modern software packages allow a cause-and-effect analysis to determine the reasons for deviations from target values.

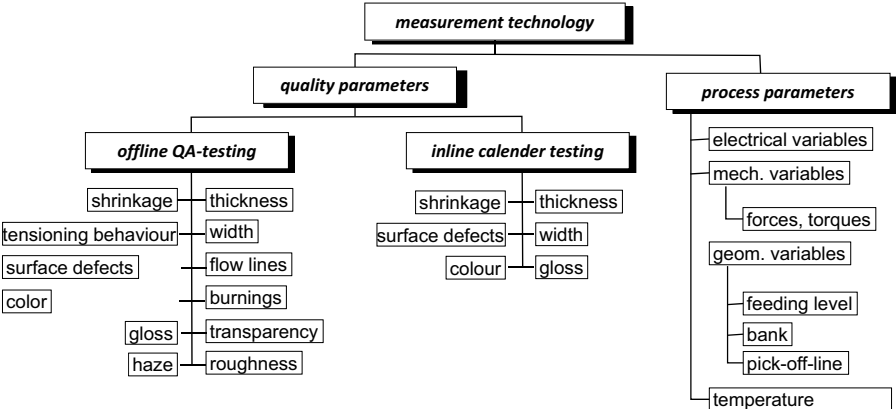


Figure 2.14 Status of measurement technology for calendering at Klöckner Pentaplast (Source: [2])

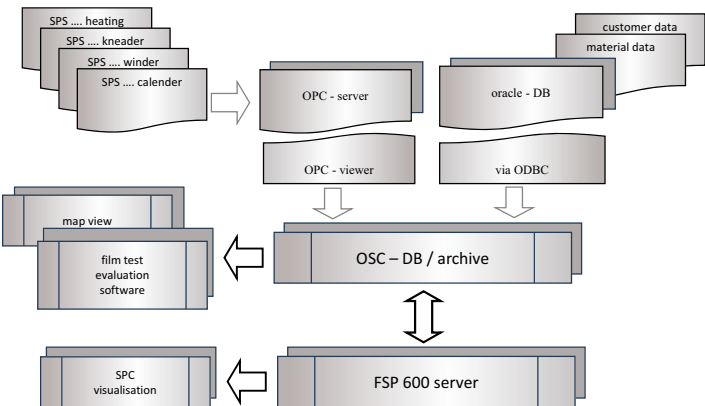


Figure 2.15 Status of data linkage during calendering at Klöckner Pentaplast (Source: [2])