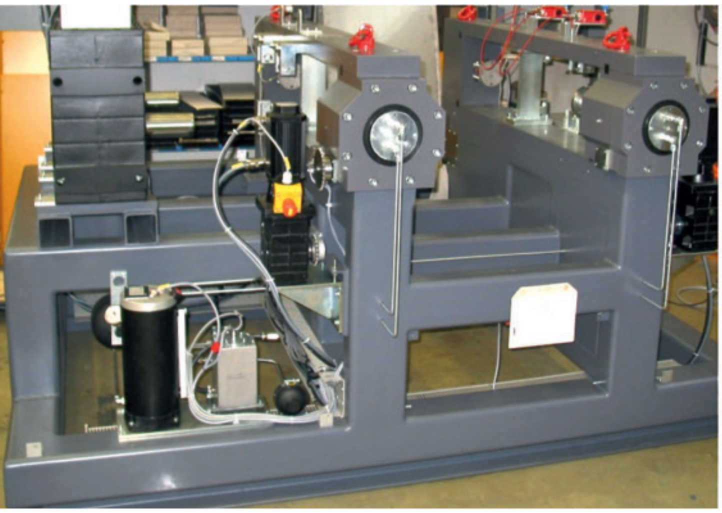

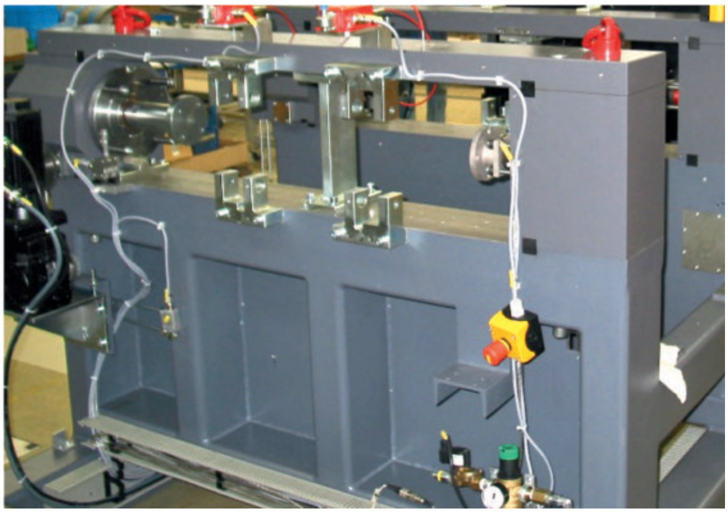

**Heart of a two-roll horizontal calender: the basis for high-precision flat film is a rigid and straw machine frame. Bearing forces of up to 20 t per roll end can thus be accommodated without difficulty**

# Film with a Function

**Extrusion.** Production of high-quality film for optical and electronic applications poses significant challenges for the manufacturing process and the flexibility of the equipment. Laboratory-scale machines are ideal for this processing window. On the one hand, they keep material consumption low during prototyping, while on the other they are very well-suited for cost-effective production of short runs.

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Flexible substrates for electronic circuits are currently growing at an annual rate of about 12 %, with most of this rapid growth occurring in Asia. The most important applications are found in computers, telecommunications and display units. Compared to the above-mentioned fields, automotive applications are at a relatively low level, although new opportunities are expected to open up here.

Flexible substrates are expensive products and offer a number of benefits:
- Significant potential for weight savings because of the ever thinner substrate films,
- flexibility permits three-dimensional design,
- ability to withstand dynamic loads.

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The continuous pressure to reduce costs and the highly dynamic market demand new developments with a short time-to-market in order to beat the competition. Expensive high-performance resins such as PEEK, LCP or PI that produce ever more precise and thinner films are being used increasingly [1].

Similar dynamics are seen in the development of so-called optical films. The best-known applications include flat screens and displays of all kinds. There are also numerous other fields of applications such as advertising, transparent machine enclosures, roofing for stadiums and aircraft windows.

There are also micro-structured films for traffic signs, lane markings and sign posts. The most commonly employed materials are PMMA, PC, PS, and PET, which, at present, employ very expensive pigments to satisfy the variety of optical requirements. Requirements regarding film quality are becoming ever more stringent especially when it comes to display applications. The films are becoming thinner in conjunction with increasingly tight thickness tolerances and greater flatness.

Against this backdrop, it is clear that use of flexible and high-precision flat film lines is economically justifiable for short production runs. The increasing use of such systems, especially in Asian countries, speaks for itself.

## Calendering Systems for Precision Flat Film

The basic requirements for prototype development and short-run production faced by equipment manufacturers are summarized in the information box on page XX. Depending on film thickness and the slit die used, line speeds of up to 30 m/min can easily be achieved over a throughput range of 30 kg/h to 150 kg/h. This represents an operating window that, on the one hand, means low material usage during prototype development, while at the same time permitting cost-effective production of short runs. Experience has shown that processes that have been optimized on such equipment can be scaled up for production easily.

A wide range of film structures is possible via coextrusion (up to seven layers). The standard approach is to use either water (up to 150 °C) or oil (up to 230° C) to control roll temperature. The decision as to which temperature control fluid to use depends primarily on whether high cooling capacity (water) or high heating capacity (oil) is required. Roll temperatures can be controlled to an accuracy of ±1 °C. Electric heating systems are available for even higher roll temperatures, but their temperature control is not as precise, since they only generate heat and any excess heat must be dissipated via the extrudate or by means of free convection. The extruders are designed for extrusion temperatures of up to 400 °C.

The initially mentioned requirements for ever thinner film with tighter tolerances present significant challenges for machine manufacturers, measurement technology and equipment control systems. The **Title photo** shows in the form of a two-roll horizontal calender where the cornerstone for technologically challenging film lies. Without a rigid and precisely manufactured machine frame, production of high-tech products is not possible on a laboratory scale either. What is self-evident for production equipment is often overlooked when "small equipment" is involved or intentionally disregarded for cost reasons.

The same is true for the measurement technology installed on a machine. **Figure 1** shows what is indispensable on a pilot calender to really achieve close to real-world quality: for very tight tolerances (± 5 µm), bearing play must be compensated for completely with a film thickness of 50 µm or less. Measurement of the nip provides the basis for controlling the gap between the rolls. The measuring range for nip measurement extends from 0.05 mm to 2.99 mm, with a tolerance of ±0.002 mm.

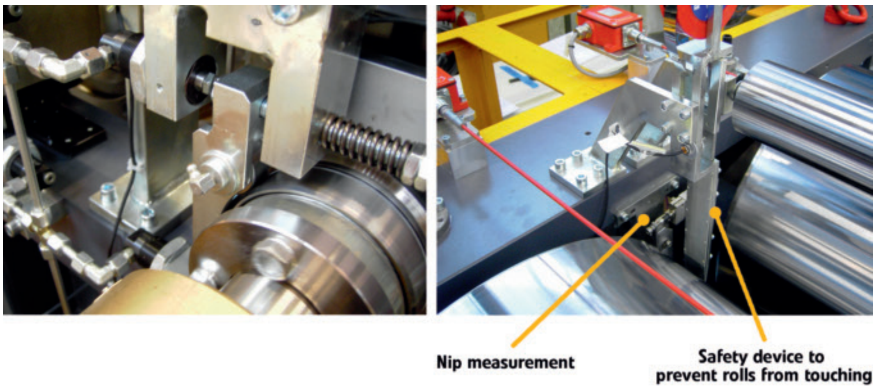


**Fig. 1. Equipment at the roll nip for high quality: bearing preload, measuring and safety device**

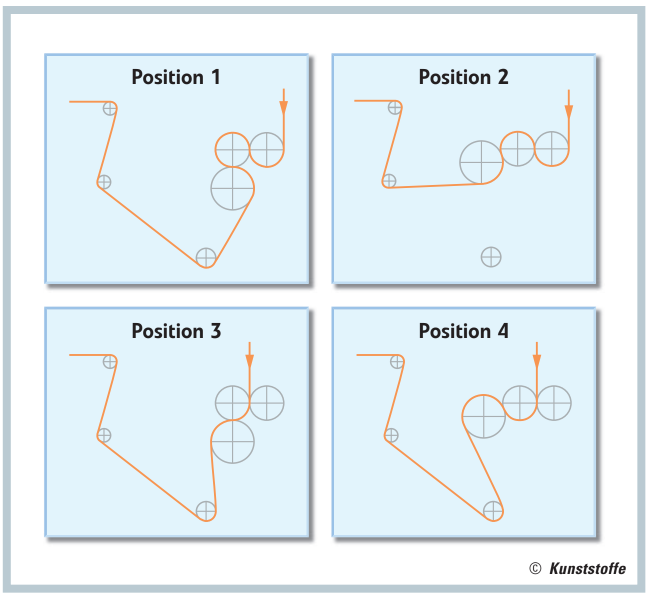


**Fig. 2. Roll configurations for a three-roll calender (diameter 144, 144, 180; working width 250 mm)**

## Requirements

**Requirements for Calendering Systems: Prototype development and short-run production**

- Throughput range of 30 kg/h to 150 kg/h
- Thickness range of 30 µm to 1,000 µm
- Working width of rolls 250 mm to 600 mm
- Roll temperatures up to 230°C
- Product close to those of the end product for more extensive tests and sampling
- Minimal costs for trials
- Scale-up necessary

In the case of very tough, high-viscosity materials and thin films in particular (<30 µm), the consequence of film breakage is touching of the rolls and a damaged roll surface. To prevent this, a suitable safety device was developed. It employs two metal bands that are thinner than the thinnest film to be produced. The two bands are located at the left and right in the nip, but outside the working range. If the film breaks, the line load in the nip drops abruptly and the band is pulled in. This triggers an emergency stop immediately, and the rolls separate automatically.

## Processing Considerations

In addition to the machinery design measures on the calender described above, flexible short-run production and prototype development involves a wide range of processing parameters that determine the quality of the end product. Because of space restrictions, the many effects associated with material preparation, especially drying, shear and deformation history in the extruder and die cannot be discussed here . Only processes downstream from the die outlet and the resultant machine requirements will be considered in this article.

Along with other criteria, the degree of crystallization plays an important role in determining the final properties. For instance, increasing the degree of crystallization with PEEK results in a definite improvement of mechanical properties. This is a desirable effect when used as a flexible substrate for electronic circuits [1]. In contrast, the lowest possible degree of crystallization is needed for optical applications. For any given material, this is determined essentially by →

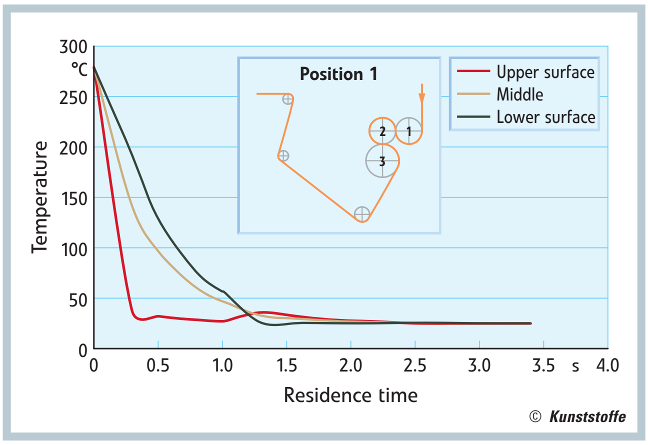


**Fig. 3. Cast film cooling rates: film temperature controlled via residence time at calender position 1 (film thickness: 400 µm)**

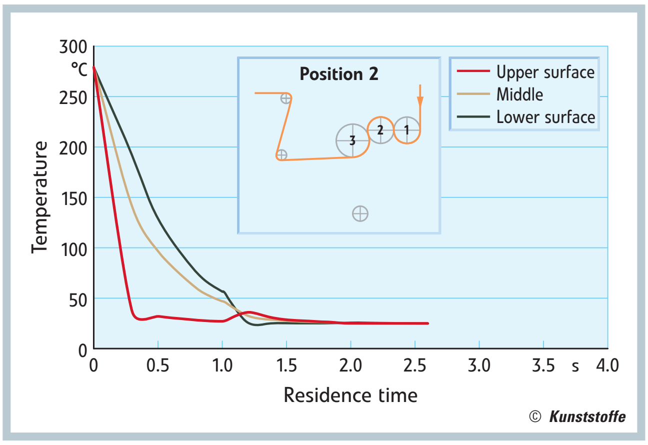


**Fig. 4. Cooling rates of cast film: film temperature controlled via residence time at calender position 2 (film thickness: 400 µm)**

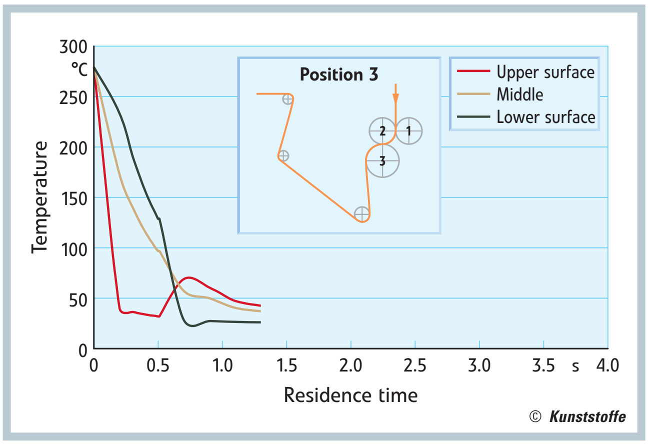


**Fig. 5. Cooling rates of calendered film: film temperature controlled via residence time at calender position 3 (film thickness: 400 µm)**

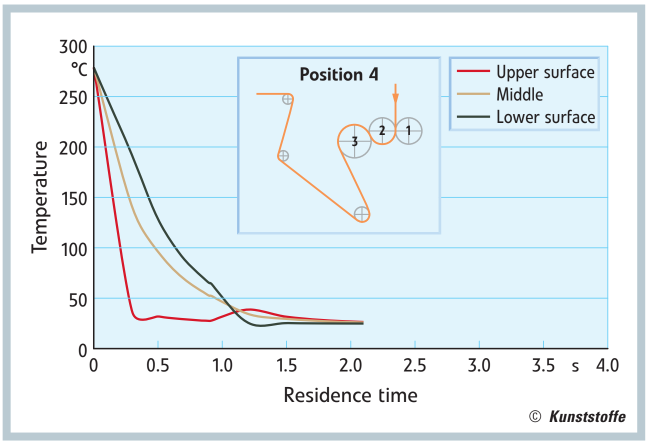


**Fig. 6. Cooling rates of calendered film: film temperature controlled via residence time at calender position 4 (film thickness: 400 µm)**

the cooling rate. The cooling rate, in turn, depends on how the film runs through the calender. **Figure 2** shows four different roll arrangements in a three-roll calendar, each of which has considerably different wrap-around conditions. The variants shown are achieved by rotating the third roll 70° around roll 2. Position 1 and Position 2 represent the situation for cast film. Positions 3 and 4 show a calendered film.

The cooling behavior at a line speed of 15 m/min has been calculated for a 400 µm film. A surface temperature of 25 °C has been assumed for all three rolls. **Figures 3 and 4** show almost identical cooling behavior, although the wrap angle around roll 2 in Position 1 is 90° greater than in Position 2. The reason for this is that the large wrap-around angle on roll 1 allows the material to cool completely. The downstream rolls no longer have any effect on the cooling.

In addition, it can be seen that on roll 1 there are highly asymmetric temperature profiles, which will surely have an adverse effect on the flatness of the film. In this case, the temperature of the first roll ought to be raised to about 80 °C so that the upper surface of the film cools more slowly. It can be noted in general that, when operating in this manner, the film leaves the third roll entirely at the roll temperature.

**Figures 5 and 6** show the case of calendered film. The cooling behavior here is quite different. In all four cases, the upper surface of the film has taken on the roll temperature after about 0.25 s or a wrap-around angle of 45°, i.e. a longer residence time on this roll actually has no effect. This is shown especially clearly in **Figure 5:** the consequence of the considerably faster transfer from roll 2 to roll 3 is that the underside of the film has taken on the roll temperature in about half the time. The temperature of the middle layer of the film thus cools faster as well.

## Equipment

The examples shown illustrate how important free selection of a certain roll arrangement is for the desired cooling behavior. This is true especially for prototype development and short production runs, where very different requirements must be satisfied for a variety of materials.

**Figure 7** shows the roll arrangement in a calendar used for development and short-run production. The machine is designed for a line speed of up to 15 m/min and provides a film thickness range of 50 µm to 2,000 µm. The working width of the rolls is 250 mm. Two rolls have diameters of 144 mm, while that of the other roll is 180 mm. The diameters were selected so that with thin films and those with a very narrow solidification temperature range, e.g. LCP, the die could approach the roll nip as closely as possible.

In the left illustration roll 3 corresponds to the 0° position. The right illustration shows the third roll in the 70° position. The roll can be moved by motor to every possible position between 0° and 70°. Machine components have been sized in a way that a line load of 1.2 kN/cm can be accommodated without difficulty. The machine is characterized by extremely smooth operation.

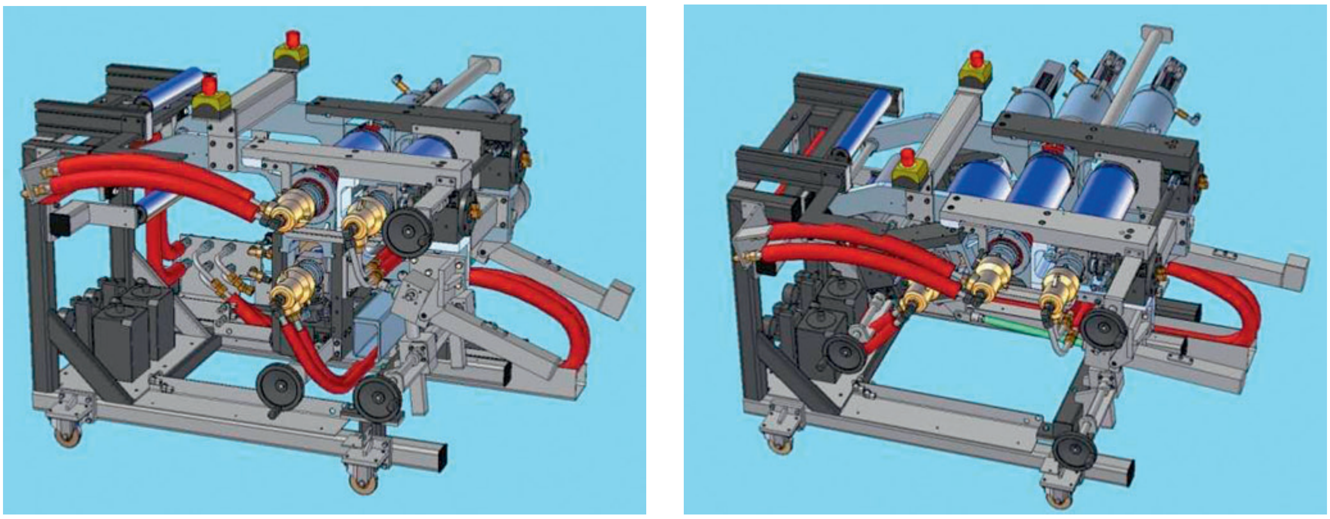

**Fig. 7. Affecting the cooling rates on the calendar via the position of the rolls**

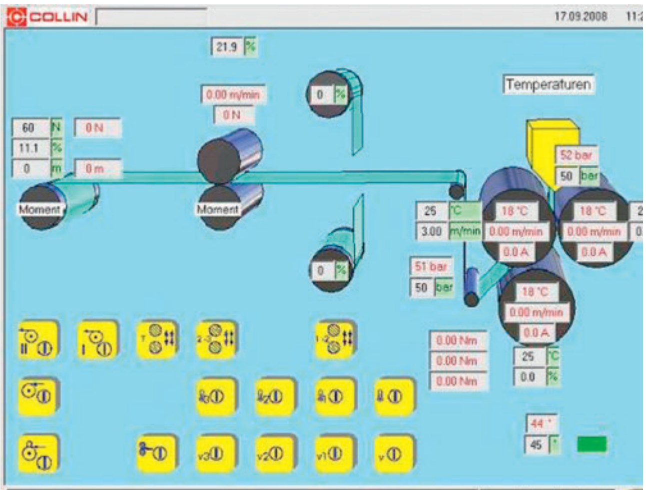


**Fig. 8. Process diagram for the calender**

With products having to satisfy ever more stringent requirements, providing precision machinery and a high degree of flexibility is not the only challenge. More complex processes required exact control of the entire line. For this reason, machines intended for pilot production and short runs are equipped today, at a minimum, with controls comparable to those found on production lines.

**Figure 8** shows the control capabilities of the calender described above: all relevant process parameters can be viewed at the user-friendly interface. The operator sees the setpoint and actual values at a glance, and can easily make entries on the touch screen at any time. A so-called data wheel is available, or a keyboard can be displayed. All process parameters are recorded continuously and are available for trend evaluation and documentation directly within the system. Controls for all other components of a line are displayed in a similar manner, so that the entire line can be operated in full synchronization.

## Conclusions

The flat film calender shown represents only one embodiment of such a system. It would take too much space to describe all previously built configurations for high-performance film here. In fact, one of the most flexible variants in terms of processing has been presented.

All conceivable variants up to seven layers have been built for coextrusion, as well as combinations of coextrusion with in-line laminating. This includes laminating of metal film onto various polymer substrates.

It should be mentioned the conclusion that while these machines are "smaller in size than production machines" they lack nothing when it comes to precision and control capabilities. With regard to flexibility, they are usually even quite superior and considerably more economical than large production lines for specialties such as small lot sizes in particular [2, 3]. ■

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