

A Study for the Statistical Optimization of a High Speed Curtain Coater

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ABSTRACT

High-speed curtain coating is an emerging technology trying to gain commercial acceptance by the paper industry as a non-impact coating process. Curtain coating could offer enormous economic and process advantages over conventional coating methods, due to its non-impact and excellent coverage at reduced coat weights. Due to its contour nature, it enables excellent coating coverage, resulting in equal coverage at lower coat weights than needed with contact metering coating methods, i.e., rod and blade. Due to non-impact and non-contact type of coating operation, curtain coating will operate with fewer sheet breaks or the strength requirements of the base sheet can greatly reduced. Being a contour coater, there is no film split patterning, and scratching. This results in the production of a defect-free coated surface. It is a versatile coating process, in that it enables a wide range of coating viscosities and coat weights to be applied with a single coater head.

In the current study, process and material parameters were varied through a Taguchi OA (first phase) and D-optimal (second phase) design of experiments (DOE), to stabilize a pilot curtain coater at high speeds. The statistical DOE, enabled us to recognize contribution of variables to the curtain stability and optimized them in a relatively few number of trials. The variables studied were curtain height, steam flow rate of a steam substitution system, measures of coating rheology, surfactant dosage, coat weight, web speed, base sheet roughness and base sheet sizing. Trials were conducted at Mitsubishi Heavy Industry's state of the art coating research center in Hiroshima, Japan.

The role of boundary layer air removal system was found to be critical to the stability of the curtain, especially at high speeds. Base sheet roughness, in combination with the parameters of the coating formulation, was found to be very important. Coating coverage improved with the smoothness of the base sheet and excellent coating coverage was possible at low coat weights.

Higher curtain height and shear thinning coating rheology was favored for obtaining curtain stability at high speeds. The sizing of the base sheet impacted coverage and curtain stability at high speeds due to its impact on the wettability of the base sheet by the liquid curtain. The role of surfactants, although good theoretical understanding exists, was inconclusive.

INTRODUCTION

High-speed curtain coating is an emerging technology seeking to gain commercial acceptance as a pre-metered and non-impact coating process⁽¹⁻⁴⁾. Curtain coating has the potential to provide significant economic and process advantages over conventional coating methods due to its ability to provide excellent coverage at low coat weights. Due to non-impact and non-contact type of coating operation, curtain coating will operate with fewer sheet breaks or the strength requirements of the base sheet can greatly reduced. Curtain coating can be considered as a wet lamination process, where lamination follows the contour of the base sheet, so there is no film split patterning; resulting in a defect-free coating surface. Curtain coating is a versatile coating process that enables the widest range of coatings and coat weights to be achieved with a single coating head⁽¹⁻³⁾.

High-speed curtain coating for pigmented coatings is still in its early stages of development⁽¹⁻²⁾. As a result, various phenomenological behaviors are still not very well understood. The stability of the curtain⁽¹⁾ and air entrapment at high speeds^(1,2) is two of the major technical problems limiting the commercial acceptance of the curtain coater. To understand the causes for these limitations, an understanding of the basic operations of a curtain coater needs to be achieved.

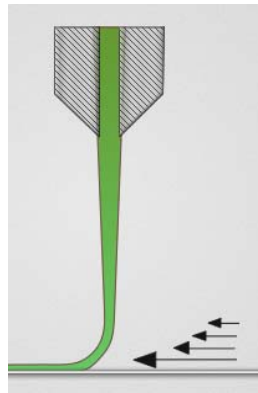


Figure 1. High Speed Curtain Coating

Dynamics of wetting line, heel dynamics, air entrapment, curtain stability and rupture, coating rheology and surface topology of the curtain coated paper are some of the most researched areas in curtain coating. In addition, dynamic surface tension and surfactants die design and flow profile within die are extensively studied. Generally accepted operating window^(1,7) is reflection of understanding of these areas of interest in curtain coating.

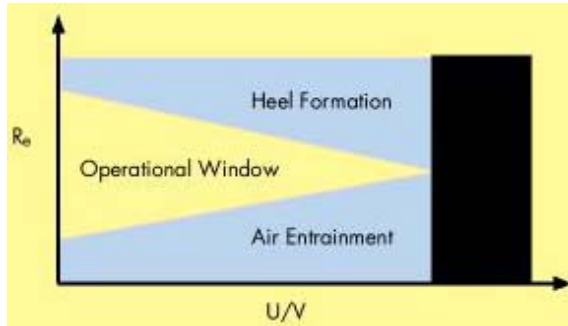


Figure 2. Proposed operating window for curtain coaters.

Although much work has been done to understand the dynamics of the individual parameters of a curtain coating operation, no comprehensive work has been done to understand the influence of the process, substrate, and formulation parameters on curtain stability. Many parameters interact and produce a synergic effect on curtain operation. Developing a complete and comprehensive understanding of curtain parameters and their interaction is a prerequisite for stabilizing a curtain coater operation at high speeds.

INTRODUCTION OF VARIABLES IN CURTAIN COATING

An explanation of the role of each of variables on the curtain coating process and their level in the this study will now be discussed to understand the importance.

Curtain Height

A curtain flow field is result of complex interactions between gravitational extensional and surface forces, which are influenced by such factors as coating rheology, web-curtain speed difference and curtain height. As the coating leaves the applicator nozzle, it falls under gravity until the point where it contacts the moving web. The curtain height influences the speed of the curtain as follows:

$$U^2 = U_o^2 + 2gH \quad (8)$$

Here, U_o is the velocity of the curtain as it leaves the applicator lip and H , is the height of the curtain from the applicator lip. The Reynolds number is generally low in the die so the velocities in the die are very low (of the order of 0.1- 0.20m/s). Thus, U_o can be neglected for all practical purposes and curtain speed can be considered free falling. A stable curtain, $We > 2$, can be achieved by changing the velocity of the curtain by adjusting the curtain height. The effect of curtain height on curtain stability, at a given surface tension, is a dominant factor. Viscous effects, as it exits the slot, affect the velocity of liquid. A correction suggested to account for these effects is given below for the above equation as:

$$2gH = 2g(H - 0.5(\mu/\rho)^{2/3}) \quad (9)$$

Comment [PDF1]: What is μ ? Is this equation dimensionally correct?

The effect of curtain height is indirectly related to the lip opening. As the lip opening changes, the outlet velocity changes, for the same flow rate. Nevertheless, due to the low Reynolds number flow within the die, the contribution of the initial exit velocity of the curtain to the velocity at any given height is still dominated by gravitational forces. In

preliminary studies conducted, the optimum height for the curtain coater is in the range of 100 to 400 mm. Based on these findings, the curtain height was maintained in the 150 to 250 mm range for the current study.

Coating Rheology

The rheological parameters important to the runnability of a curtain coater vary within the 3 zones of the curtain coater described earlier (flow distribution through the die, curtain forming zone and impingement zone). Since the flow field is extensional, extensional rheology parameters are applicable. The coatings applied were typical clay-carbonate-latex web offset formulations. Carboxymethylated cellulose, CMC, was used as the rheology modifier to alter the shear thinning properties of the coating. The viscosity was kept in a narrow range (400-700 cps, Brookfield, # 4 Spindle, 100 rpm) and rheology changed from Newtonian to shear thinning by altering the amount of CMC applied.

Surface Tension and Surface Age (Surfactant Dosage)

To form a stable curtain at low flow rates, surface tension must be reduced to maintain a proper Weber number ($We > 2$). Surfactants are used to reduce the surface tension of a coating. Low surface tensions favor a stable curtain at low flow rates. A large number of surfactants are commercially available that differ substantially in efficiency and effectiveness, so the choice of surfactant is critical. As a curtain falls under gravity, the surface area of the curtain increases. The surface tension of a curtain will increase, depending on the initial surface excess of surfactant. Also, in a dynamic process surface age becomes important. The surface age of the process is the time the curtain takes from slot exit to impingement on to the substrate. The curtain height dictates the surface age. As shown in Figure 9, the surface tension of a curtain will change with curtain height due to the change in surface. The height of the curtain dictates the time available for surface aging. Change in surface tension with surface age may be the most important property of the surfactant. To reduce the surface tension of the coating, an anionic surfactant, Niaproof 4, was used. This surfactant was used because it is a highly soluble anionic surfactant known to industry to be effective in lowering the surface tension of aqueous coatings.

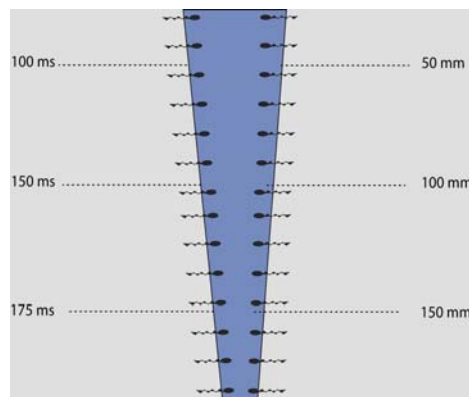


Figure 3. Surface tension and surface age.

Flow Rate (Coat weight)

The flow rate, along with web speed, determines the achievable coat weight. Curtain stability is also related to coat weight through the inertia term in the Weber number. Since curtain coaters are contour coaters, complete coverage is possible at much lower coat weights than with conventional contact surface coaters. Coat weights between 4-10 gsm are attainable and sufficient for coverage for most curtain coater applications. In the present study, coat weights of 12, 8 and 6 gms/m² were applied.

Web Speed

Web speed is also an important process variable in curtain coating, as it affects the process via many different mechanisms. In curtain coating, web speed affects the onset of air entrapment, the amount of viscous drag, curtain stability, boundary layer air and effects of base sheet-coating interactions. The most important effect of web speed on the process is the dependence of boundary layer air, (BLA), on the substrate speed. Web speed governs the thickness and ease of removal of BLA. As web speed increases, removal of the BLA becomes progressively difficult and manifests itself on the process as the onset of air-entrapment in the impingement zone. Viscous drag of the curtain is governed by the web-curtain speed difference, thus, along with coating rheology, it affects the shape of the impingement zone and curtain extension. In addition, as speed increases, the time scale for the wetting of the substrate by the coating becomes critical. Wetting is critical in the curtain as it affects the process in multiple ways. An acceptable coating viscosity operational range is also related to web speed. At low viscosities, a coating may splash in the impingement zone. Thus, web speed is an important process parameter and high-speed curtain coating puts additional constraints on the process.

Since high-speed curtain operation was the focus of the present study, 3 web speeds were used in the first phase of this study (800, 1400 and 1800 MPM).

Surface Sizing

The wetting properties of the paper affect the interaction between the curtain and the paper surface. The degree of interaction between the coating and the paper determines the amount of viscous drag on the curtain. The faster the coating wets the paper, the higher the viscous drag.

The type and amount of sizing agent present in the basepaper controls the wetting properties of the basepaper. Viscous drag influences the curvature of the curtain in the impingement zone. At higher machine speeds, there is a need to increase the wettability of the basesheet to account for the shorter contact time between the coating and basesheet at the point of impingement. To control the wettability of the papers, the papers were size press treated with an oxidized starch (Oji Inc., oxidized starch) prior to being curtain coated. The amount of starch applied was 1 gm/m² (C1S).

Base sheet Roughness

The roughness of the basesheet (Figure 10) influences the runnability of the curtain coater as it affects the efficiency of the BLA removal system and coating coverage. BLA is known to disrupt the stability of the curtain at high speeds and create coverage and surface defect issues in the dried coating layer. The effect of base sheet roughness and its mechanism on curtain coating is largely unknown. Roughness of the basesheet hastens the formation of the transition zone causing turbulent air flow to be achieved in a relatively short distance. The roughness scale of the moving substrate also affects the thickness of the boundary layer. The amplitude and frequency of the substrate roughness will affect coverage. The curtain simply follows the contour of the low amplitude roughness. However, for a high frequency and high amplitude roughness, the description of the film (curtain) becomes complex. High basesheet roughness may create craters, a unique problem in curtain coating.

In the present study, roughness was recognized to be of high importance and was assigned 3 levels of variance. Relatively high basesheet roughnesses of 7.7 PPS, 5.5 PPS and 3.5 PPS were used.

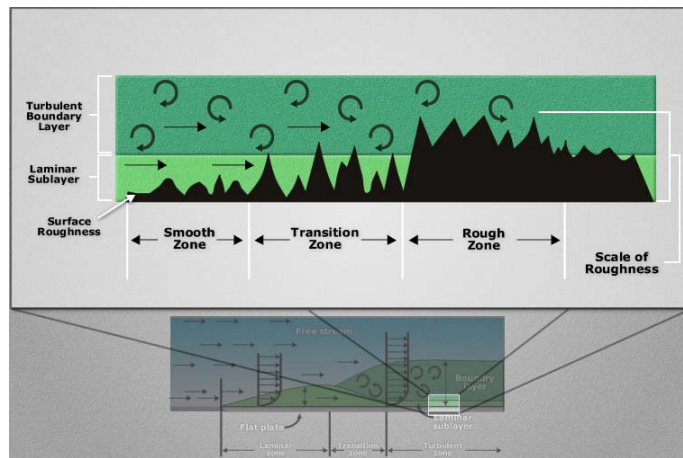


Figure4. Scale of roughness and BLA thickness.

Boundary Layer Air Removal System

As a rough substrate moves at high speed, it drags air along, forming a boundary layer air; BLA. As this boundary layer hits the curtain it leads to air entrapment and curtain instability. Air entrapment at the impingement zone is one of the technical challenges in high-speed curtain coating. Even a minor entrapment leads to severe defects in coating quality. Efficient removal of boundary layer air is one of the pre-requisites for high-speed curtain coating. A BLA removal system was proposed (fig.5) to be used in curtain coating to delay the onset of air entrapment.

There are primarily two BLA removal systems currently proposed; in plate-vacuum system and steam substitution system. For in plate-vacuum systems, a polymeric plate in touch with the moving web followed by a vacuum box does the initial air removal. Mitsubishi Heavy

Industries (MHI) is the pioneer to employ a novel steam substitution system (2), (SSS), to delay the onset of air entrapment at high curtain coating application speeds. The SSS (Figure 11) works by employing high velocity air through an ejector (air knife) onto the moving web to remove the bulk air being carried by the web towards the impingement zone. The incident angle of the air knife is optimized such that the total pressure on the downside of the web can be kept the lowest. After removal of the bulk air, steam is substituted for the air by mixing saturated steam with the remaining thin film of trapped air. The saturated steam, on mixing with the air, loses temperature and condenses, creating a mild vacuum in the impingement zone. The vacuum is controlled by the steam flow rate. The combined effect of heat and condensation of steam from the steam-air mixture attenuates any air current in the down side of SSS, resulting in a more stable curtain. Slight vacuum conditions and absence of convection currents also helps to stabilize the curtain.

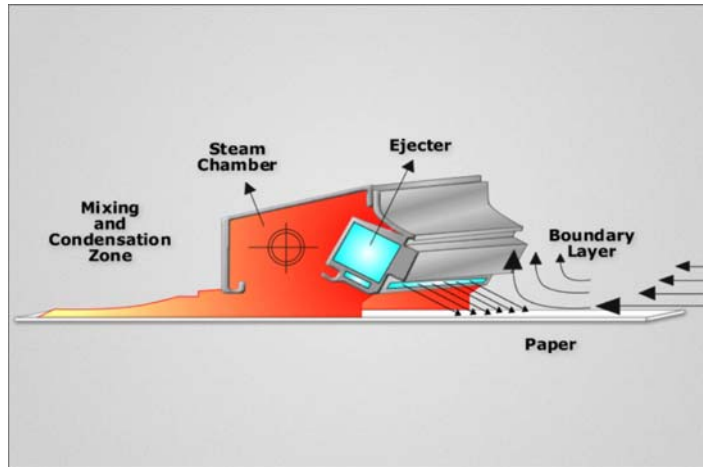


Figure 5. Steam Substitution System.

High temperature disturbs the BLA and immobile air in the micro roughness of the paper. As the air jet hits the moving web, a bifurcation of the jet takes place. A majority of the air jet goes away from the moving web but a fraction of the jet moves in the direction of the web even at the optimized air ejector angle. To minimize the effect of the partial air jet that moves with the web, the air pressure in the ejector must be adjusted according to the web speed and should be kept as low as possible. In this study, the level of steam in the SSS was changed by adjusting the steam flow rates per unit width of the coater and the air ejector pressure was changed with web speed according to an algorithm created by MHI.

CONSIDERATIONS OF CURTAIN STABILITY

A stable curtain is a prerequisite for a good curtain coating. Due to the absence of any definitions for curtain stability, curtain stability is difficult to describe and measure. Before attempting to measure, curtain instabilities needed first to be defined and a method to

quantify them established. To accomplish this, videos of the curtain coater during operation were captured and analyzed by a group of observers to define the various curtain instabilities. Next, the videos were again observed and the severity of the instabilities was quantified on a scale of 1 to 5 with 1 indicating a very unstable curtain and 5 representing a stable curtain (Figures 6a-6d).

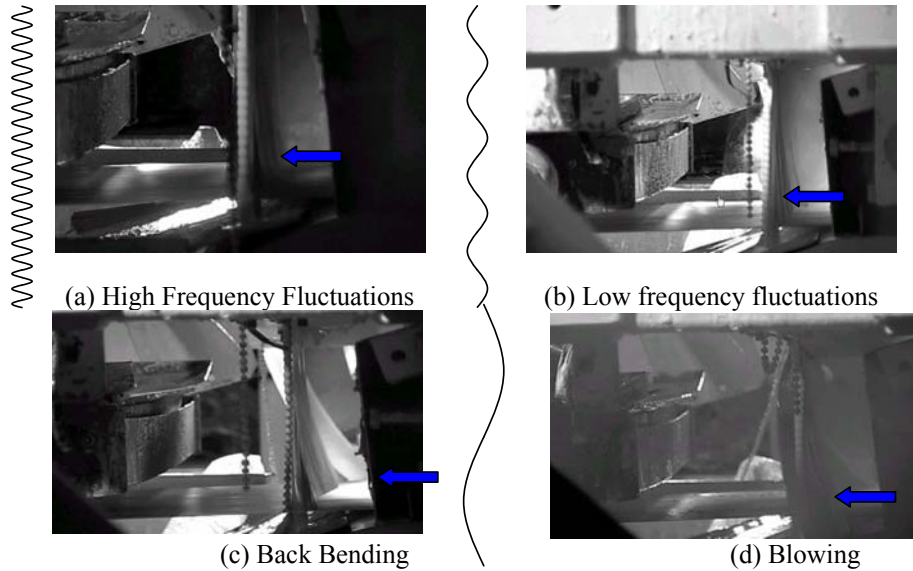


Figure 6. Curtain instabilities.

At high speeds, the curtain fluctuates in the cross direction of the paper machine. These fluctuations can be characterized by their sinusoidal frequency and amplitude. At stable operation, these fluctuations can have almost the same amplitude but very different frequencies. It was determined that the fluctuations originated from the uneven performance of the boundary layer air removal system in the cross direction of the machine. Upon further study of the problem, an uneven air ejector and steam profile in SSS was found. The problem was attributed to the way the SSS was machined. Upon remachining and adjustment of the profile, the problem was eliminated.

It was observed that at higher vacuum levels on the upside of the curtain, the curtain would bend backwards (c). The back bending seemed to have a positive effect on the overall stability of the curtain, as it delayed the onset of air-entrapment. In severe cases of unoptimized boundary layer air removal, blowing of the curtain occurred. Blowing was characterized by the violent down stream movement of the curtain as shown in Figure 12d.

Other types of curtain instabilities identified in this study were splashing (fig 7) and burps. Both effects were observed to be induced by low coating viscosity and poor surfactant miscibility respectively. If the viscosity of the coating was low, splashing occurred. Operating at a low Weber number (low flow rate or high surface tension at a given flow rate)

resulted in the presence of intermittent “burps” being introduced into the curtain. Both splashing and burps led to coating defects in the dried coating layer.

Based on these definitions, a stable curtain was defined as, one that is totally free of any of the effects mentioned above, and one that fell in the same plane as the curtain die or pulled forward (Figure 8).

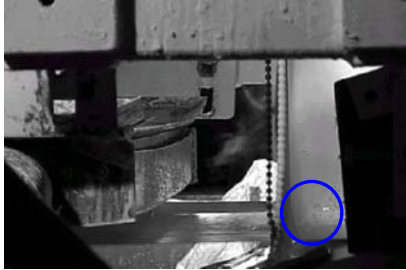


Figure 7. Splashing.

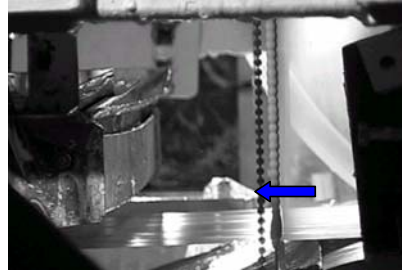


Figure 8. Straight curtain.

OBJECTIVE

The objective of the proposed research was to stabilize a curtain coater at ultra high speeds and develop a fundamental understanding of the process. A comprehensive trial plan was devised to study the effect of various process, substrate, and coating parameters on curtain stability, runnability and coating quality (coverage).

EXPERIMENTAL DESIGN

The study was divided into two phases. In the first phase, a Taguchi OA design of experiment (DOE) was employed to quantify the effect of all 8 variables on curtain stability. The Taguchi OA was selected because it enables the quantification of the main effect of selected variables on the response variables in relatively few experiments. This step enabled us to determine the relative importance of process variable in the process. The results of Phase I was then used to select the 4 most important variables contributing to curtain coating stability and quality (coverage). These 4 variables were carried forward to Phase II. A partial-factorial DOE, D-optimal, was used in the phase II, A partial factorial design was selected to determine the extent of variable interaction and its effect on the process. Thus, it allowed for a more close examination of the contribution of the selected 4 factors.

The coating studies were performed on a pilot curtain coater Hiroshima, Japan. The coater was 850mm wide and equipped with a high-speed video camera to capture images of the curtain film during operation. The process variables considered were curtain height, steam flow rate of a steam substitution system, coating rheology, surfactant dosage, coat weight, web speed, base sheet roughness and basesheet sizing.

Comment [PDF2]: How is “coating rheology” a process variable?

Prior to performing the curtain coater machine trials, rheological and surface tension studies were performed to set the levels of surfactant and rheology modifier, CMC, to be used in the coating formulations. The properties of the basesheet were adjusted by coating the paper with a 10% oxidized starch solution (Oji, Inc., Oxidized starch) with a metered size press (C1S).

The paper was then calendered to adjust the roughness profiles and lower the permeability of the paper. Calendering was performed on an off-machine super calender at the pilot plant facility.

The wetting properties of the basesheet were characterized by performing a 60 second Cobb test. The Parker Print roughness and permeability of the basepaper were also measured. The properties of the basesheets studied are given in Figure 15.

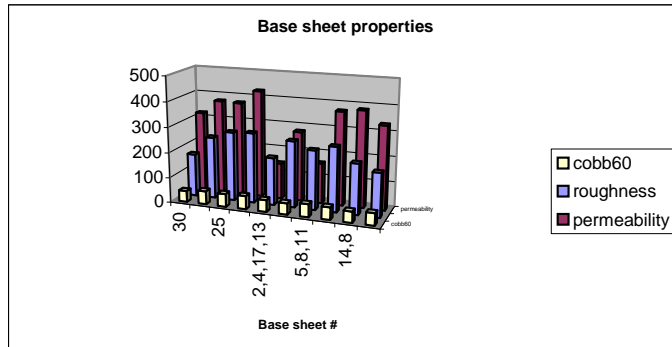


Figure 9. Differences in basesheet properties.

A model offset coating formulation appropriate for a LWC heat set web offset commercial publication grade was used.

Table 1. Coating Formulation

	Coating Components	Commercial name	pph
Pigments	Clay	Ultra White 90	40
	GCC	Carbitol 90	60
Binders	S/B latex	JSR 2600	15
	CMC	Cellogen PR	0.55
Additives	Surfactant	Anionic	As required
	Lubricant	Nopcote C-104	0.6
	Water retention	SPI resin 102A	0.5

A low molecular weight CMC was used as the rheology modifier and to improve the coating surface strength. The amount of CMC added to the coatings was varied by adding CMC solutions of different solids to the coating and adjusting the final coating solids with dilution water. The solids of the CMC solutions ranged from 0.1 % to 5.0%. The interactions between the different coating components; CMC, Clay and latex were characterized using several

rheological test methods. To study the degree of interactions between the individual coating components, the rheology of the CMC alone, with clay, and with clay and latex were measured separately. The low shear viscosities of the coatings were measured using a Brookfield RVT viscometer. The high shear properties of the coatings were measured with a Hercules DVT viscometer. Dynamic rheological measurements were performed using a Haake dynamic stress rheometer using multiple geometries. At low levels of CMC addition, couette geometry was used. At higher levels of addition, a cone and plate geometry was used.

High shear studies were performed using a Hercules high shear DV10 rheometer, E bob. Based on the findings of high shear tests, it was determined that the 0.3 to 0.60 % CMC levels should be used to give a broad range of shear thinning properties. The addition of CMC gradually increased the low shear viscosity of the clay and coating (clay and latex). The exponential increase in viscosity with clay addition levels above 2.0% is not observed for the coatings. This is probably due to the absorption of the CMC onto the clay surface decreasing the concentration of the CMC in the bulk solution.

Having determined the level of surfactant and CMC to be applied, the coating formulations parameters for the first phase statistical DOE experiments for the pilot curtain coater trials were determined. The coatings were prepared and applied on the curtain coater. A diagram of the curtain coater is shown in Figure 10.

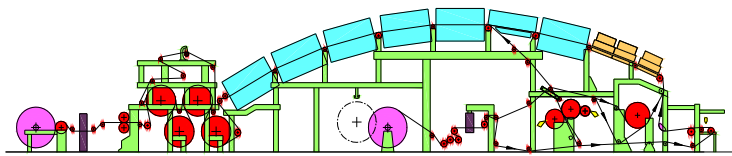


Figure 10. Flow diagram of MHI pilot curtain coater.

FIRST PHASE DOE

A Taguchi Orthogonal Array (OA) was used in the first phase, which allowed for the quick screening of variables in relatively few numbers of trials (Table 3). Taguchi OAs are interesting statistical tools for researchers as they allow for a large number of variables at different levels to be investigated quickly. The model contains only the main effects and does not account for parametric interactions. Therefore, large inherent statistical error, low overall R^2 values, is characteristic of this model, but is useful nonetheless for initial screening of factors. When using this array, the level of variables in the model should be selected in such a way that it reduces wild variations in the response variables. To reduce statistical error, a decent knowledge of the levels of all variables is a pre-requisite. This was accomplished by selecting the levels of our variables from the prescreening experiments performed. Six of the variables, perceived to be important, were assigned 3 levels. The remaining two variables were assigned 2 levels (Table 4).

Table 2. First Phase Statistical Layout

Study Type	Factorial	Experiments	18
Initial Design	Taguchi OA	Blocks	None
Center Points	0		
Model	Main effects		

Factor	Name	Units	Type	Low	High		
A	Nozzle Height	mm	Categorical	1	2	Levels:	2
B	Surface Sizing	gm/m ²	Categorical	1	2	Levels:	2
C	Roughness	PPS	Categorical	1	3	Levels:	3
D	Coating form		Categorical	1	3	Levels:	3
E	Surfactant	pph	Categorical	1	3	Levels:	3
F	Coat weight	gm/m ²	Categorical	1	3	Levels:	3
G	Web speed	mpm	Categorical	1	3	Levels:	3
H	SSS	Kg/min/m	Categorical	1	3	Levels:	3

Table 3. First Phase Variables and Their Levels

Variable	Level of the variable		
	Low (1)	Medium (2)	High (3)
Roughness	3.5 PPS	5.5 PPS	7.7 PPS
Sizing	1 gm/m ² (C1S)	-	None
Coat weight	6	8	12
Coating Formulation*	I	II	III
Surfactant Dosage	0.02 pph	0.20 pph	0.80 pph
Web Speed	800 mpm	1400 mpm	1800 mpm
Curtain Height	150 mm	-	250 mm
Steam Flow rate	0.20 kg/min/m	0.55 kg/min/m	1.0 kg/min/m

*Coating formulations I, II and III represent different rheologies.

Table 4 shows the coating formulation parameters used for the first phase coating formulations. The levels of all other additives were kept the same. The lubricant, Nopcote C-104, was added at 0.06 pph, resin SPI at 0.5 pph and NaOH at 0.1 pph, to keep coating pH between 9-9.5. Surfactant was added at the predetermined levels of 0.02, 0.20 and 0.8 pph. The low shear viscosities of the coatings are given in Figure 11.

Table 4. First Phase Coating Formulations

Coating #	Clay/Carbonate	CMC	Latex
	pph	pph	pph
I	30/70	0.5	7
II	40/60	0.4	12
III	40/60	0.45	12

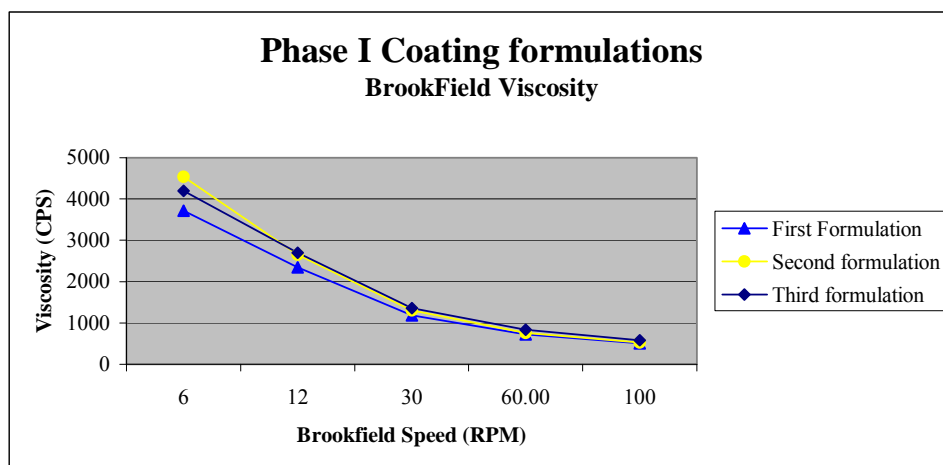


Figure 11. Brookfield viscosities of first phase coatings.

Coatings were prepared in a high shear Cowles mixer in a coating kitchen and then transferred to a constant temperature tank. The average temperature of the coatings for the trials was 30 °C. Trials were run according to the above-mentioned DOE. The coverage of the coated samples was measured using a burnout method. Samples were soaked in a 10% solution of 50% Isopropanol and 50% ammonium hydroxide for an hour. The samples were then blotted to remove any excess solution and then burned in an oven at 100 °F for one hour. The samples were scanned and analyzed using Adobe Photoshop. Black and white area pixels of the scanned pictures were recorded using a gray threshold and the coverage defined as the ratio of white pixels to total (black +white) pixels.

FIRST PHASE RESULTS AND DISCUSSION

Trial conditions and result of first phase are summarized Table 6 (also see Appendix I). The statistical contribution of each formulation, substrate and process parameter studied to coverage (response variable) is summarized in Table 7. The coverage values were very high for the 3 coat weights applied. Although coverage improved with coat weight, it was

found to be only weakly dependant. This result was expected, as curtain coating is considered to be a true contour coating method. So the results support existing theory and demonstrate the potential benefits of curtain coating.

A higher nozzle height resulted in improved curtain stability, thus favored coverage. No conclusive explanation can be offered at this time but some of the effects of curtain height are well known. Higher curtain height increases curtain velocity and available surface age. Both of these phenomena will result in a higher Weber number, increasing the curtain stability. In addition, a higher inertial force will delay the onset of air-entrapment. It was observed during the trials that at a lower curtain height, the space between the steam substitution system and the curtain nozzle was reduced, resulting in a build up of pressure behind the curtain, increasing the amount of air entrapped in the coating.

As discussed above, Coating I and III are shear thinning (degree of thinning is higher in that order), whereas coating II was Newtonian. The shear thinning behavior favored better coverage, while the Newtonian rheology resulted in poor coverage. Again, no conclusive explanation can be offered at this time, but the results support the reported findings from other curtain coating researchers. Extensional rheological experiments are needed to possibly reach a better conclusion.

The smoother basesheet favored coverage. Again, coverage was very high at all base sheet roughnesses. These results again support the concept of a curtain coater being a true contour coater. Other researches have shown an optimum lower value of basesheet roughness, but as roughness levels are varied in this study, coverage continued to improve with basesheet smoothness.

Sizing with hydrophilic starch improved coverage. Surface sizing with starch improved the wettability of the basesheet. Improving the wettability delays the onset of air-entrapment and resulted in a higher viscous drag on the curtain, increasing the radius of curvature of the pulled film on the impingement zone, reducing total pressure. This resulted in delayed/less air entrapment.

Very low and high surfactant dosages (high and low corresponding surface tensions) resulted in improved coverage. The surface tensions at 0.20 and 0.80 pph surfactant dosage were almost the same and much lower than the surface tension at 0.02 pph dosage. This result contradicts established concepts of curtain stability and is considered in error.

Web speed was the single most dominant process variable. Higher speeds resulted in poor coverage. Air-entrapment and poor curtain stability were clearly visible at high speeds. At high speeds the curtain was fluttering violently and air-entrapment was severe. It is very clear that an efficient boundary layer air removal system is critical at high speeds. It must be noted, though, that the boundary layer air removal system was fixed at predetermined levels; according to the DOE. A stable curtain could have been realized by manipulating the air ejector pressure and steam flow rate of steam substitution system. The first phase trials did result in a better understanding of the ejector pressures and steam flow rates required to stabilize the curtain at high speeds.

There seems to be an optimum level of steam flow rate, which should be used for each condition. Steam flow rates above or below the optimum level led to unstable and sometimes violent curtain instabilities.

Table 5. First Phase Result Summary

Run #	Roughness	Sizing	Formulation*	Surfactant Level	Coating Weight	Coating Speed	Nozzle Height	Steam Flow rate	Ejector Air Flow rate	Actual Coat weight	Coverage
	PPS (μm)	g/m ²		Parts	g/m ²	mpm	mm	kg/min	m ³ /min	g/m ²	%
1	7.20	none	I	0.4	6	800	150	0.20	1.0	6.0	65
2	3.74	1	I	0.4	12	1400	150	0.60	1.8	8.8	75
3	5.57	1	I	0.02	6	1800	150	0.75	2.3	4.3	85
4	3.74	1	I	0.2	8	1800	250	0.20	2.3	6.6	50
5	5.57	1	I	0.2	12	800	250	0.55	1.0	9.1	84
6	7.20	none	I	0.02	8	1400	250	1.00	1.8	6.9	91
7	7.61	1	II	0.2	12	1400	150	0.20	1.8	9.0	90
8	5.57	1	II	0.02	8	800	150	0.20	1.0	6.7	50
9	3.72	none	II	0.02	12	1800	150	1.30	2.3	8.2	87
11	5.57	1	II	0.4	6	1400	250	1.00	1.8	4.4	92
10	7.61	1	II	0.4	8	1800	250	0.75	2.3	5.2	50
12	3.72	none	II	0.2	6	800	250	0.35	1.0	4.1	88
13	3.74	1	III	0.4	8	800	150	0.55	1.0	7.8	85
14	5.54	none	III	0.2	8	1400	150	2.00	1.8	7.8	84
15	7.61	1	III	0.2	6	1800	150	1.30	2.3	5.1	95
16	7.61	1	III	0.02	12	800	250	0.35	1.0	9.5	85
17	3.74	1	III	0.02	6	1400	250	0.20	1.8	4.9	60
18	5.54	none	III	0.4	12	1800	250	0.20	2.3	9.6	50

* (I,II,III) are different coating rheologies

Table 6. First Phase - Overall Statistics

Variable		Coverage	
		Mean Sum of squares	% Contribution*
Nozzle Height	mm	97.72	3.11
Surface Sizing	gm/m ²	7.53	0.24
Roughness	PPS	123.00	3.92
Coating formulation		365.41	11.63
Surfactant	pph	498.09	15.86
Coat weight	gm/m ²	19.90	0.63
Web speed	mpm	2016.46	64.20
Steam Flow	Kg/min/m	12.97	0.41

* % Contribution of a variable is contribution it makes in explaining variance in the response variable

Curtain stability was analyzed by studying videos of the trials and assigning a number between 1-10, higher the better. The videos were analyzed by assessing the straightness of the curtain, the amount of backflow and fluctuations, and the amount of air entrainment and splashing that occurred just around the dynamic wetting line. Three observers were used and the scores averaged to rate the contribution of the input variables to curtain stability. The results are summarized in Tables 8 and 9. The dark colored boxes depict the most important variables. These are the variables that were found to have the strongest effect on air entrainment and curtain stability.

Table 7. Overall Statistical Summary for Air Entrapment

Variable		Air-Entrapment	
		Mean Sum of squares	% Contribution
Nozzle Height	mm	0.89	1.75
Surface Sizing	gm/m ²	15.34	30.24
Roughness	PPS	2.06	4.05
Coating Form		8.76	17.28
Surfactant	pph	0.89	1.75
Coat Weight	gm/m ²	3.35	6.60
Web Speed	mpm	17.60	34.69
SSS	Kg/min	1.85	3.64

Table 8. Summary of Statistical Contribution of Process and Formulation Parameters on High Speed Curtain Stability (colored boxes represent strong dependence)

	N. H	Sizing	Roughness	C. form'n	Surf't	CW	Webspeed	SSS
Straightness	-	↑	↑	↑	↑	↓↑	↓	↑↓
Fluctuation	-	↑	-	↑	↑	↑	↓	↑↓
Back Flow	↑	↑	↓	↓	-	↑	↓	↑
Air Entrainment	-	-	-	↑	↓	↓	↓	↑
Splash	-	-	↓	↑	↓	↓	↓	↑

Surface sizing, web speed and coating formulation have the greatest impact on air-entrainment and curtain stability in that order. Colored boxes represent a stronger effect of the parameter on the particular stability phenomena. These results corroborate with the current understanding of curtain operation as discussed earlier. Surface sizing with starch improves substrate wettability increasing viscous drag. Higher viscous drag results in a higher radius of curvature of the curtain in the impingement zone, reducing total pressure in the zone. Coating formulation affects the stretchability of curtain in viscous drag. Air entrainment is affected by steam substitution, coating formulation and coat weight. Comparing the results for coverage and curtain stability, it is clear that curtain stability and coverage is not governed by the same variables or by the same extent by a variable. The chosen process parameters are interacting strongly.

SECOND PHASE DOE

Phase I resulted in a good understanding of how to utilize the boundary layer air removal system (ejector pressure and steam flow rate) to improve the stability of the curtain, but stabilizing the curtain at high speeds remained a concern. To address this concern, web speed (higher side) was kept as a variable in the next phase of pilot plant trials.

From the results of the first phase study, it was determined that shear thinning rheologies clearly favored curtain coater stability at higher speeds. As a result, rheology would be further explored in the next phase of trials. As the degree of shear thinning is also a factor, coating formulations will be formulated to produce coatings of different degrees of shear thinning behavior. Since web speed was found to be the single most important factor. The effect of web speed needs to be examined more closely. As the curtain is very stable at low speeds, only high speeds were considered in the next phase of pilot trials. Since it was determined that the boundary layer air removal system must be fine tuned to the web speed, it was decided that steam flow rates would remain a variable in the next phase.

Although base sheet smoothness had a positive impact on coverage, high coverage was achieved even for high basesheet roughness. As a result, base sheet roughness effects would not be further explored. Because curtain coating coverage was almost insensitive to the coat weight, this parameter was also not considered further. It was also decided that the curtain height would be fixed, as well as the level of surfactant added.

In the second phase, an irregular factorial model, D-optimal, was used (Table 10). This model allowed the two-way interactions between variables to be analyzed, which was critical in understanding the influence of curtain coating stability on coverage. Three variables were assigned 3 levels and one variable was assigned 2 levels. The levels assigned were based on the relative importance of each variable determined from the first phase of pilot studies.

Table 9. Second Phase Statistical Layout

Study Type	Factorial	Experiments	26
Initial Design	D-optimal	Blocks	No Blocks
Center Points	0		
Design Model	2FI		
Response	Name		
Y1	Coverage		
Y2	Air entrapment		

Factor	Name	Units	Type	Low Actual	High Actual		
A	Roughness	PPS	Categorical	-1	1	Levels:	3
B	SSS	Kg/min/m	Categorical	-1	1	Levels:	3
C	Formulation		Categorical	-1	1	Levels:	3
D	Speed	MPM	Categorical	-1	0	Levels:	2

The levels of variables and constant parameters are summarized in Table 11 and 12 for the second phase. The formulations for the second phase coating trials are given in Table 12. Lubricant, Nopcote C-104, was added at 0.06 pph, resin SPI at 0.5 pph and 0.1 pph NaOH to keep coating pH between 9-9.5. Surfactant was added to achieve the desired levels of 0.02, 0.20 and 0.8 pph. The low shear viscosity properties of the coatings are shown in Figure 26.

Table 10. Second Phase Variables and Their Levels

Variable	Level of the variable		
	Low (-1)	Medium (0)	High (1)
Roughness	7.2 PPS	6.2 PPS	5.5 PPS
Web Speed	1500 mpm	-	1800 mpm
Coating Formulation*	I	II	III
Steam Flow rate	0.80 kg/min	1.2 kg/min	1.6 kg/min

*Coating formulations I, II and III represent different rheologies

Table 11. Second Phase Fixed Parameters

Sizing	None
Coat weight	6 gms/m ²
Surfactant Dosage	0.20 pph
Curtain Height	250 mm

Table 12. Second Phase Coating Formulations

Coating #	Clay/Carbonate	CMC	Latex
I	40/60	0.55	14
II	40/60	0.55	15
III	40/60	0.5	12

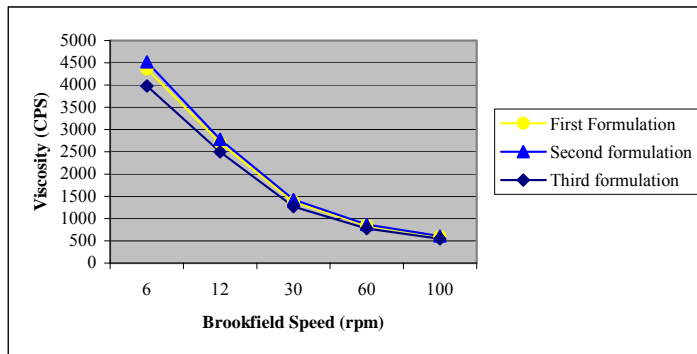


Figure 12. Brookfield viscosities of second phase coatings.

SECOND PHASE RESULTS AND DISCUSSION

The results of the second phase pilot trials are summarized in Tables 13 and 14 (also see appendix II). As shown, the steam flow rate was the only significant main effect. Roughness, in combination with web speed and coating formulation, and steam flow rate in combination with web speed were found to be significant. The roughness/formulation interaction was the single largest effect (39%) followed by the steam substitution flow rate (24%). The next two significant effects are much smaller; roughness-speed (4.7%) and web speed-steam flow rate (6%).

The effect of web speed was surprisingly small but can be explained by the better manipulation of the boundary layer air removal system. The effect of web speed was offset by the dominant contribution of the steam substitution system. In the first phase, the web speed was dominant, whereas the contribution of the steam substitution was insignificant. Web speed – steam flow rate was significant in combination with each

other. This supports the conclusions from the first phase that showed the effect of steam substitution to be dominant for curtain stability. Thus, steam substitution is critical for realizing a stable curtain and it should be tuned with web speed.

Roughness was not found to be significant by itself, but in combination with the coating formulation and web speed it critically impacted the curtain stability. The roughness-web speed interaction can be explained by the effect of roughness on boundary layer air thickness. Roughness also affects the ease of boundary layer air removal, thus the efficiency of the steam substitution system. Its interaction with the coating formulation can be explained with current data or any existing theory.

Table 13. Second Phase Result Summary

Run #	Roughness	Steam Flowrate *	Formulation	WebSpeed	Coverage
	PPS (µm)	Kg/min/m	**	MPM	%
1	5.5	0	III	1800	90
2	6.2	-1	III	1800	73
3	6.2	-1	I	1500	67
4	7.2	0	II	1800	89
5	5.5	0	I	1800	55
6	6.2	0	I	1800	86
7	5.5	0	II	1500	87
8	6.2	0	III	1500	72
9	5.5	-1	III	1500	90
10	7.2	0	III	1800	68
11	6.2	1	II	1500	80
12	7.2	1	II	1800	82
13	7.2	0	I	1500	95
14	5.5	1	I	1500	89
15	6.2	1	I	1800	82
16	7.2	-1	II	1500	73
17	6.2	-1	II	1800	68
18	5.5	-1	I	1800	66
19	7.2	-1	III	1800	70
20	6.2	1	III	1800	86
21	7.2	1	III	1500	84
22	5.5	1	II	1800	84
23	5.5	-1	II	1800	72
24	7.2	1	I	1800	90
25	6.2	0	II	1800	78
26	7.2	-1	I	1800	78

* (-1,0,1) are the levels of steam flow rates.

** (I, II, III) are coating rheologies differing in order of shear thinning

Table 14. Second Phase - Overall Statistics

	Sum of squares	DF	Mean SOS	% Contribution
Roughness (A)	81.74	2	40.87	3.13
SSS (B)	660.80	2	330.40	24.24
Formulation (C)	2.83	2	1.41	0.26
Speed (D)	32.40	1	32.40	3.93
Interaction AB	219.02	4	54.75	3.35
Interaction AC	1024.88	4	256.22	39.37
Interaction AD	5.84	2	2.92	11.36
Interaction BC	164.40	4	41.10	3.20
Interaction BD	209.02	2	104.51	6.43
Interaction CD	115.17	2	57.59	4.73

% Contribution of a variable is contribution it makes in explaining variance in the response variable

CONCLUSIONS

Employing an efficient boundary layer air removal system can alter the operating window of a curtain coater. The boundary layer air removal system should be tuned with web speed. The role of the boundary layer air removal system is especially critical at high speeds. Base sheet roughness, in combination with coating formulation, is the most important variable in curtain coating operation. A smooth base sheet improves coverage. Very high coating coverage is possible at low coat weights with a curtain coater. Shear thinning coating rheology favors curtain coating. The degree of shear thinning is important however, considering the extensional flow field in the process, more rheological studies are needed to establish the single most important rheological parameter to curtain coating. Coat weight does improve coverage, but coverage is only a weak function of coat weight. Higher curtain height and Base sheet wettability improves overall curtain operation stability.

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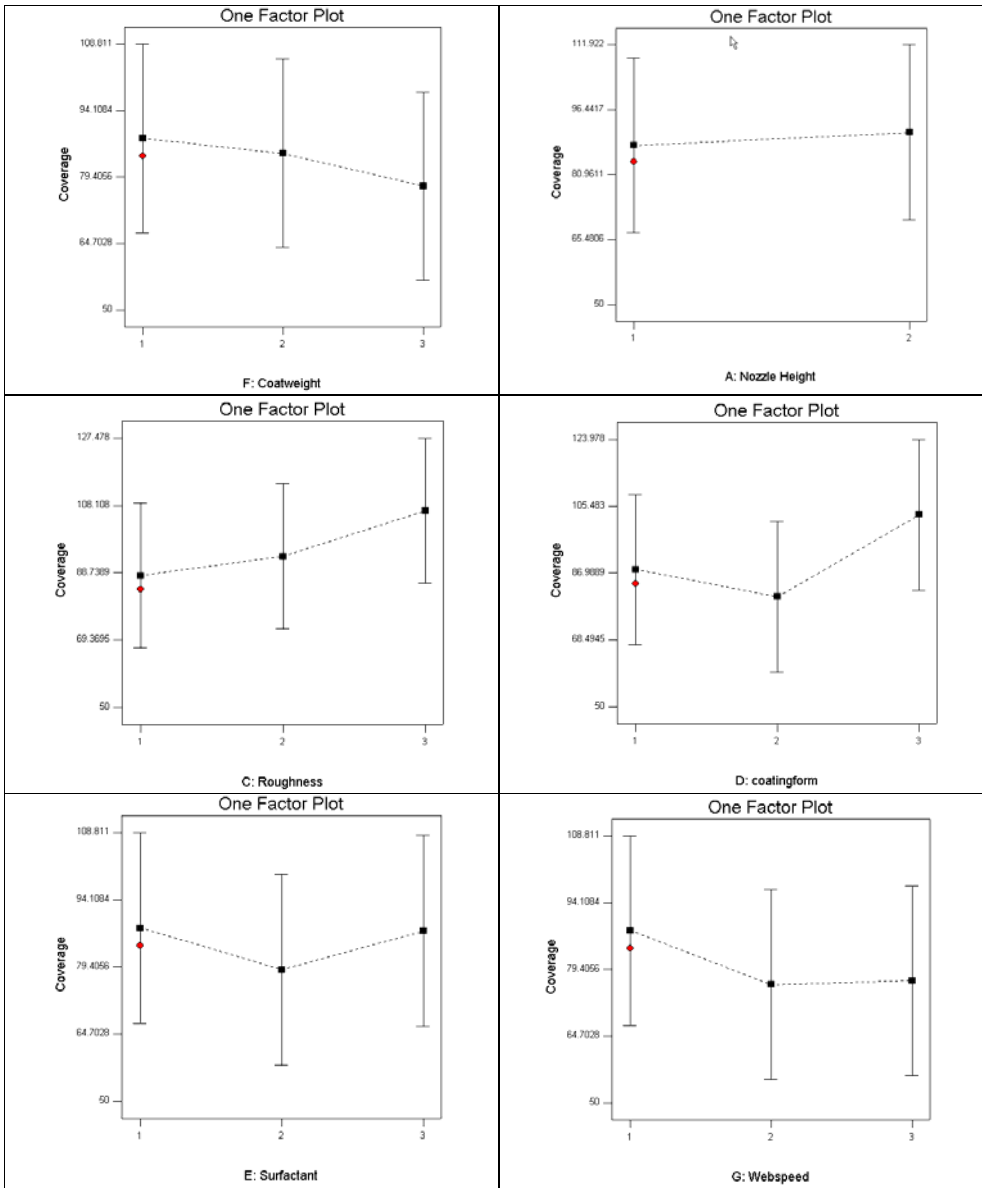
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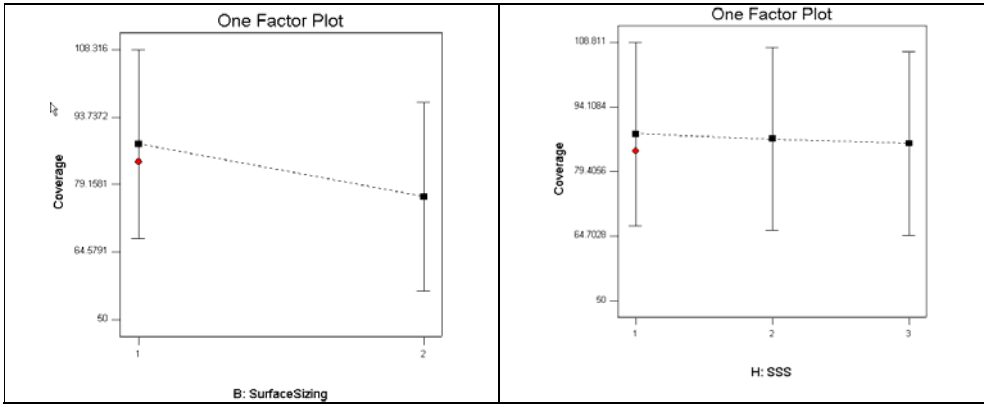
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APPENDIX -I

First Phase Results





APPENDIX II – Second Phase Results

