Modelling of the curtain coating process as a basis for the development of coating equipment and for the optimisation of coating technology

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Abstract

Voith Paper is developing applications for Curtain Coating to cover the needs of the producers of graphic papers and board as well as speciality papers. Coating trials with the Curtain Coater were performed on our R&D Pilot Coater at speeds of up to 2500 m/min. We primarily increased our know-how by empirical means. The relationship between the most important operating parameters has been understood. The number of parameters involved is high and the relationship between them is complex. To optimize the curtain coater and to obtain a better understanding of the correlations between operating conditions and quality parameters, it was necessary to create practical and simple theoretical and mathematical models to describe the curtain coating process. This paper offers an overview of the fundamental calculations of the curtain coating process and describes some correlations between operating conditions and coating quality.

1. Introduction

Over the past few years, the paper industry's interest in the curtain coating process has greatly increased, because producers of paper and board require simple and reliable coating techniques for high production speeds and for enhanced coating quality. The development of a curtain coater and the implementation of the curtain coating process for the mass production of graphic paper and board on an industrial scale are Voith Paper's main goals. Curtain coaters have therefore been installed at Voith's Research and Development Centres in Germany and Japan and are used for further optimisation of the equipment and to increase our technological know-how. Commercial curtain coaters are currently used for the industrial production of speciality papers. The R&D activities focus on the optimisation of the curtain coater for coating at high speeds with coating colours containing pigment.

The adjustment of proper viscous-elastic features is a central objective of the development activities to make the coating colour suitable for curtain coating, because it has to resist high extensional rates during transfer of the liquid film onto the substrate.
The measurement and the characterisation of appropriate rheology parameters is required to describe the extensional behaviour of the liquid curtain under the low and high elongation strains that are possible during the coating process. The investigation is currently focused on the examination of the correlations between those rheology parameters and the parameters that are used to describe the coating quality and the runnability of the curtain coater.

Numerous physical and technological parameters involved in the curtain coating process complicate the understanding of their relationships. Experimental data gained on the pilot curtain coaters by means of coating trials helped to increase our know-how, but coating trials on the scale of pilot coaters are expensive and require a relatively long development time. Modelling of the curtain process contributes to reducing the development costs of the curtain coater and helps to clarify the correlations between the process parameters and the coating quality.

2. The Curtain Coating Process

The function of the curtain coater used by Voith is based on the principle of the formation of an even and homogeneous liquid film by using a specially designed applicator die with a narrow longitudinal slot. The formation and downward movement of the curtain film are promoted by the pressure inside the applicator die and by gravity. The substrate has to be passed through the liquid curtain in order to be coated. The linear velocity of the substrate as well as the curtain flow and the solids content of the coating colour define the amount of coating colour that is transferred to the substrate. To avoid air entrainment between the transferred curtain film and the substrate, it is necessary to use a special device against the air boundary layer. Vacuum deaerators are employed for the extraction of gas and air bubbles from the liquid coating colour. Pneumatic dampers prevent the pulsation of the curtain flow and lead to a stable coating profile.

The curtain coater has to work in a wide range of operating conditions in order to cover the current and future requirements of the producers of coated papers and boards: e.g. machine speeds from 300 to 2500 m/min, coat weights from 1 to 30 g/m² or higher, solids contents between 5 to 70% and Brookfield viscosities between 300 and 2000 mPas. [1,2,3]

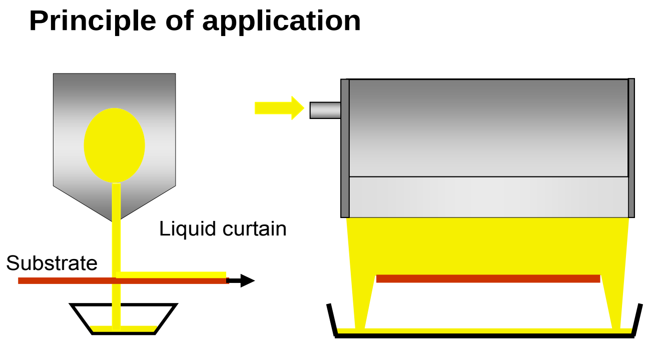


Figure 1: Curtain Coater

3. Modelling of the Curtain Coating Process

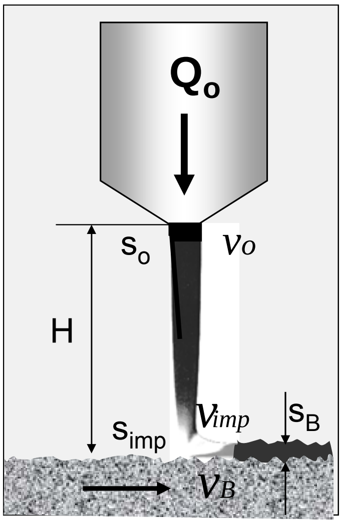


Figure 2: Curtain parameters

In general, the user of curtain coaters formulates the technological target by indicating the required coating velocity v_B and the desired coat weight Δm as well as the solids content **K** of the coating colour. The necessary flow Q_o to form the curtain could be calculated with Eq. (1).

$$Q_o = s_B \cdot v_B \qquad \text{Eq. (1).}$$

The thickness S_B of the applied liquid film on the substrate surface can be determined with Eq. (2).

$$S_B = \frac{\Delta m}{K \cdot \rho_{coluor}} \qquad \text{Eq. (2).}$$

The density of the coating colour ρ_{colour} can be described as a function of the solids content with Eq (3), if the densities of the pure liquid phase ρ_{liq} and the pure solid phase ρ_{sol} are known.

$$\rho_{colour} = K \cdot \left[\rho_{sol} - \rho_{liq}\right] + \rho_{liq} \qquad \text{Eq (3)}$$

A curtain flow can be generated by setting a relative pressure P_o inside the applicator die. The curtain flow is proportional to this pressure according to Eq. (4).

$$Q_o = \Phi_\eta \cdot P_o \qquad \text{Eq. (4).}$$

The parameter Φ_η is constant for a given liquid medium (coating colour) with a defined solids content, and viscosity. Φ_η decreases if the viscosity of the coating color increases and Φ_η increases if the viscosity decreases. Φ_η is also influenced by the dimensions of the applicator (slice gap S_o and applicator width B_o).

The outflowing velocity v_o of the curtain colour depends on the curtain flow and on the extension of the slice gap S_o.

$$v_o = \frac{Q_o}{S_o} \qquad \text{Eq. (5).}$$

Gravity **g** accelerates the downward movement of the liquid curtain. Viscosity and surface tension retard the falling velocity of the curtain. The exact calculation of the impingement velocity of the curtain, for instance toward a surface located at the distance **H** from the applicator die, is complex. [4, 5]. The impingement velocity v_{imp} can be determined using Eq (6).

$$v_{imp} = v_o + \sqrt{2 \cdot (g - a) \cdot H} \qquad \text{Eq (6)}$$

The retardation **a** is a function dependent on viscosity and surface tension. Eq (7) can be used for approximated calculations of the impingement velocity, because **a** is significantly smaller than **g.**

$$v_{imp} = v_o + \sqrt{2 \cdot g \cdot H} \qquad \text{Eq (7)}$$

To understand the process of curtain acceleration and the development of the curtain thickness, it is also necessary to determine the thickness of the curtain at the impingement line. The impingement thickness S_{imp} can be derived from Eq 8. This equation represents the mathematical description of the law of conservation of mass.

$$Q_o = v_o \cdot S_o = v_h \cdot S_h = v_{imp} \cdot S_{imp} = v_B \cdot S_B \qquad \text{Eq (8)}$$

We assume the fluid (meaning the coating colour) is incompressible. The product of average velocity v and average thickness **S** of the curtain is always constant for each considered cross-section of the curtain. The index **o** characterises the position at the exit of the applicator, and the index **h** a cross-section of the curtain at the distance **h** from the exit of the applicator. The index **imp** indicates the cross-section of the curtain at the impingement line and the index **B** that on the substrate.

$$S_{imp} = \frac{Q_o}{v_{imp}} \qquad \text{Eq (9)}$$

The greater the distance **h** between the applicator exit and the considered cross-section of the curtain, the higher the falling velocity of the curtain and, at the same time, the lower the curtain thickness. A stretching of the curtain occurs because of the gravitational acceleration. This gravitational stretching can be calculated with Eq (10):

$$\chi_g = \frac{v_{imp}}{v_o} = \frac{s_o}{s_{imp}} \qquad \text{Eq (10)}$$

The gravitational stretching χ_g can be influenced by changing the curtain length **H** or by adjusting the slice gap $\mathbf{S_o}$ of the applicator die. χ_g can also be modified by variation of the curtain flow Q_o.

When the curtain impinges on the substrate, different behaviours and effects can be observed as function of the impingement angle and the speed of the substrate.

If the speed of the substrate is zero, the curtain decelerates, increases its thickness and changes the flow direction at the impingement line. If the impingement angle φ is equal to 90 deg. the curtain flow is divided into two equivalents and opposite liquid currents. As a function of the adjusted impingement angle, a receding or a forward flow can be induced at the impingement line. When the speed of the substrate is different from zero, the curtain behaviour is defined by the level of the substrate speed. At substrate speeds lower than the impingement velocity, the thickness of the applied film becomes bigger than the impingement thickness and an upsetting deformation of the curtain occurs.
In most cases the speed of the substrate is higher than the impingement velocity of the curtain and therefore an extensional deformation of the curtain is induced.

During coating transfer the impingement velocity v_{imp} of the liquid curtain grows up to the speed of the substrate v_B within a very short time **t**. The acceleration of the curtain takes place at the impingement line within the limits of a short distance **L**. The distance **L** required for this operational acceleration can be determined by means of Eq 11.

$$L = \frac{\sigma \;\; .t}{\eta} \qquad \text{Eq (11)}$$

The time **t** for the curtain elongation can be deduced from Eq 12

$$t = \frac{s_B}{v_B} - \frac{s_{imp}}{v_{imp}} \qquad \text{Eq (12)}$$

The viscosity in Eq 11 is a function of the stretching rate $\frac{\partial v}{\partial s}$ according to Eq. 13

$$\eta = A \cdot \left(\frac{\partial v}{\partial s}\right)^{-B} \qquad \text{Eq (13)}$$

Because of the operational acceleration, a stretching of the curtain occurs at the impingement line. The operational stretching χ_o can be calculated with Eq (14):

$$\chi_o = \frac{v_B}{v_{imp}} = \frac{s_{imp}}{s_B} \qquad \text{Eq (14)}$$

The total stretching χ_T of the curtain results from the mathematical product of the operational stretching χ_o and the gravitational stretching χ_g..

$$\chi_T = \chi_O \cdot \chi_g \qquad \text{Eq (15)}$$

The total stretching can also be calculated with Eq 16.

$$\chi_T = \frac{v_B}{v_o} = \frac{s_o}{s_B} \qquad \text{Eq (16)}$$

The strain that the liquid curtain has to resist during the coating process depends on the stretching factors χ_g and χ_o and is also a function of the ratio between the variation of the curtain velocity and the variation of the film thickness. The stretching rate γ can therefore be defined according to Eq 17 as the ratio between the variation of the curtain velocity and the variation of the curtain thickness at the impingement line. The stretching rate γ describes the elongation process of the curtain at the impingement line. The factor γ integrates two independent processes: the kinematics of the substrate and the kinematics of the liquid curtain.

$$\gamma = \frac{\Delta v}{\Delta s} = \frac{(v_B - v_{imp})}{(s_B - s_{imp})} \qquad \text{Eq (17)}$$

The factor χ characterises how much the curtain thickness decreases and the factor γ describes how fast the thickness of the curtain film changes.

If the stretching factor and the stretching rate overcome critical values (χ_{crit} and γ_{crit}), coating defects (e.g. micro skip coating or rheology streaks) appear on the coated surface because of overstretching of the liquid curtain. Depending on the stretchability of the liquid coating colour, the critical values for the stretching factors and for the stretching rate can change.

The parameters χ and γ can be calculated on the basis of known or desired operating conditions for the curtain coating process. The parameters χ_{crit} and γ_{crit} can be determined or deduced either from rheological measurements of the coating colours (e.g. capillary break-up rheometer) or by means of coating trials on the pilot coater.

A comparison of the calculated and critical values of χ and γ allows an analysis and assessment of the feasibility of the curtain coating process for different operating conditions at the curtain coater. This comparison also permits the simulation of virtual conditions for the operation of the curtain coater and helps to forecast the impact of those conditions on the coating quality.

Figure 2 shows an example of the stretching factors χ_o and χ_T in relation to the coating quality for curtain coated samples produced on the pilot coater.

Figure 2 and Figure 3 help to discover some systematic correlations between curtain strain and the operating conditions of the curtain coater. Those graphs contribute to clarifying the limits of the operating conditions that lead to good or bad coating quality.

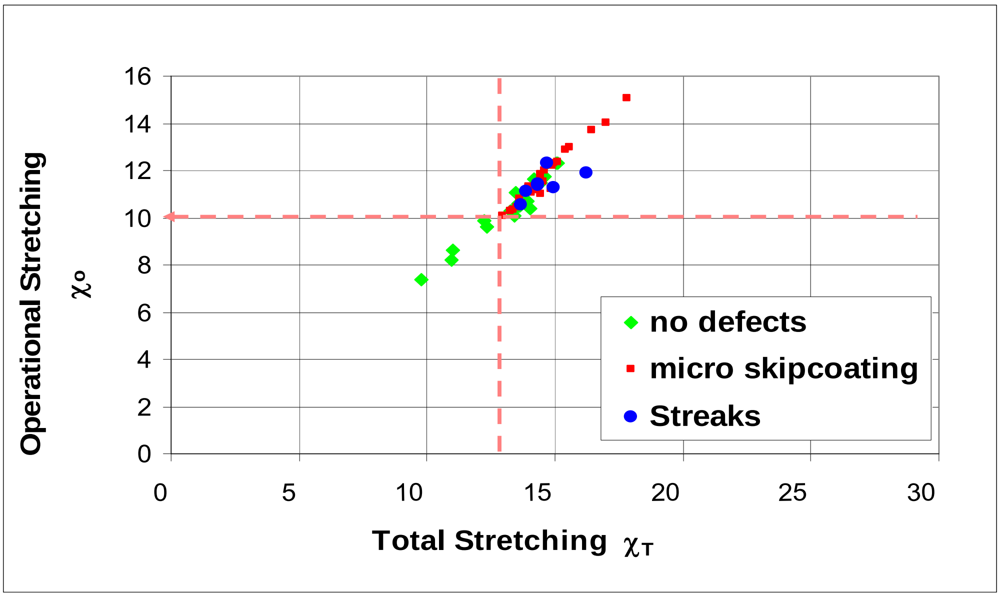


Figure 3: Coating quality as a function of stretching factor

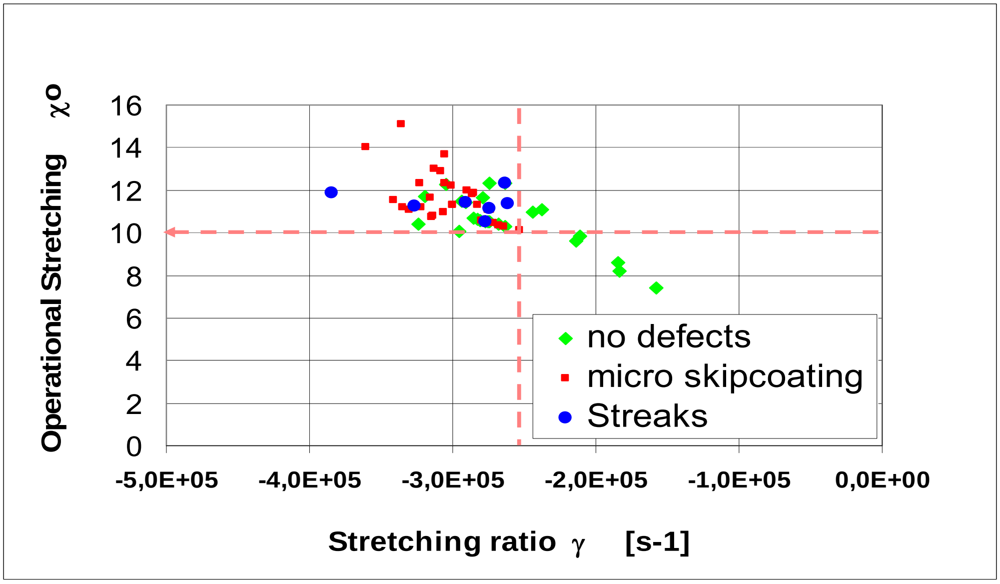


Figure 4: Coating quality as a function of stretching ratio

The critical values χ_{crit} and γ_{crit} depend on the viscous and elastic properties of the coating colour. The composition of the coating colour therefore influences the limits for the stretchability of the liquid curtain. Thickeners and surfactants used as additives in the coating colour have an important impact on the stretchability limits and consequently on the values for χ_{crit} and γ_{crit}.

The rheological features of the liquid medium have to be characterized in order to ascertain their influence on the runnability and on the coating quality. The capillary break-up rheometer and the Brookfield viscometer can be used to examine the stretchability properties of the coating liquid.

The ratio $\frac{\partial D}{\partial t}$ shows the diameter variation of a liquid filament when it is stretched in a very short time by using the capillary break-up rheometer. The ratio $\frac{\partial D}{\partial t}$ is used to characterise the elongation behaviour of a coating liquid. The lower the value of the ratio $\frac{\partial D}{\partial t}$ (determined with the capillary break-up rheometer)**,** the higher is the stretchability of the liquid filament. [6]

The apparent viscosity determined with the capillary break-up rheometer is calculated by means of Eq.18:

$$\eta = \frac{\sigma \cdot Dx}{\left(\frac{\partial D}{\partial t}\right) \cdot Lx} \qquad \text{Eq (18)}$$

The value for $\frac{Dx}{Lx}$ can be calculated from the functional dimensions of the capillary break-up rheometer (stamp diameter = D_x, and L_x = filament length).
The development of the function $\frac{\partial D}{\partial t}$ is the basis to describe the stretchability, because this function is a characteristic feature of the tested liquid.

If a liquid filament is stretched, the initial diameter decreases from D_o to D_1 in a relatively short time **t**. We can use, for instance, two different coating liquids with different viscous elasticity and we can try to obtain the same diameter variation $\Delta D = D_0 - D_1$ of the liquid filament. The coating liquid with the higher value for **t** will show the better stretchability. It means the coating colour with the longer elongation time **t** will be more suitable for this stretchability test at the capillary break-up rheometer. The break time **t** of the liquid filament is a characteristic value for the coating liquid that has been examined with this rheometer.

In order to increase the stretchability of the liquid medium, the value of the ratio $\frac{\Delta D}{t}$ (determined by means of the capillary break-up rheometer) has to be reduced, for instance by the addition of a special thickener. It means the time **t** required for the diameter reduction of the liquid thread has to be increased for a better stretchability. Fig. 5 shows an example of the influence of content and type of the used thickener on the break time **t** of the liquid filament**.**

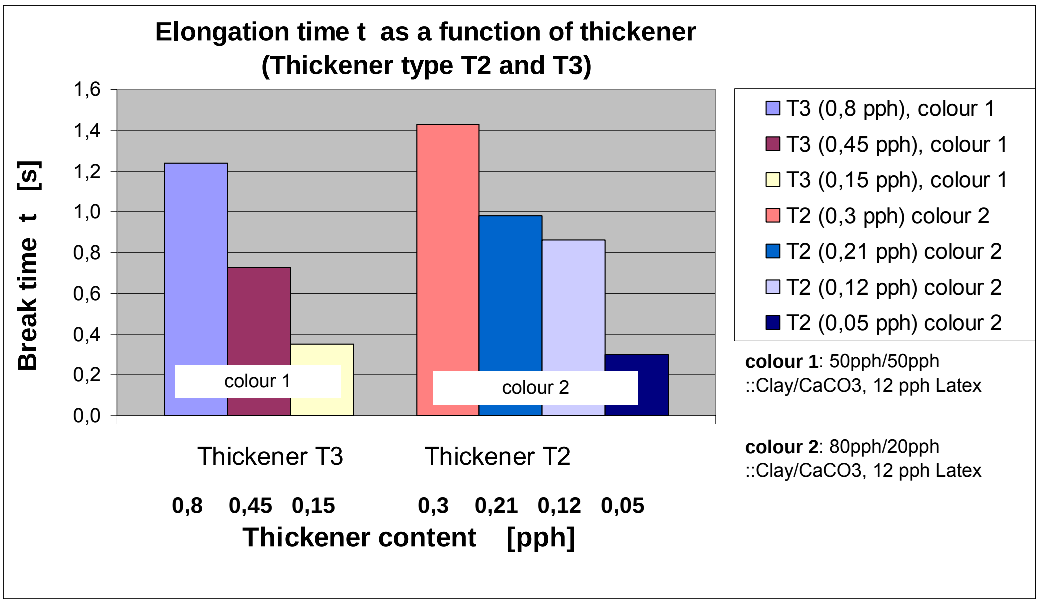


Figure 5: Measurements done with capillary break-up rheometer

The Brookfield viscosity can also be used for the characterisation of the properties of the liquid medium, for instance to examine the effects of the thickener addition.

The empirical equation Eq 19 describes the measured values for the Brookfield viscosity with relatively good accuracy. The factors A and B can be determined by arithmetical regression.

$$\eta = A \cdot (f)^{-B} \qquad \text{Eq (19)}$$

The development of the factors **A** and **B** in correlation with the content of thickener or surfactant and in dependence of the viscous elastic properties of the coating colour offer a further possibility to make comparisons between the stretchability of the coating colour and the measured curves of the Brookfield viscosity. It has been observed on the pilot coater that high values for **A** and B contribute to improving the viscous elastic behaviour of the coating colour (which means that high values for A and B lead to a long elongation time **t** at the capillary break-up rheometer) and promote the suitability of the liquid medium for curtain coating. The higher the factor B, the faster the Brookfield viscosity decreases when increasing the shear rate. The higher the factor A, the higher is the measured viscosity.

Fig 6 shows the influence of the thickener type and the thickener content on the development of the factors A and B for different Brookfield viscosity curves.

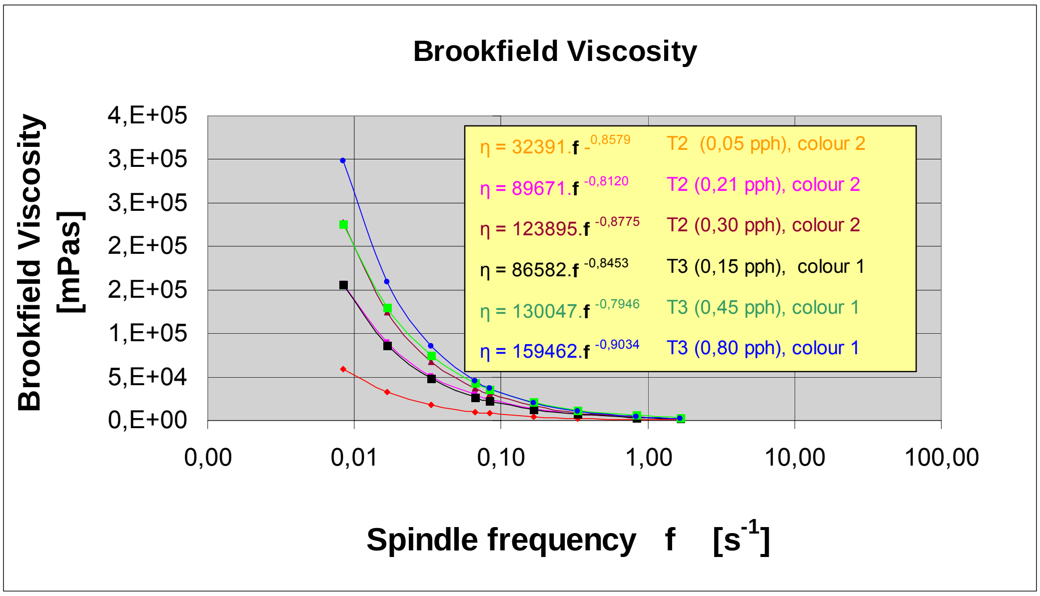


Figure 6: Measurements done with Brookfield viscometer

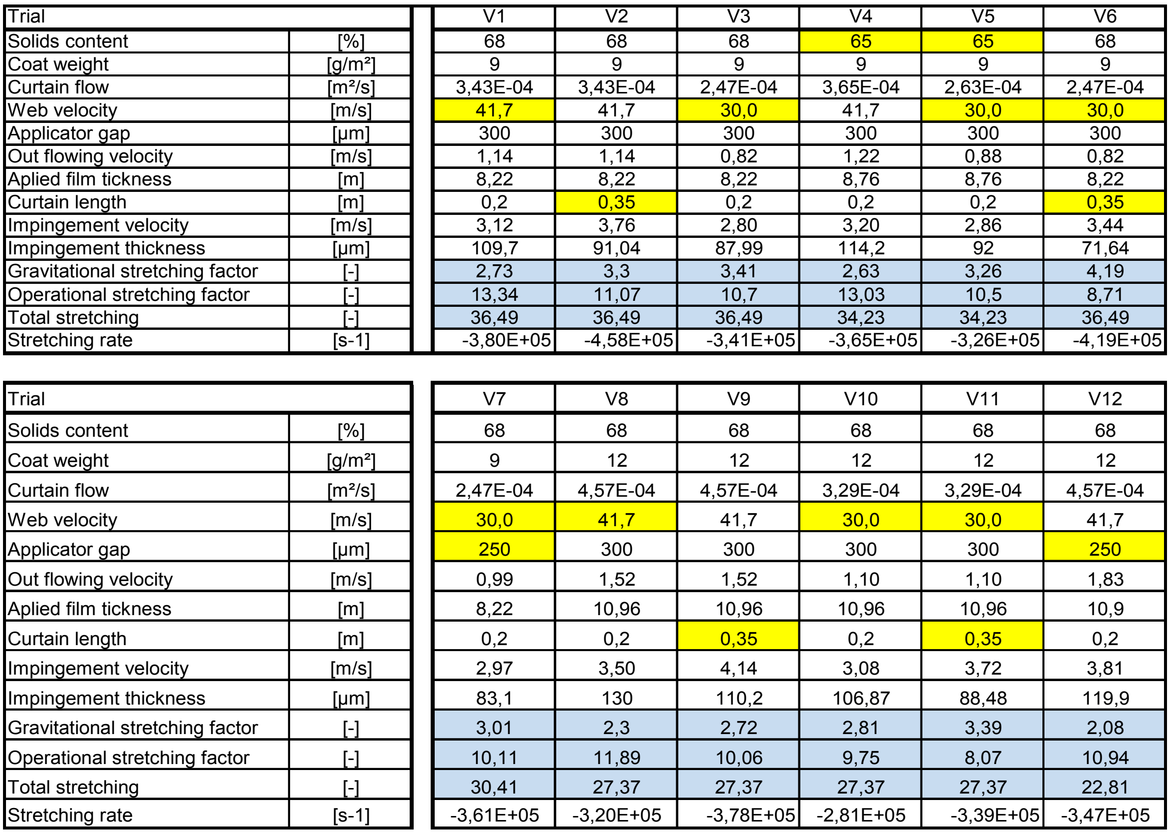
To find functional correlations between operating parameters and the properties of the coating colour, it is necessary to compare the stretching factors χ and the stretching rate γ of the curtain with the parameters of the coating colour (for example **A**, **B** and **t**).

4. Results

The critical values for the stretching factors and stretching rate can be determined by means of coating trials. On the basis of the comparison of those critical values with the calculated values could be possible to determine and to forecast the appearance of possible coating defects for different operating conditions of the curtain coater.

Fig. 7 shows the comparison of different operating conditions of the curtain coater and the impact of those operating conditions on the stretching factors and on the stretching rate. The variation of the gravitational stretching and of the operational stretching in dependence of the variation of web speed, coat weight, curtain length, solids content or slice gap of the applicator was performed for different values of the total stretching of the curtain. If the used liquid coating has a critical stretching factor for example of $\chi_{crit} = 12$, it is possible in this case to deduce from table1 the operational conditions that can lead to an overstretching of the curtain. The conditions V1 and V4 are characterized by an operational stretching greater than 12. At the Pilot Coater were observed critical stretching factors between 8 and 10 for coating colours containing pigment. By addition of special thickener and of surfactant in the coating colour it is possible to increases the critical stretching factor of the coating colour to avoid overstretching and to avoid skip coating.

Table 1. . Influence of operating conditions



Trial		V1	V2	V3	V4	V5	V6
Solids content	[%]	68	68	68	65	65	68
Coat weight	[g/m²]	9	9	9	9	9	9
Curtain flow	[m²/s]	3,43E-04	3,43E-04	2,47E-04	3,65E-04	2,63E-04	2,47E-04
Web velocity	[m/s]	41,7	41,7	30,0	41,7	30,0	30,0
Applicator gap	[µm]	300	300	300	300	300	300
Out flowing velocity	[m/s]	1,14	1,14	0,82	1,22	0,88	0,82
Aplied film tickness	[m]	8,22	8,22	8,22	8,76	8,76	8,22
Curtain length	[m]	0,2	0,35	0,2	0,2	0,2	0,35
Impingement velocity	[m/s]	3,12	3,76	2,80	3,20	2,86	3,44
Impingement thickness	[µm]	109,7	91,04	87,99	114,2	92	71,64
Gravitational stretching factor	[-]	2,73	3,3	3,41	2,63	3,26	4,19
Operational stretching factor	[-]	13,34	11,07	10,7	13,03	10,5	8,71
Total stretching	[-]	36,49	36,49	36,49	34,23	34,23	36,49
Stretching rate	[s-1]	-3,80E+05	-4,58E+05	-3,41E+05	-3,65E+05	-3,26E+05	-4,19E+05

Trial		V7	V8	V9	V10	V11	V12
Solids content	[%]	68	68	68	68	68	68
Coat weight	[g/m²]	9	12	12	12	12	12
Curtain flow	[m²/s]	2,47E-04	4,57E-04	4,57E-04	3,29E-04	3,29E-04	4,57E-04
Web velocity	[m/s]	30,0	41,7	41,7	30,0	30,0	41,7
Applicator gap	[µm]	250	300	300	300	300	250
Out flowing velocity	[m/s]	0,99	1,52	1,52	1,10	1,10	1,83
Aplied film tickness	[m]	8,22	10,96	10,96	10,96	10,96	10,9
Curtain length	[m]	0,2	0,2	0,35	0,2	0,35	0,2
Impingement velocity	[m/s]	2,97	3,50	4,14	3,08	3,72	3,81
Impingement thickness	[µm]	83,1	130	110,2	106,87	88,48	119,9
Gravitational stretching factor	[-]	3,01	2,3	2,72	2,81	3,39	2,08
Operational stretching factor	[-]	10,11	11,89	10,06	9,75	8,07	10,94
Total stretching	[-]	30,41	27,37	27,37	27,37	27,37	22,81
Stretching rate	[s-1]	-3,61E+05	-3,20E+05	-3,78E+05	-2,81E+05	-3,39E+05	-3,47E+05

Figure 7: Influence of the operating conditions of the curtain coater on the stretching factors and on the stretching rate

5. Conclusions

The calculation of the stretching factors and stretching rate of the curtain as a function of the operating conditions of the curtain coater as well as the rheological description of the properties of the liquid coating colours allow a more exact analysis of the curtain coating process.

Useful parameters can be deduced with this proposed method and functional correlations can be obtained to perform the assessment of the feasibility of the coating process with a good coating quality.

The parameter **t** deduced from the capillary break-up measurement as well as the factors **A** and **B** determined with the Brookfield viscometer and the calculated stretching factor χ_o and χ_g can be used to infer correlations with the coating quality. The description of those parameters as a function of the coating quality helps to determine the limits of the operational window as a function of the operational conditions of the coater and as a function of the features of the coating liquid.

6. References

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7. Appendix

Parameter	**Unit**	**Description**
$\mathbf{a}$	m/s^2	Curtain retardation
A	mPas	Viscosity factor of the Brookfield curve
B	-	Viscosity factor of the Brookfield curve
χ_g	-	Gravitational stretching factor
χ_o	-	Operational stretching factor
$\chi_{crit.}$	-	Critical stretching factor
χ_T	-	Total stretching factor
$\Delta \mathbf{m}$	g/m^2	Coat weight
$\mathbf{D_x}$	m	Stamp diameter of the capillary break-up rheometer
$\mathbf{t}$	s	Elongation time / break time
$\Phi\mathbf{o}$	m^2/s/Pa	Proportional factor
$\mathbf{g}$	m/s^2	Earth acceleration
γ	s^{-1}	Stretching ratio = dv/ds
$\gamma_{crit.}$	s^{-1}	Critical stretching ratio
$\mathbf{H}$	m	Curtain length
$\mathbf{h}$	m	Distance from applicator clearance to any cross section of the curtain
$\mathbf{K}$	%	Solids content of the coating colour
$\mathbf{L}$	m	Acceleration length
Lx	m	Maximum length of teh liquid thread at capillary break-up rheometer
Po	Pa	Relative pressure inside the applicator die
Qo	m^3/s/m	Curtain flow
ρ_{colour}	kg/m^3	Density of coating colour
ρ_{liq}	kg/m^3	Density of the pure liquid phase
ρ_{sol}	kg/m^3	Density of the pure solid phase
σ	mN/m	Surface tension of coating colour
$\mathbf{S}$	m	Curtain thickness
$\mathbf{S_B}$	m	Thickness of applied liquid film
$\mathbf{S_{imp}}$	m	Impingement thickness of the curtain
So	m	Slit clearance of applicator die
v_B	m/s	Velocity of the substrate
$\mathbf{v_{imp}}$	m/s	Impingement velocity of the curtain onto the substrate
v_o	m/s	Outflowing velocity of the coating liquid at the applicator gap

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