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Determine the Effect of Pulp and Paper Properties Such As Basis Weight, Degree of Refining on the Drying Proportions of both Hardwood and Softwood

Vidit Kumar

DETERMINE THE EFFECT OF PULP AND PAPER PROPERTIES SUCH AS BASIS WEIGHT, DEGREE OF REFINING ON THE DRYING PROPORTIONS OF BOTH HARDWOOD AND SOFTWOOD

by

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DETERMINE THE EFFECT OF PULP AND PAPER PROPERTIES SUCH AS BASIS WEIGHT, DEGREE OF REFINING ON THE DRYING PROPORTIONS OF BOTH HARDWOOD AND SOFTWOOD

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Paper drying is a very important unit operation and a highly energy intensive operation in the paper industry. Various studies have been made to discuss the effect of various variables on the drying behavior of the paper. Extensive efforts have been made to reduce the energy requirement in this operation.

This study tries to find the effect of basis weight, refining level on the drying behavior of the paper of both hardwood and softwood. The basis weight, the degree of refining and type of wood affects significantly the drying rate, the drying time and the contact coefficient between the paper web and the metal shell. It is found that the drying rate, the drying time and the contact coefficient increase with the increasing basis weight. The degree of refining also shows its effect on these behaviors, as with more refining, the drying rate goes down and so the drying time increases. The effect of type of wood is also very much significant on the drying rate and the drying time, as less drying rate observed of softwood sheets, so the sheets took more drying time in compare of hardwood sheets.

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CHAPTER I

INTRODUCTION

In United States, paper, pulp and paperboards production account about 12 % of total energy used in manufacturing. Paper is one of the basic material for which per capita demand has continuously increased. The increase in per capita consumption averaged 1.8% per year from 1960 to 1980, 1.6% per year from 1980 to 1993, and is projected at 0.6% per year during 1990 to 2040 (1).

The production of paper involves preparing the stock from pulp, forming the sheet, dewatering, drying, and sometimes coating the paper. All paper machines have three basic elements: wet end, press section, and drying section. Economies of scale have resulted in larger and faster paper machines. However, there is a parallel trend toward low cost, simple, and small paper machines for recycled paper minimills.

Energy intensity in the paper and allied products industry in 1991 was 21 MJ (20,000 Btu) per dollar value of shipments, ranking it as the second most energy-intensive industry group in the manufacturing sector. The industry has made important strides in reducing total energy use since 1973 and in increasing the fraction of energy provided from self-generated biomass sources.

Paper drying operation is an important unit operation in the pulp and paper industry as it is very difficult to obtain a paper web with moisture content lower than 1.4 Kg water per Kg dry fiber by mechanical pressing. The remaining moisture must therefore be removed by thermal drying. Drying is a highly energy intensive operation and therefore, it is important to understand the factors that affect the drying behavior of the paper.

Drying of paper is the largest steam user at any mill. Drying starts by heating the pulp or paper sheet from the temperature at which it leaves the press section. Drying of paper is the largest steam user at any mill. Following the press section, drying starts by heating the paper sheet. Important ways of improving the efficiency of paper drying, in addition to higher solids from the press section, include reducing overall heat losses, using less air, and increasing the heat extraction from each unit of steam used for drying. Several technologies to increase solids from the press section and alternatives to the conventional cylinder drying that would impact energy use are being developed or are already in use. More revolutionary drying concepts include the Condebelt process and impulse drying.

In the Condebelt drying concept, the wet sheet of paper is carried between two steel bands, one hot band and one cold band, and subjected to high pressure (max. 10 bar) and temperature (max. 180°C). Heat is transferred from the hot band to the sheet; moisture evaporates and traverses through two wire screens to the cold band, where it condenses. The condensate is carried away by the thickest of the two wire screens. The sheet is dried in absence of air. In contrast with conventional pressing technologies and impulse drying the pressure is maintained for several seconds, resulting in good paper qualities (2 & 3).

In impulse drying method, a moist web is passed through a high temperature press nip. Elements of both, wet pressing and hot surface drying used in this method. Roll surface temperatures of 150oC -500oC, nip pressure of 0.3 -7 MPa and nip residence time up to 100 ms (4), are the typical characteristics of the nip (5).

The objective of this thesis is to quantify the effects of pulp and paper properties specifically: basis weight, degree of refining on the drying of both Hardwood & Softwood. The drying characteristics measured in this study are the length of drying time, drying rate, general shape of drying curve and contact coefficient between the paper web and metal shell.

CHAPTER II

STATEMENT OF THE PROBLEM

The paper drying unit operation is one of the most highly intensive energy operations in the paper industry. So far, several attempts had been made to reduce the energy consumption in paper drying section or to do the drying in more efficient way. However these attempts have met with limited success and paper drying remains highly energy intensive.

The objectives of this thesis are to determine the effects of sheet properties on drying specifically: basis weight, degree of refining on the drying properties of both hardwood and softwood. The drying behavior that was measured includes: the length of drying time, drying rate and general shape of the drying curve and paper-shell contact coefficient. The experiments were conducted using the apparatus previously built by Dr. John Cameron.

CHAPTER III

LITERATURE REVIEW

INTRODUCTION

"The paper making process is a very huge drainage operation or a dehydration process" (6). While entering the paper machine headbox, the solid content is merely around 0.2% to 1%. Following the formation section using vacuum, gravitation and pulsation the stock consistency is increases to around 20%. Following the formation section, the press section comes where water is removed by mechanical compression and the web consistency goes up to 35% – 50%. After the press section, the paper web enters the dryer section where the remaining water is removed by thermal operation i.e. evaporation and leaves the consistency around 5% to 9%. A large amount of thermal energy, supplied in the form of steam is required in the evaporation process (7).

Paper drying is an important unit operation in the pulp and paper industry. It is difficult to obtain a paper web with moisture content lower than 1.4 kg water per kg dry fiber by mechanical pressing, therefore the remainder of moisture must therefore be removed by thermal drying, a highly energy intensive operation. Paper drying is very much expensive process than mechanical drainage on the wire and press sections. The runnability also improves if the paper web has high dryness before the dryer section because web strength increases as dryness increases. But dryness of the web before the dryer section has some restrictions like press technology limitations and the bulk of the paper web. So if the paper requires high bulk, the initial dryness before the dryer section must be lower.

During paper drying, the bonding between the fibers takes place and so the paper web increases. The paper web also shrinks during drying and therefore the drying process is a very critical parameter for the final paper qualities. Table 1 shows typical compositions of the stock in various stages of the paper drying and the amount of water removed (based on the production of 1 tonne of paper at 94% solids).

Table 1. Compositions of the Stock in Various Stages

Stage	**Fibers (kg)**	**Waters (kg)**	**Solid content (%)**	**Water Removed**	
				Kg	%
Ingoing	940	93060	1		
After forming	940	3760	20	89300	96
After pressing	940	1410	40	2350	2.5
After Drying	940	60	94	1350	1.5
				93000	100

After pressing, the residual water in the sheet is removed by evaporation in the dryer section of the paper machine. The evaporation process requires a large amount of thermal energy, which is supplied in the form of steam. Efficient transfer of the thermal energy from steam to the paper web requires low thermal resistance. For example, the condensate film should be minimum, and the surface of the dryer should be free from scale.

DRYING SECTION REQUIREMENTS

A drying section and the drying process should have the following basic requirements:

1. Drying Efficiency

   As the drying equipments are very large and expensive the drying should be efficient using minimum machinery. It should be designed in a way that it can evaporate maximum water per dryer unit to minimize the equipment requirement for all paper grades produced (7).

2. Paper Quality

   With high evaporation efficiency the paper quality should remain high. The cross machine evaporation profile is especially very important because moisture profile variations of paper in this direction cause variations in paper properties and affects runnability.

3. Dryer Section Runnability

   For production efficiency of a paper machine, the runnability of the dryer section is very important. The major causes of the lost production time are the breaks occurring on the dryer section. As the paper machine operating speeds increases gradually, the significance of runnability is becoming greater. (7)

4. Energy Economy

   The dryer section and the associated process components such as steam, condensate, and ventilation system should be designed in a way to minimize the energy consumption in the drying process and to recover the surplus heat for other sections of the process.

DRYING METHODS

Since the initial development, the paper machine dryer section and its operating principle has not changed much. To dry paper and board, contact drying with steam heated cylinder is still the most common method used in the paper industry. Attempts have been made to develop new drying methods other than cylinder drying to achieve higher drying efficiency, reduction in energy consumption and better functional properties of finished paper. Impingement, Condebelt-, impulse and press drying processes are the few methods which are being developed or in developing process. The Condebelt has already reached production stage and impulse drying is ongoing study in a pilot scale. (7)

Conventional Cylinder Drying

From the press section, the wet paper is passed over a series of steam heated cylinders. The cylinders are typically 1.2, 1.5 or 1.8 meters in diameter. 1.8 meters cylinders are mostly used in the modern paper machines. Steam is supplied into the cylinders and the energy from the steam is transferred through the cast iron shell and into the paper web. From sub-atmospheric pressure to 1000 kPa are the various steam pressures used depending upon the paper grade. Synthetic fabrics are used to press the sheet tight against the cylinder to improve the heat transfer by providing better contact between the paper web and the drying cylinder. The majority of the evaporation is happened in the open draw between the cylinders. The ventilation air carried away the evaporated water (7, 8).

BASIC DRYING THEORY

There are two basic components in the drying process:

A: Heat transfer into the paper web from the drying cylinder.

B: The evaporation of water from the paper web.

These are discussed below.

Heat Transfer

Heat is transferred from the steam through the dryer shell into the paper. As the paper web contacts the dryer surface, the dryer fabric presses the sheet against the dryer surface to improve the contact. The fabric also restricts the evaporation while the sheet is on the dryer. Therefore while on the dryer, the sheet temperature rises as heat is transferred into the paper and only a little evaporation takes place.

Heat transfer into the sheet follows this basic equation:

$$Q = U * A * (Ts - Tp) \qquad [1]$$

Where

Q = rate of heat flow from steam to paper (KJ/h)

U = overall heat transfer coefficient which is a measure of the resistance to heat flow (KJ/h/m^2/ °C).

A = dryer surface area in contact with the paper web (m^2).

Ts = steam temperature (°C).

Tp = paper temperature (°C).

The temperature of the paper web is the variable that relates the heat transfer and evaporation process. Increasing the heat transfer will increase the paper temperature as it leaves the dryer that will increase the evaporation in the space between the cylinders. In the same way, an efficient evaporation process reduces the paper temperature in the draw between cylinders as the water evaporates. This result in a lower sheet temperature as the sheet comes back onto the next cylinder and improves heat transfer.

There are only two variables with a fixed number of dryers, which can be controlled in the heat transfer equation are the saturated steam temperature (Ts) and the overall heat transfer coefficient (U).

By increasing the steam pressure or contact pressure inside the dryers, the temperature can be increased. But there are practical limitations to the maximum pressure that can be used. Pressure must start out low and be graduated to higher pressures as the paper progresses through the dryer section. Higher pressures cause the fibers on the outer surface to the paper to stick to the dryer. This causes a rough sheet surface and can also induce runnability problems due to the non-uniform release of the paper from the dryer cylinder.

The overall heat transfer coefficient is a measure of the resistance to heat transfer. It is possible to improve this coefficient on many machines and improves the drying rate. (7)

Major barriers to heat transfer that have to be overcome or minimized are:

1. The condensate layer thickness and turbulence level. As the steam a transfer heat and condenses so to form a condensate layer inside the dryer. The layer provides a resistance to heat transfer.

2. Any scaling takes place on the dryer surface.

3. The dryer metal shell thickness is a resistance to heat flow. The thickness of the shell is determined by the pressure requirement of the dryer.

4. A thin air film is trapped between the sheet and dryer shell as the sheet comes onto the cylinder.

5. The sheet properties can also affect the resistance to heat flow. The water content, thickness, surface roughness, porosity, etc., will influence the ability to transfer heat effectively. Drying rates vary significantly from one grade to another. It must be recognized that all furnishes do not dry at the same rate (7).

Evaporation

The heat that is transferred into the sheet while on the dryer cylinder is used to change the phase of water from a liquid to a vapor. For conventional drying conditions, the amount of heat required for this phase change is about 2290 KJ / kg water evaporated. The majority of the evaporation takes place in the free draw between cylinders. The evaporation from the sheet follows the basic mass transfer equation.

$$EVAP = K * A * (Ps - Pa) \quad [2]$$

Where,

EVAP = water evaporated from the sheet (kg water/ h).

K = mass transfer coefficient (a measure of the resistances presented by the air film on surface of the sheet).

A = evaporation area determined by the length of the draw (m2).

Ps = vapor pressure of the water in the sheet (Pa).

Pa = partial pressure of water vapor in air surrounding the sheet (Pa).

It is difficult to reduce the resistance of the boundary layer of air accompanying the sheet (K) because of the physical arrangement of the dryer section.

The vapor pressure of the water in the sheet is directly related to the temperature of the sheet. Efficient heat transfer will result in a high sheet temperature and a high value for the vapor pressure of the water in the sheet (Ps). The temperature of the sheet drops as water evaporates.

The partial pressure of the water vapor in the air surrounding the sheet is directly related to the absolute humidity of the air. High humidity in the dryer pocket results in a high partial pressure and reduced evaporation. (7)

Thermal conductivity of a paper is mostly affected by the following parameters: Moisture Content, web density and temperature. Thermal conductivity of gas filled pores is poor at low temperature. Evaporation and condensation mechanism becomes more significant at high temperature. Thermal conductivity of paper increases with increasing moisture content. This is partially because of the contribution of thermal conductivity when water fills gas-filled pores and builds thermal bridges between fibers. Thermal conductivity of paper gradually increases at higher temperature as the evaporation and condensation process becomes more significant at high temperature. If a fiber network at certain moisture content, has higher paper web density that means it will have lower volume fraction of gas filled pores or vice versa. As the thermal conductivity of gas pores is poor so the thermal conductivity decreases with decreasing of paper web density (9, 10, and 11).

DRYING ZONES

The drying rate is different at different points in the dryer section. Initially the sheet enters the dryer section at a temperature lower than the temperature where most evaporation occurs. The dryer must heat up the fiber and water in the sheet to the evaporation temperature. This is known as the "sheet-heating phase". The sheet-heating phase generally takes from one to four dryer cans depending on the initial temperature, the dryer steam pressure, the moisture content, and the basis weight of the sheet. The sheet evaporation increases to a peak rate then enters the "constant rate drying zone". The constant rate-drying zone has the highest rate of evaporation. Free water is readily available for evaporation in this zone.

The next drying zone is the "falling rate drying zone". In this zone, free water is no longer available at the surface of the fibers in the sheet. Some of the larger pores in the sheet are empty of water and the effective area for mass transfer is reduced. The evaporation rate is reduced and continues to reduce as more of the pores become empty. The point at which the sheet enters the falling drying zone is difficult to determine. Early in the zone the evaporation rates are very high; at a level close to those in the constant rate zone (6). A typical drying curve is shown in Figure 1.

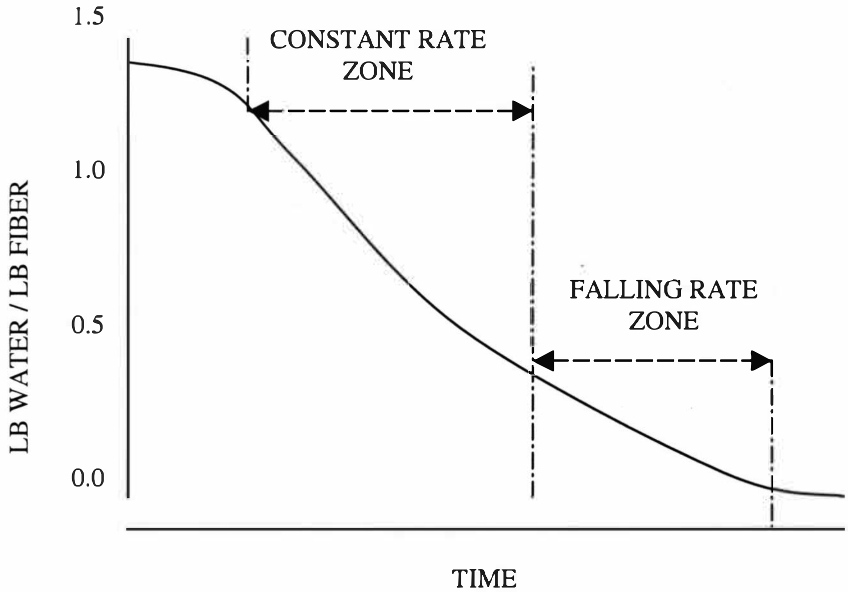

Figure 1. Typical Drying Curve

The drying rate will vary with the paper grade and furnish conditions. The drying rate is evaluated in terms of kg water evaporated /h/m^2 of total dryer surface. Figure 2 shows the relation between moisture content and drying time and between drying rate and moisture content. Figure 2 describes the drying process in a paper machine to three phases. The phases are the heating phase, the constant rate phase and the falling rate phase. This ideal condition takes place if the drying conditions are same over the entire drying process but in practical, the constant drying rate phase does not exist. (6)

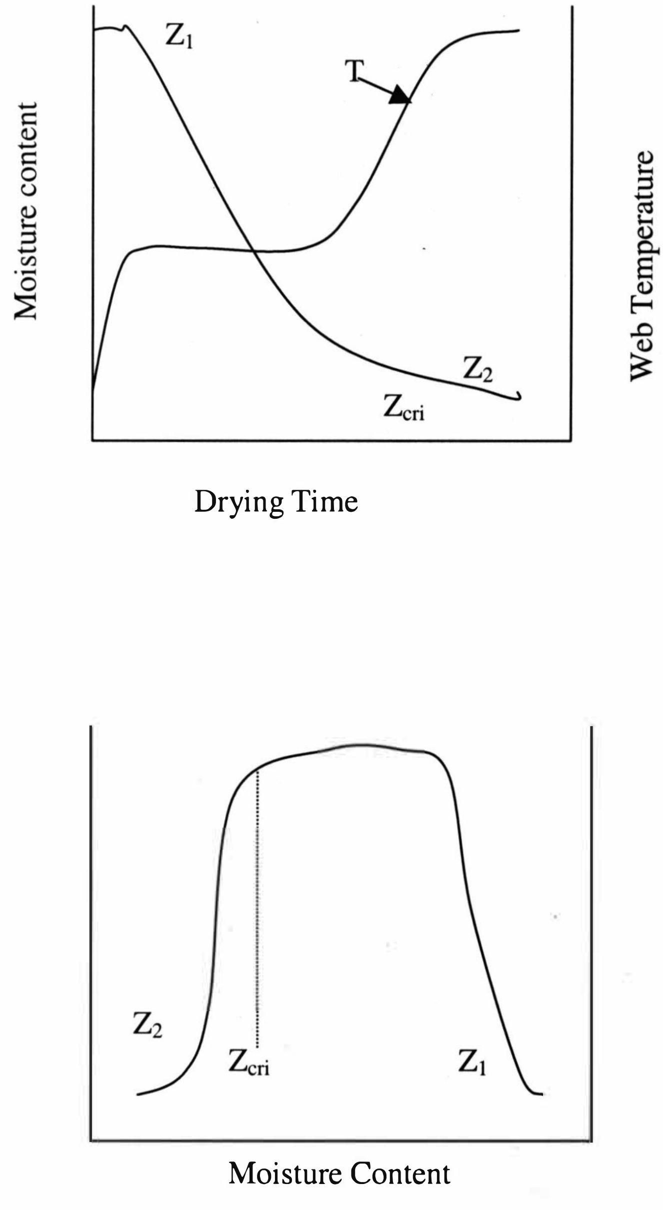

Figure 2. Drying Rate Curves

In the heating phase, the web temperature and drying rate increases and approach constant rate conditions. In the constant drying rate phase, the energy transferred to the paper web is equal to the energy required for water vaporization and so the web temperature and evaporation rate are constant. Evaporation can happen inside the web or on the web surface. In any case, the resistance is very poor for the diffusion of the vapor to the outer surface. The drying rate starts to go down in the falling rate phase, because of non-uniform wetted surface and increasing resistance for vapor diffusion. This is because of a decrease of vapor partial pressure from the interior of the web to its surface. The reason for this is a decrease of vapor partial pressure because of the hygroscopic nature of pulp and fiber and more resistance for heat transfer because of decreasing thermal conductivity of the web. And due to decreasing drying rate, the energy used for evaporation also decreases. Web temperature increases because of system tries to find a thermal balance (6).

CONTACT COEFFICIENT

"Estimates made by several investigators suggest that 35%- 75% of the total resistance to heat transfer in the paper is encountered at the contact surface" (12). This means that up to 75% of a sheet's drying rate is dependent on the contact coefficient between the paper and the dryer shell. This coefficient is known as paper-shell contact coefficient (13). Previous studies (12, 14, 15) showed that the contact coefficient decreased with a decrease in moisture content from about 900 -1200 W/m^2s at 1.5 Kg water/ Kg solids to about 250 W/m^2s when nearly dried.

The model used in this thesis is written in visual basics for application. This allowed the Excel spreadsheet to serve as an input-output platform for the program. The associated graphs then can be quickly generated using Excel's chart feature. The two programs are in the form of modules that can be imported to an Excel spreadsheet.

CHAPTER IV

EXPERIMENTAL APPROACH

EXPERIMENTAL DESIGN

Drying System

The experimental system was designed in the same way as a steam-heated cylinder dries paper in paper drying process. The drying system is shown in Figure 3.

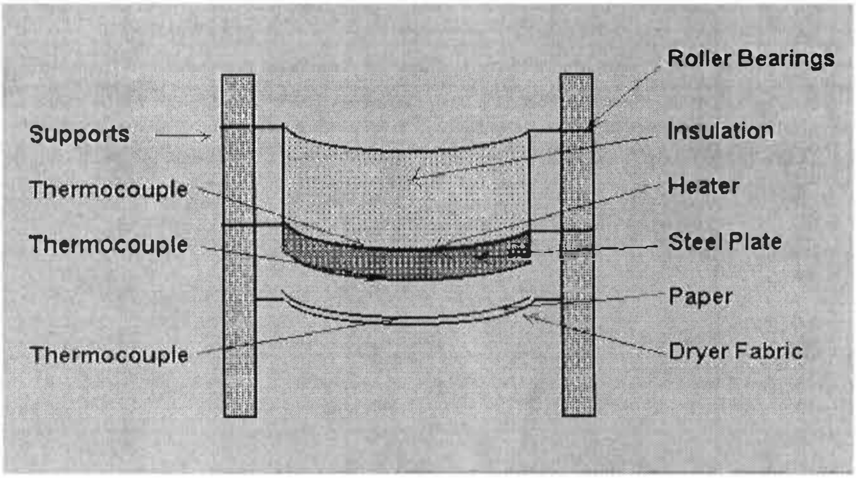

Figure 3. Drying Apparatus

In this experimental system, there is a heated steel plate, having a curvature of 6 ft diameter dryer can, a dryer fabric, and thermocouples. We collect data by using three type E thermocouples and a temperature data acquisition system manufactured by Computer Boards Inc. The thermocouples are attached with the surface of the paper, paper-heater interface and the heater shell interface.

In this system, the lower portion is dryer fabric and above it there is steel plate. In the space between a dryer fabric and the heated steel plate, the paper sheet is placed. The steel plate is ½ inch thick, and has semicircular groves of 0.003 inch diameter, E type thermocouples (see Appendix A) were soldered into these grooves of steel plate. Previous studies (13) have shown that the soldering of thermocouples into the grooves is important to achieve rapid temperature measurements and consistent heat transfer analysis. If there was any gap between the thermocouples and the steel plate that affected the difference between the amounts of heat calculated, to be transferred to the paper, the amount of heat lost by the steel plate and the amount of heat needed to dry the paper. "The silver solder was sanded flush to steel surface, an electrical heater was stick to the back of the steel plate and mineral wool installation was placed behind the plate." (16)

DATA ACQUISITION AND ANALYSIS PROGRAM

The data acquisition and analysis program is described in Appendix B. The data acquisition and analysis program includes: 1) All data are analyzed using Visual Basic for Application and presented on Sheet 1 of an Excel spreadsheet. 2) Sheet 1 presents six graphs. These are: a) Paper and Shell Temperature and Heat Flux Rate versus time, b) Paper-Shell Contact Coefficient versus Moisture Ratio, c) Paper-Shell Contact Coefficient versus Time, d) Paper-Shell Contact Coefficient versus Moisture Ratio, e) Drying Rate versus Time and f) Drying Rate versus Moisture Ratio.

Drying Experiment

Run Identification: The represented drying experiment was conducted with a softwood sheet, refined to 500 CSF and a basis weight of 60 g/m^2. The sheet was cut into 10 cm x 10 cm and was pressed to around 40% solids. The wet weight of the sheet came to 1.700 gram. The operator enters this information, which is then stored in the program and printed on the spreadsheet as shown in the following Table 2.

Table 2. Representative Run Number, Date, Wet Weight, Dry Weight, Area, Basis Weight, CSF, Fiber Type, Target Basis Weight

Run number	Date	Wet Weight (gms)	Dry Weight (gms)	Area (m^2)	Basis Weight (g/m^2)	CSF	Fiber Type HW = 1 and SW = 2
5	7/18/01	1.70	0.6244	.0104	60.0384	500	2
					Target Basis Weight		
					60		

Experimental Technique

The most reliable data was produced by the following experimental technique. First the sheet was cut into 10 cm x 10 cm and then was pressed to the around 40 % solids content. The steel plate was heated to about 3 °C above the target initial shell temperature then cooled down to the target temperature. The data acquisition program was started, and the paper sheet was put on the dryer fabric, the sheet thermocouple inserted into the paper sheet, and the steel plate lowered onto the paper sheet. In this representative experiment, the steel shell temperature was targeted to about 120 °C.

The program records temperatures of the two sides of the steel plate, sheet temperature. Data from the representative run is shown in Table 3.

Table 3. Representative Heater Temperature, Shell Temperature, Paper Temperature and Time

Column C	Column D	Column E	Column F
Temperature Heater 'C	Temperature Shell 'C	Time Seconds	Temperature Paper 'C
125.01	125.01	0.01	23.17
121.76	122.06	0.01	23.21
121.76	122.06	0.02	23.21
121.76	122.06	0.04	23.22
121.76	122.06	0.05	23.22

The heater was turned off during the experiment because of that Table 3 shows the shell temperature is greater than the heater temperature. The program uses the data from Table 3, and utilizes the Explicit method to calculate the heat flux based on temperature differences between nodes, a corrected heat flux that incorporates the change in temperature of the steel element containing the sheet and the total amount of heat transferred. The program presents this information in columns G through I and is shown in Table 4 for the representative case.

Table 4. Representative Heat Flux, Corrected Heat Flux and Total Heat Transferred

Column G	Column H	Column I
Heat Flux W/m^2	Corrected Heat Flux W/m^2	Total Heat Transferred J/m^2
17454	22110	3822
17782	22438	4120
18159	22815	4422
18560	23215	4730
18970	23626	5043

The paper-shell contact coefficient, water/solids ratio, drying rate, and the heat flux to paper (corrected for the actual size of the paper) are presented in the columns K through N, and are shown in Table 5.

Table 5. Contact Coefficient, Water/Solids ratio, Drying Rate and Heat Flux

Contact Coefficient (W/m^2- °C)	Water/Solids Ratio	Drying Rate (g/m^2-s)	Heat Flux to paper (W/m^2)
1008	1.527	9.51	443.8
1023	1.525	9.59	446.1
1038	1.523	9.63	448.2
1053	1.521	9.73	450.1

If there is no heat lost to the surroundings i.e. in an ideal situation, the energy transferred from the steel and the total energy transferred to the paper, the energy needed to heat the paper and the energy needed to evaporate all the water would be equal. However experience on commercial dryers and with this dryer system shows that there is some loss of heat to the surroundings during drying of the paper. To calculate the water/solids ratio, it is necessary to determine this lost of energy. The method used to determine this is described below.

Moisture Ratio During Paper Drying

To calculate the moisture content present in the paper during paper drying the amount of energy transferred to the sheet can be used and further paper drying rate can be calculated from this information. Heat transfer graphs show that amount of heat needed to dry the paper was less than the heat transferred to the paper from the steel.

These can be possible reasons for this -

(a) Some heat was lost to the surrounding environment.

(b) Some heat is lost due heating the fabric.

(c) More heat was used due to the water- water bonding in the paper.

Heat Loss Model

A heat loss model was developed to account for the energy lost to the fabric and atmosphere during paper drying. The model was written with two constants; the first representing the heat transferred to the fabric and the second representing the constant loss of heat to the surrounding atmosphere.

Heat Loss = Constant1 * Temp increase of the paper + Constant2 * difference between paper and air temp [6]

To estimate the first constant, the heat transfer to the felt was measured. Constant1 is then calculated by measuring the total energy transferred to the felt, subtracting the constant heat loss during this period and dividing the remainder by the increase in temperature of the felt. After implementing this technique, Constant1 was estimated to 165 KJ/°C.m^2. Drying different weight papers and measuring the constant heat loss after drying determined the second constant (constant2) in Equation 6. During some preliminary trials, it was found that the amount of heat loss after drying is a function of basis weight and could be described by the Equation 7. This equation could be further refined based on the trials in this report.

$$\text{Hlos (KJ)} = -0.067 * \text{TBW} + 15.35 \qquad [7]$$

Here TBW, is the target basis weight, which is in the most cases is the same as the actual basis weight.

Graphs Used In The Program

By combining the various columns in the Excel spreadsheet, different graphs can be easily obtained. The six graphs generated and displayed by the data acquisition and analysis program are shown below. Figure 4 shows the temperature of the steel shell in contact with the paper, the temperature of the paper and the heat flux calculated by the explicit program.

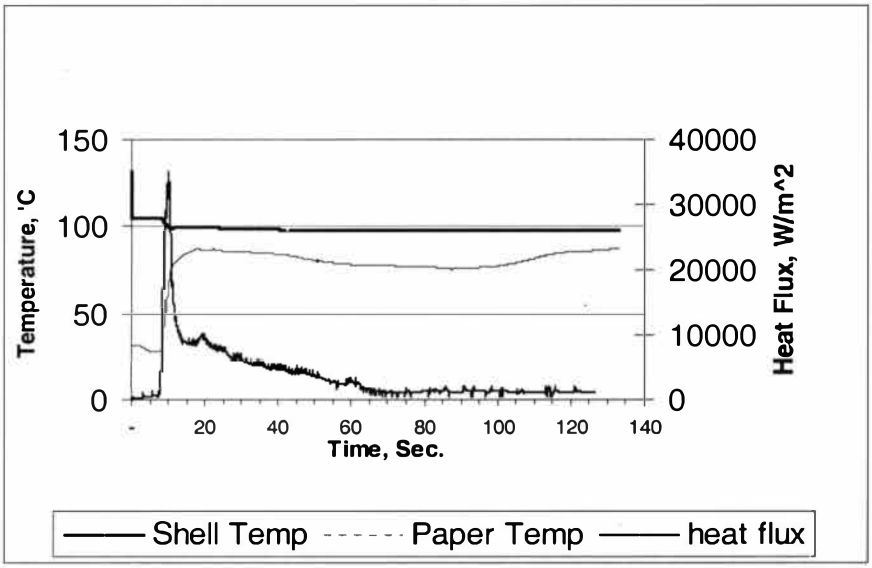

Figure 4. Shell and Paper Temperatures and Heat Flux versus Time

Figure 5 shows the paper-shell contact coefficient versus the paper's moisture ratio.

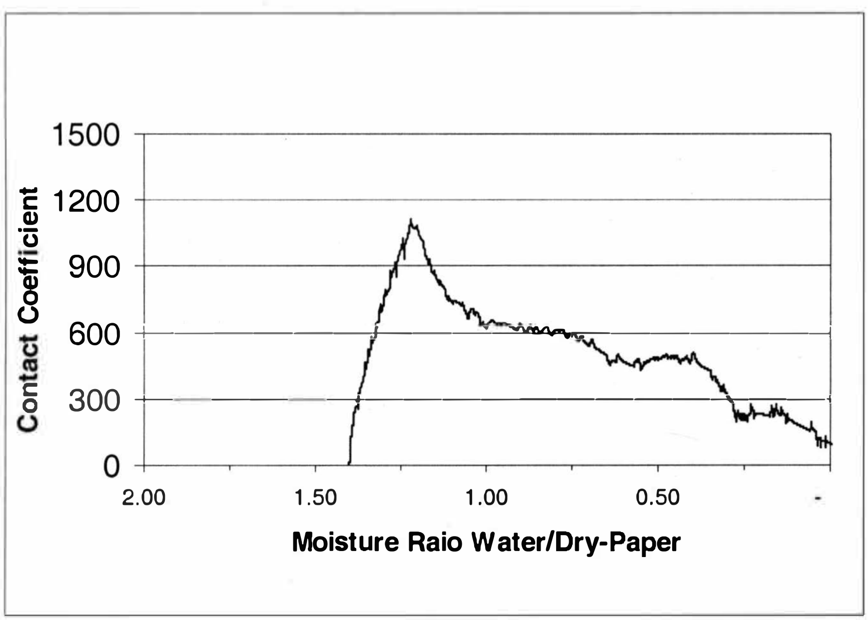

Figure 5. Contact Coefficient versus Moisture Ratio

Figure 6 shows the contact coefficient versus time.

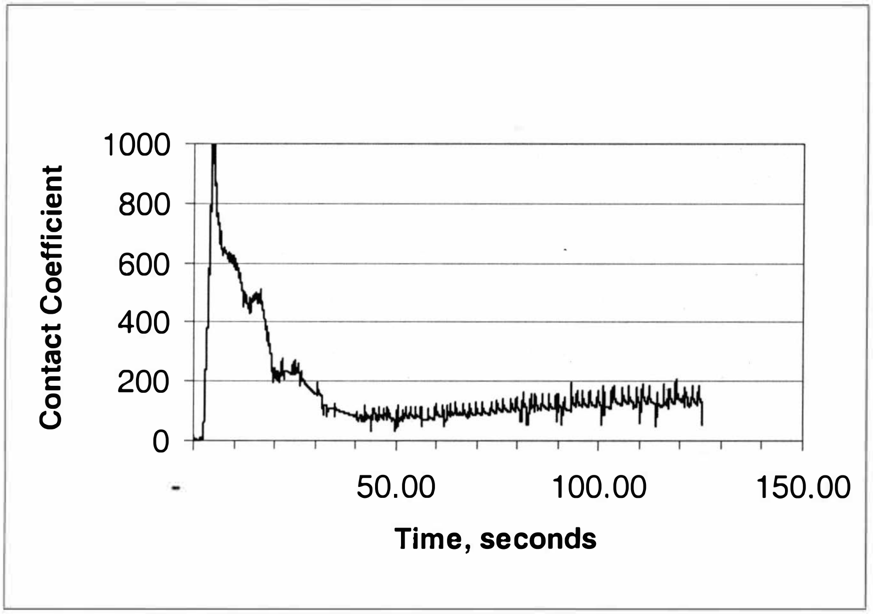

Figure 6. Contact Coefficient versus Time

Figure 7 shows the water/solids ratio versus time.

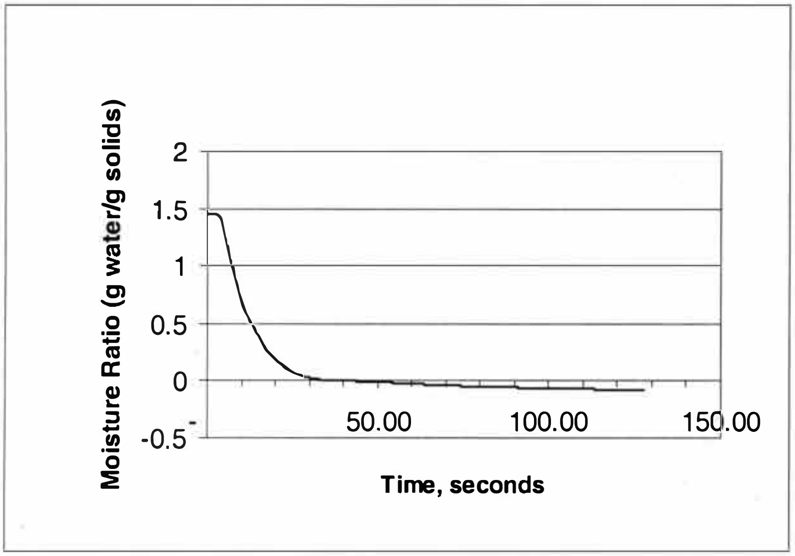

Figure 7, Moisture Ratio versus Time

Figure 8 shows the drying rate in terms of grams of water evaporated per sq. meter per second versus time.

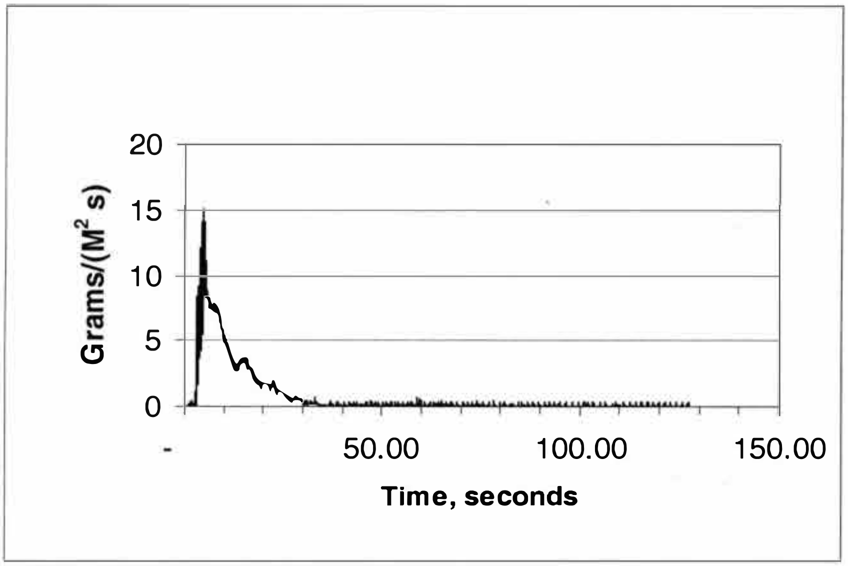

Figure 8. Drying Rate versus Time

Figure 9 shows the drying rate versus water/solids ratio.

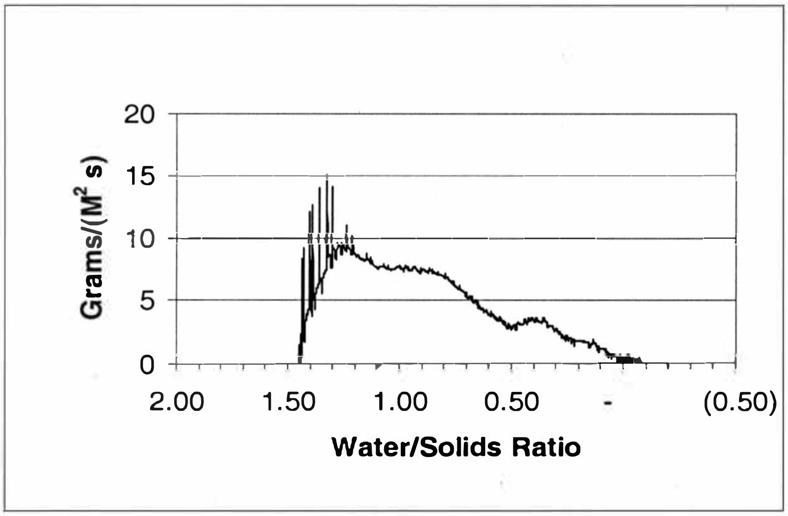

Figure 9. Drying Rate versus Water/Solids Ratio

Steel Internal Temperatures

In columns Z through AY, the two surface temperatures and the 24 internal node temperatures, calculated by the Explicit program are displayed. Representative temperatures for some of these nodes are shown in Table 6. Since these are before the inserting the paper, they show a constant temperature profile.

Table 6. Representative Internal Node Temperatures

Node Loc	Node Loc	Node Loc	Node Loc	Node Loc	Node Loc
119.86	119.90	119.89	119.89	119.88	119.88
119.86	119.89	119.89	119.89	119.88	119.88
119.86	119.88	119.89	119.89	119.88	119.88
119.86	119.88	119.89	119.89	119.88	119.88

Energy Balance Closure

The program also measures the energy balance closure. If the program has correctly calculated the energy transferred from the steel into the paper, the final value of the amount of energy transferred calculated by the program should be close to that lost by the steel and that required to heat the paper and evaporate all water.

Table 7 shows the energy closure for the representative case used in this report, where the paper reaches 100% solids. Column S shows the fraction of the energy transferred to the paper calculated by the loss model divided by the total transferred energy. Column T shows the ratio of the energy required to heat the paper and the water and to evaporate the water divided by the energy calculated to be transferred by the program. Column U shows the energy lost by temperature drop in the steel divided by the transferred energy (16).

Table 7. Energy Closure for Base Case

Column L	S	T	U
Water / Solids Ratio	Fraction of Q to Paper/Q	Q required to Dry Paper/Q	Energy Lost by Steel/Q
0.0005	0.89	0.86	1.16
0.0003	0.89	0.86	1.16
9.19E-05	0.89	0.86	1.16

Column U shows that the energy calculated by the program is within 16% of the energy lost by the steel. The reason can be for the closure is not exact, is that some of the energy is either lost by the steel to other surfaces or transferred by other surfaces into the steel as the paper dries. In the above case, some additional energy is transferred into the steel (16). The amount of energy lost by the steel is normally within 0 to 16% of the energy calculated by the heat flux program. "Column T shows the amount of energy required to dry the paper based on the wet and dry weights entered by the operator. Due to the effect of basis weight on this ratio, its value normally is between 0.7 and 0.9" (16). Column S is based on the model for energy lost by the paper. The value in column S is normally between 0.85 and 0.92. The energy transferred to the sheet (Q) is that needed to dry the paper completely. (16)

CHAPTER V

RESULTS AND DISCUSSION

The objective of this thesis was to determine the effect of basis weight, refining and fiber type on drying. Of the plots generated by the program perhaps, the most informative is the drying rate versus moisture ratio. The following graphs show the effect of basis weight, refining on drying and fiber type on drying. The data shown below are typical drying behavior, effect of basis weight, effect of refining and hardwood versus softwood fiber.

TYPPICAL DRYING PROFILES

Figures 10 through 15 show three types of different profiles for 84 g/m^2, hardwood, 275 CSF sheets, dried at 120 °C. Figures 11, 13 and 15 are typical drying rate profiles.

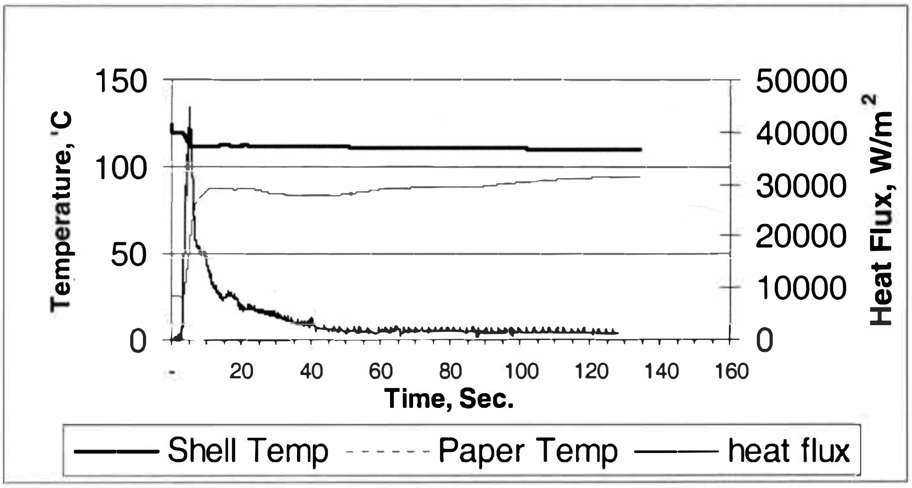

Figure 10. Heat Flux: BW 90 g/m^2, CSF 275, HW

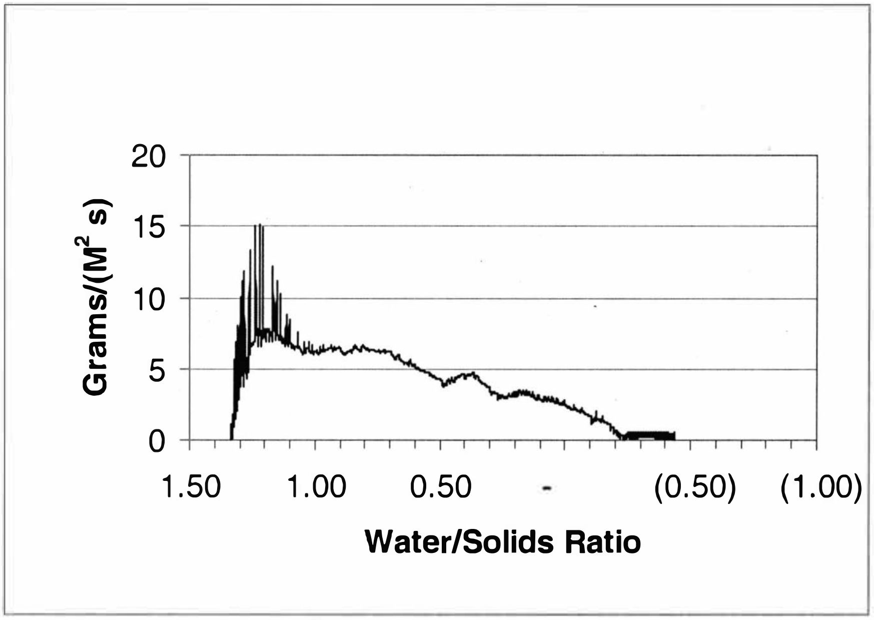

Figure 11. Drying Rate BW 90 g/m^2, CSF 275, HW

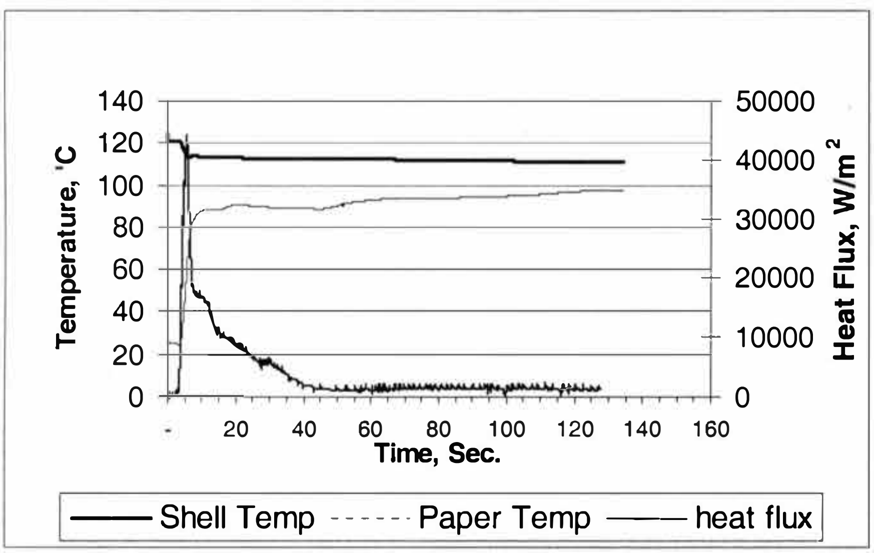

Figure 12, Heat Flux: BW 90 g/m^2, CSF 275, HW.

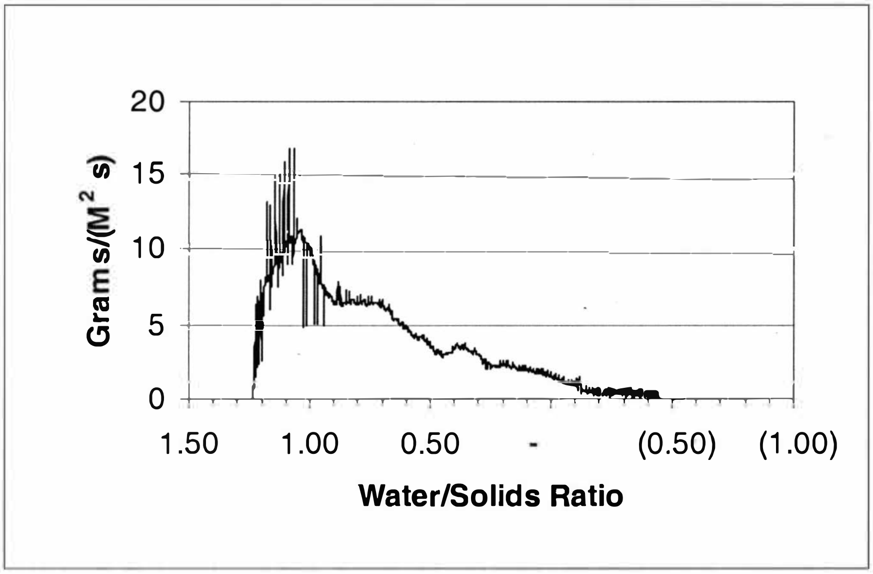

Figure 13. Drying Rate BW 90 g/m^2, CSF 275, HW

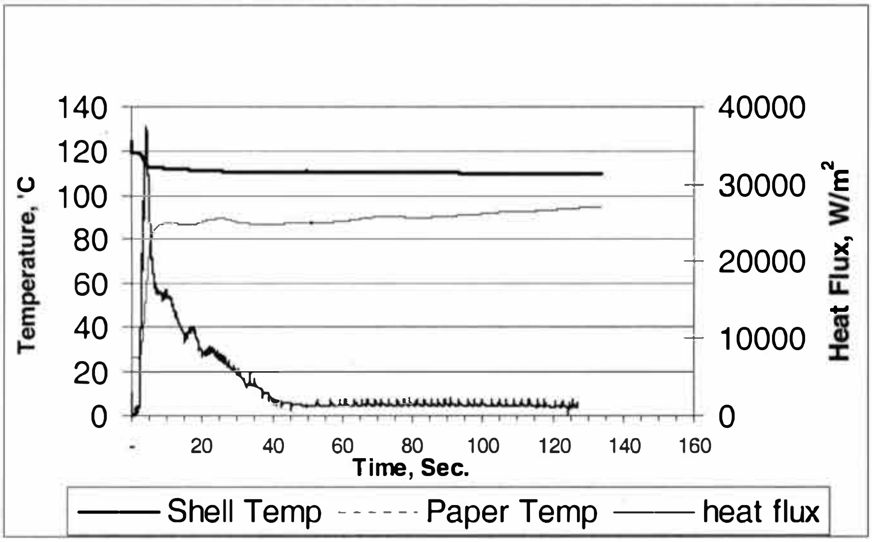

Figure 14. Heat Flux: BW 88 g/m^2, CSF 275, HW

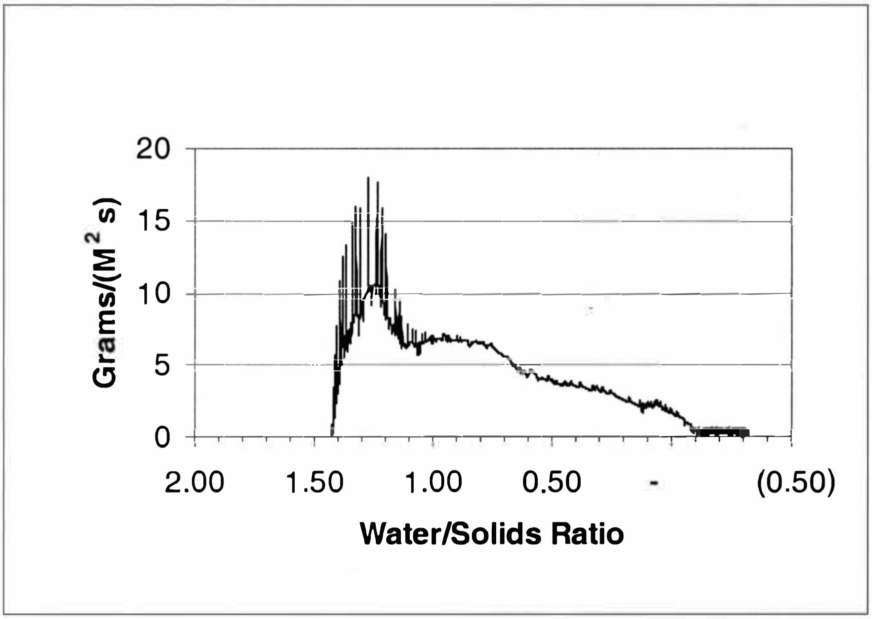

Figure 15. Drying Rate BW 88 g/m², CSF 275, HW

EXPERIMENTS CONDUCTED

Table 8 shows the experiments conducted of the sheets of different basis weights (45, 85, 90 and 140 g/m^2) with various refining level (258, 275, 510, and 535 CSF) of the both hardwood and softwood for the thesis. Table 9 shows the sheet properties (basis weight, refining level and HW/SW) and the results observed for the sheet (maximum drying rate in the heating phase, drying rate in constant and falling rate phase, drying time and contact coefficient in each phase).

Table 8. Experiments conducted

No. of Experiments conducted	Basis Weight (g/m^2)	Refining level (CSF)	HW/SW	Average initial water/solids Ratio
7	90	535	HW	1.35
3	45	535	HW	1.41
3	145	535	HW	1.46
4	90	275	HW	1.40
3	145	275	HW	1.60
3	90	510	SW	1.42
3	85	258	SW	1.65

Table 9. Drying rates, time duration, and contact coefficient for the experimented sheets of different basis weight and refining level of hardwood and softwood.

BW (g/m^2)	CSF	Initial Water/solids ratio	HW/SW	Drying Rate (g/m^2.s)			Contact Coefficient (W/m^2-°C)		
				Heating	Constant	Falling	Heating	Constant	Falling
88	535	1.35	HW	14.5	4.0	1.15	1280	500	140
87	535	1.32	HW	14.0	4.0	1.10	1200	535	135
93	535	1.37	HW	15.0	4.8	1.20	1350	600	200
92	535	1.4	HW	15.0	5.0	1.20	1400	500	170
90	535	1.42	HW	15.5	5.2	1.40	1500	670	140
90	535	1.3	HW	14.0	4.8	1.30	1170	680	130
90	535	1.3	HW	13.0	5.0	1.20	1160	700	120
43	535	1.36	HW	11.5	5.0	1.5	1200	600	170
44	535	1.42	HW	12.0	5.4	1.4	1220	650	190
46	535	1.46	HW	12.2	5.3	1.5	1100	620	160
145	535	1.49	HW	18	5.2	1.8	1420	550	225
143	535	1.43	HW	17	5.5	2.3	1520	480	170
147	535	1.46	HW	18	5.0	2.1	1500	510	190
88	275	1.46	HW	13.5	4.0	1.95	1020	400	75
90	275	1.36	HW	11.0	5.0	1.40	750	450	154
91	275	1.38	HW	11.0	6.2	1.80	800	510	100
90	275	1.42	HW	12.7	5.5	1.90	820	480	130
145	275	1.61	HW	15	5.2	2.1	1200	500	271
143	275	1.58	HW	14	4.0	2.3	1150	520	260
145	275	1.6	HW	15	5.0	2.1	1240	520	240
90	510	1.4	SW	21	4.7	1.3	1950	475	135
89	510	1.45	SW	23	5.1	1.4	2000	525	140
90	510	1.41	SW	21	5.0	1.4	1870	520	130
90	258	1.68	SW	17	4.0	2.2	1400	525	150
90	258	1.65	SW	15	4.4	2.5	1360	600	220
88	258	1.62	SW	14	6.5	1.9	1500	520	130

DISCUSSION

The research shows the effect of sheet basis weight, degree of refining and fiber type on paper drying properties. The drying behavior can be divided into 3 distinct phases. Initially the paper web enters the dryer section at a lower temperature than needed for evaporation. The fiber and the water in the sheet must be heated up to the evaporation temperature. This is called the rapid heating phase (6). The second phase is named as the constant rate phase and the third phase is called the falling rate phase. In the constant rate phase the paper web is saturated with water. The constant rate period proceeds until all the free water has been removed from the voids between the fibers. Moisture content of the web is more than the critical moisture content (the inversion point between the constant and falling rate phase (6)) in the constant rate period. After the web reaches the critical moisture content, the uniform water film disappears and the surface of the web is partly dry. The amount of evaporating surface decreases. This increases the resistance between the web and the cylinder. Simultaneously, the heat conductivity of the web decreases, and the temperature of the web starts to increase.

Result produced from above mentioned experiments were not exactly same and the average and standard deviation was calculated for the drying rate, time duration, contact coefficient for the heating phase, constant rate phase and falling rate phase. Tables 9 to 15 shows the average and standard deviation calculated for the drying rate, time duration and contact coefficient for the each phase.

Statistical analysis was also performed by using JMP software developed by SAS Institute Inc., Gary, NJ. It is explained in the Appendix C.

Table 10. Average / Standard deviation of the drying rates, time duration, and contact coefficient for 7 hardwood sheets of basis weight 90 g/m^2 with CSF 535

	AVERAGE / STANDARD DEVIATION		
	HEATING PHASE	CONSTANT RATE PHASE	FALLING RATE PHASE
Drying rate(g/m^2.s)	14.43 / 0.84	4.68 / 0.49	1.22 / 0.1
Time Duration (Sec)	13.86 / 1.21	16.57 / 1.78	29.14 / 2.90
Contact Coef.(W/m^2- °C)	1294 / 128	597 / 87	147 / 27

Table 11. Average / Standard deviation of the drying rates, time duration, and contact coefficient for 4 hardwood sheets of basis weight 90 g/m^2 with CSF 260

	AVERAGE / STANDARD DEVIATION		
	HEATING PHASE	CONSTANT RATE PHASE	FALLING RATE PHASE
Drying rate(g/m^2.s)	12.05 / 1.25	5.17 / 0.92	1.76 / 0.25
Time Duration (Sec)	13.5 / 1.73	17.75 / 1.25	27 / 2.16
Contact Coef.(W/m^2- °C)	847 / 118	460 / 46	114 / 34

Table 12. Average / Standard deviation of the drying rates, time duration, and contact coefficient for 3 hardwood sheets of basis weight 145 g/m^2 with CSF 260

	AVERAGE / STANDARD DEVIATION		
	HEATING PHASE	CONSTANT RATE PHASE	FALLING RATE PHASE
Drying rate(g/m^2.s)	14.66 / 0.57	4.73 / 0.67	2.16 / 0.11
Time Duration (Sec)	16 / 1.0	22 / 1.73	28.66 / 1.15
Contact Coef.(W/m^2- °C)	1096.7 / 85.1	513 / 11.55	257 / 15.72

Table 13. Average / Standard deviation of the drying rates, time duration, and contact coefficient for 3 hardwood sheets of basis weight 145 g/m^2 with CSF 535

	AVERAGE / STANDARD DEVIATION		
	HEATING PHASE	CONSTANT RATE PHASE	FALLING RATE PHASE
Drying rate(g/m^2.s)	17.66 / 0.57	5.23 / 0.25	2.06 / 0.25
Time Duration (Sec)	13.33 / 0.57	21.66 /.57	26.33 / 0.88
Contact Coef.(W/m^2- °C)	1480 / 52.9	513.3 / 35.1	195 / 27.8

Table 14. Average / Standard deviation of the drying rates, time duration, and contact coefficient for 3 softwood sheets of basis weight 95 g/m^2 with CSF 510

	AVERAGE / STANDARD DEVIATION		
	HEATING PHASE	CONSTANT RATE PHASE	FALLING RATE PHASE
Drying rate(g/m^2.s)	21.66 / 1.15	4.93 / 0.20	1.36 / 0.05
Time Duration (Sec)	11.66 / 0.57	12 / 1.73	36.33 / 1.5
Contact Coef.(W/m^2- °C)	1940 / 65	506 / 27.5	135 / 5.0

Table 15. Average / Standard deviation of the drying rates, time duration, and contact coefficient for 3 softwood sheets of basis weight 85 g/m^2 with CSF 258

	AVERAGE / STANDARD DEVIATION		
	HEATING PHASE	CONSTANT RATE PHASE	FALLING RATE PHASE
Drying rate(g/m^2.s)	15.33 / 1.52	4.9 / 1.3	2.2 / 0.3
Time Duration (Sec)	12.33 / 0.577	9.33 / 1.52	36 / 3.46
Contact Coef.(W/m^2- °C)	1420.1 / 72.1	548.3 / 44.8	166.7 / 47.3

Table 16. Average / Standard deviation of the drying rates, time duration, and contact coefficient for 3 hardwood sheets of basis weight 45 g/m^2 with CSF 535

	AVERAGE / STANDARD DEVIATION		
	HEATING PHASE	CONSTANT RATE PHASE	FALLING RATE PHASE
Drying rate(g/m^2.s)	11.9 / 0.36	5.23 / 0.208	1.46 / 0.05
Time Duration (Sec)	12.66 / 1.52	3.33 / 0.57	15 / 1.73
Contact Coef.(W/m^2- °C)	1173.3 / 64.3	623.3 / 25.2	173.3 / 15.28

EFFECT OF BASIS WEIGHT

As the basis weight increases the web thickness increases causes the web surface dry in an earlier phase of drying because the capillary flow to keep surface saturated stops earlier. Vapor diffusion resistance and thermal resistance also become more prominent in thick webs (6). Critical moisture content (CMC) therefore increases with increasing basis weight. It explains the increasing of drying time in the constant phase with the increasing of basis weight.

Following figures from 16 to 24 show the effect of basis weight on the drying rate. The sheets used are of basis weight 45, 90 and 145 g/m^2, with refining level 535 CSF of hardwood at 120 °C.

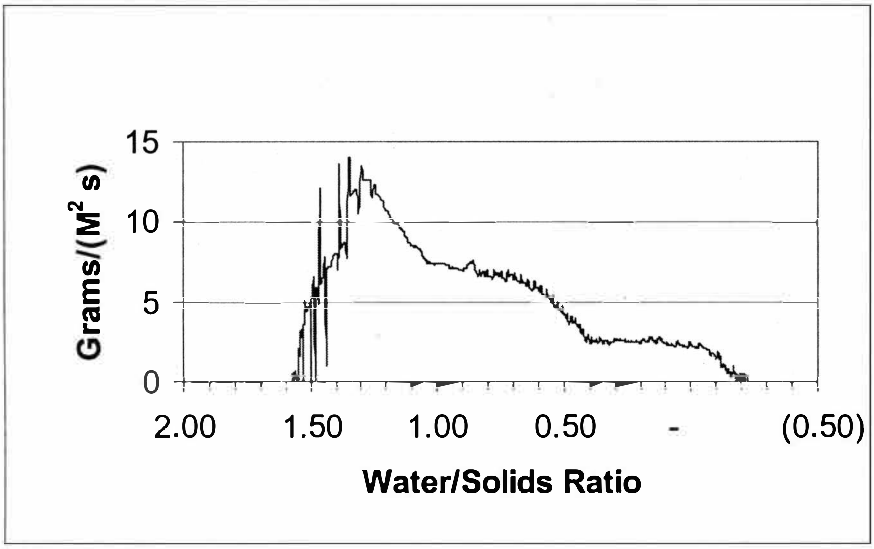

Figure 16. Drying rate versus water/solids ratio, Basis Weight 45 g/m^2, CSF 535, HW, 120 °C

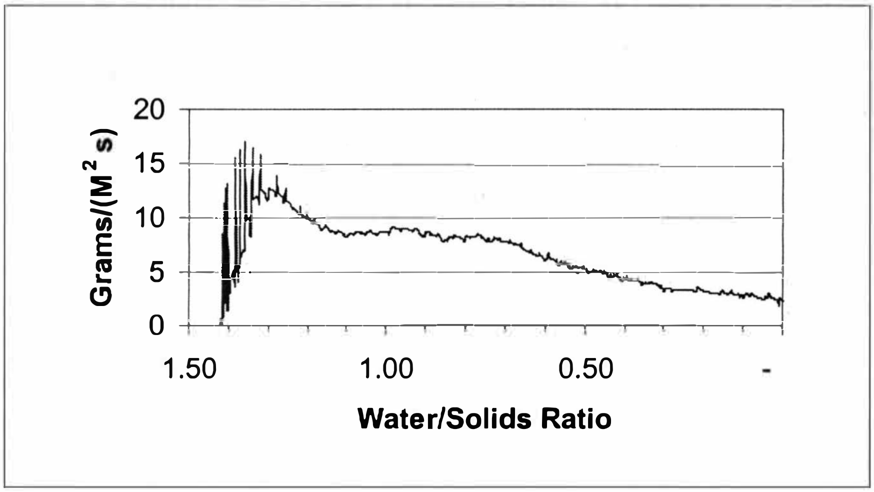

Figure 17. Drying rate versus water/solids ratio, Basis Weight 90 g/m^2, CSF 535, HW, 120 °C

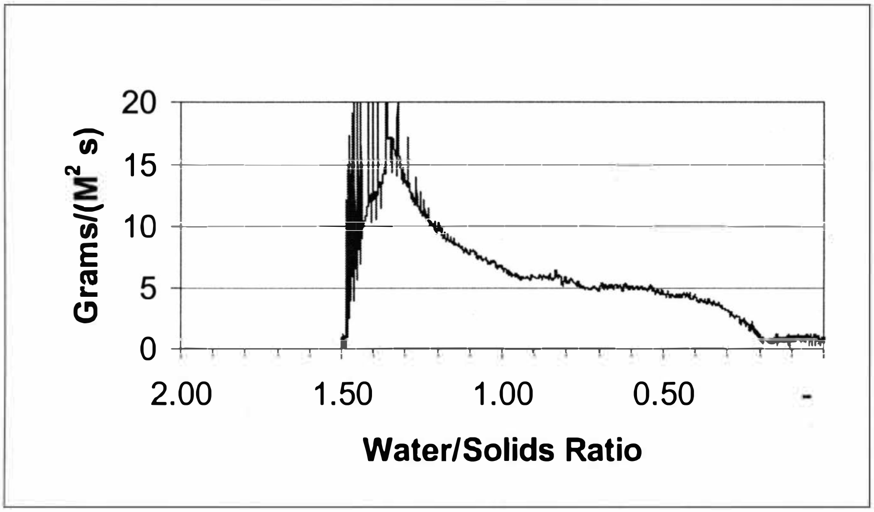

Figure 18. Drying rate versus water/solids ratio, Basis Weight 145 g/m^2, CSF 535, HW, 120 °C

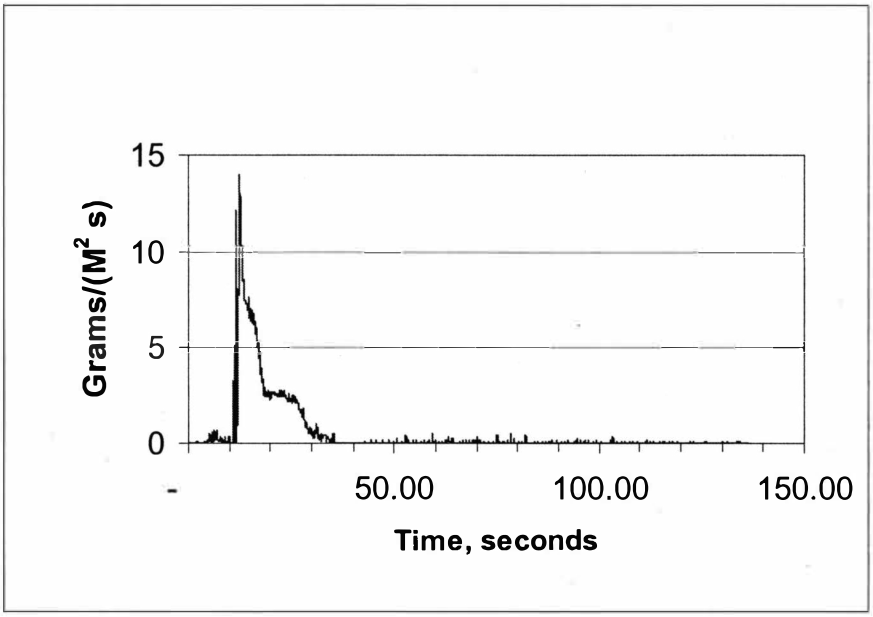

Figure 19. Drying rate versus time,

Basis Weight 45 g/m^2, CSF 535, HW, 120 °C

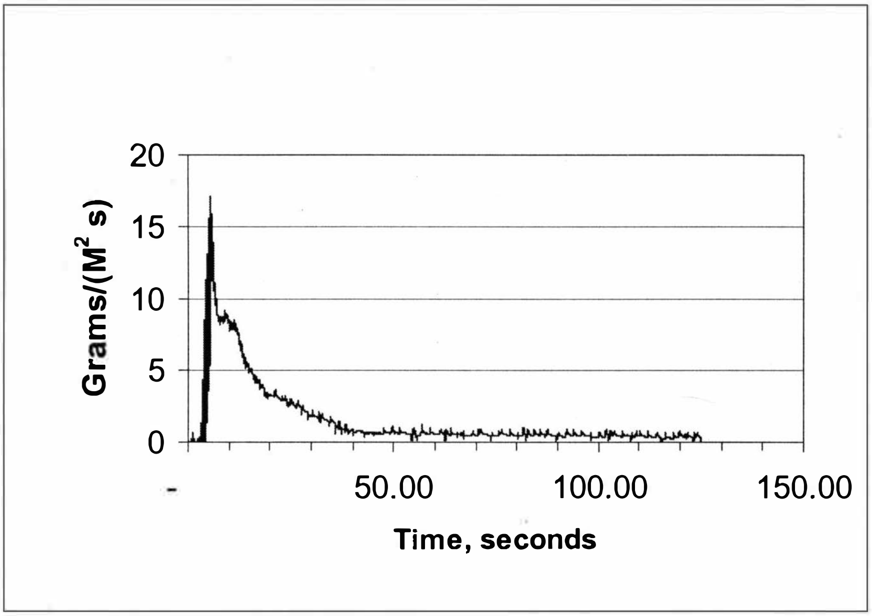

Figure 20. Drying rate versus time,

Basis Weight 90 g/m^2, CSF 535, HW, 120 °C

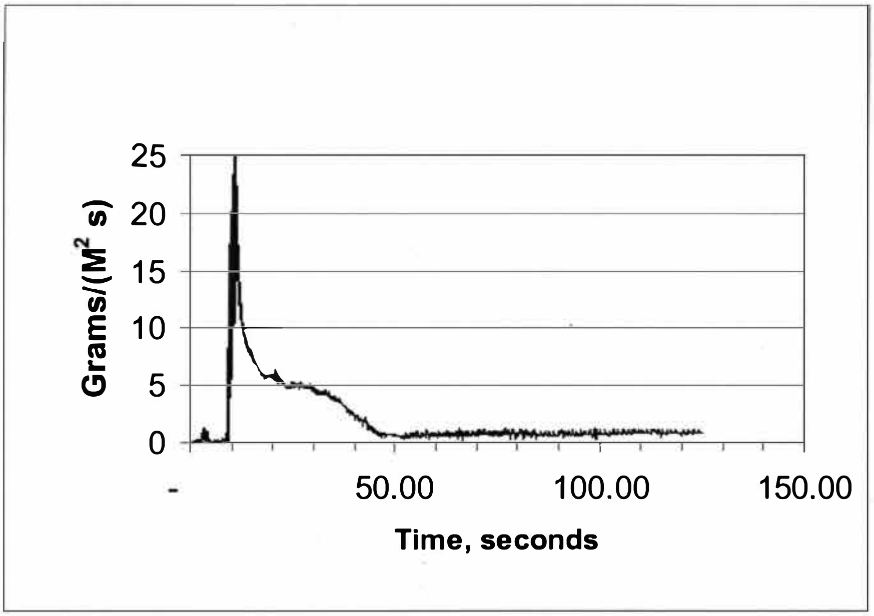

Figure 21. Drying rate versus time,

Basis Weight 145 g/m^2, CSF 535, HW, 120 °C

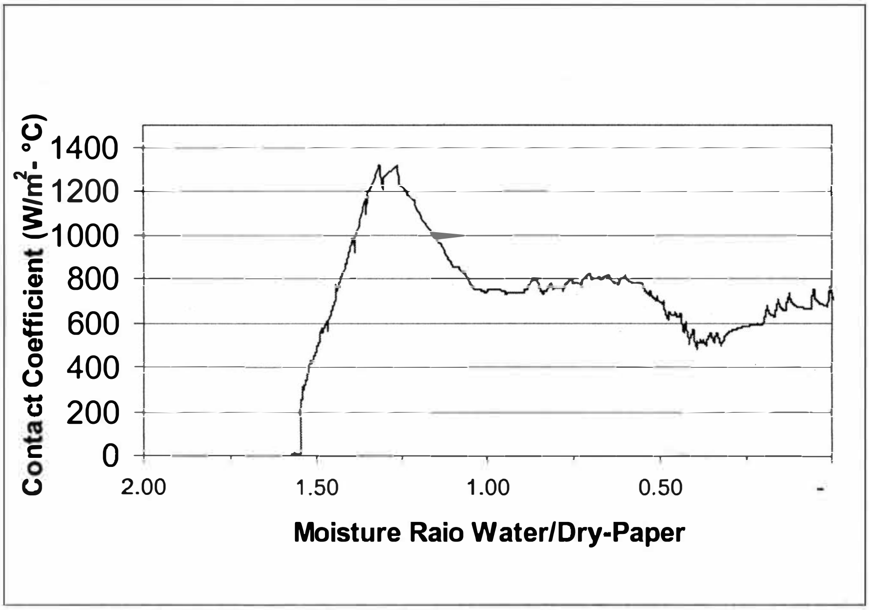

Figure 22. Paper-Shell Contact Coefficient versus Moisture ratio,

Basis Weight 45 g/m^2, CSF 535, HW, 120 °C

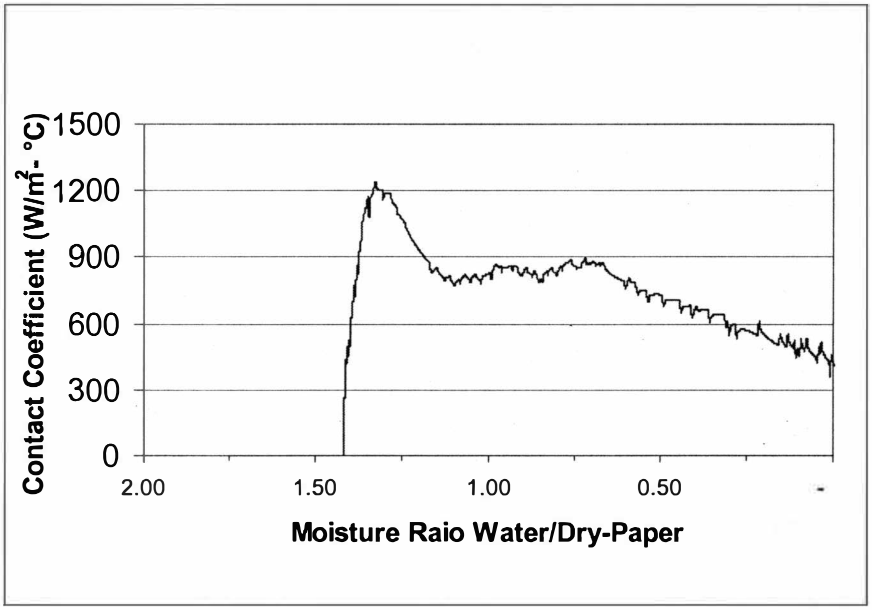

Figure 23. Paper-Shell Contact Coefficient versus Moisture ratio, Basis Weight 90 g/m^2, CSF 535, HW, 120 °C

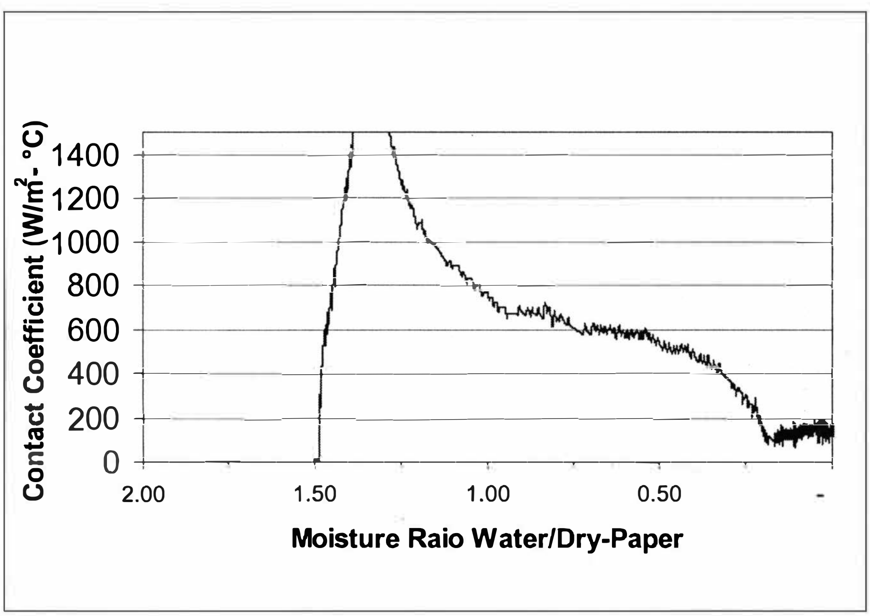

Figure 24. Paper-Shell Contact Coefficient versus Moisture ratio, Basis Weight 145 g/m^2, CSF 535, HW, 120 °C

Table 10, 13 and 16 shows the average drying rate, average drying time and average contact coefficient with standard deviation in each phase for the 90, 145 and 45 g/m^2 hardwood sheet with refining level 535 CSF. Table 17 summarizes the results from the Tables 10, 13 and 16 to observe the difference in an easier way.

Table 17. Average/Standard deviation of the drying rates, and contact coefficient for hardwood sheets of basis weight 45, 90 and 145 g/m^2 with CSF 535

		AVERAGE / STANDARD DEVIATION		
	HW Sheets CSF 535	HEATING PHASE	CONSTANT RATE PHASE	FALLING RATE PHASE
Drying rate (g/m^2.s)	45 g/m^2	11.9 / 0.36	5.23 / 0.208	1.46 / 0.05
	90 g/m^2	14.42 / 0.84	4.686 / 0.488	1.22 / 0.1
	145 g/m^2	17.66 / 0.57	5.23 / 0.25	2.06 / 0.25
Contact Coef. (W/m^2- °C)	45 g/m^2	1173.3 / 64.3	623.3 / 25.2	223.3 / 15.28
	90 g/m^2	1294.3 / 128.6	612.1 / 111.4	147.9 / 27.7
	145 g/m^2	1480 / 52.8	513.3 / 35.1	195 / 27.8

Effect Of Basis Weight In The Heating Phase

During the heating phase, the temperature of the paper web increases to the level of adiabatic saturation. Drying rate also increases in the heating phase and goes up to the maximum level. The effect of basis weight on the drying rate is very distinct in this phase, as for the 45 g/m^2; the average maximum drying rate is 11.99 g/m^{2}s with the standard deviation of 0.36, for the 90 g/m^2 hardwood sheet with CSF 535 is 14.43 g/m^{2}s with standard deviation of 0.83 and for the 145 g/m^2 hardwood sheet with 535 CSF is 17.66 g/m^2 s with standard deviation of 0.57. It is clearly understood that as the basis weight increases, the maximum drying rate increases and the effect is also shown in the figures 16, 17 and 18.

The drying time measured in this phase is around same for the three sheets. As average drying times / standard deviation in the heating phase, measured for 45, 90, and 145 g/m^2 hardwood sheets with 535 CSF are 12.66/1.52, 13.86/1.21, and 13.33/0.57 seconds respectively.

The average contact coefficient in the heating phase is seems to be increases with increasing of basis weight but it was also observed the lesser value of contact coefficient than predicted. The calculated average/standard deviation of contact coefficient for the 45, 90 and 145 g/m^2 sheets are 1173.3/64.3, 1294.3/128.6 and 1480/52.9 W/m^2- °C respectively. Figures 22, 23 and 24 shows the graphs of paper-shell contact coefficient versus moisture ratio.

Effect Of Basis Weight In The Constant Drying Phase

In this phase the drying rates measured for the 45, 90 and 145 g/m^2 hardwood sheets are very much same as it is remained between 4 and 5 g/m^2 s for the sheets. The main affected property is the drying time in this phase due to increasing of CMC with increasing of basis weight. The average/standard deviation of the drying times in this phase for 45, 90, and 145 g/m^2 hardwood sheets with 535 CSF, are 3.33/0.57, 16.57/1.78, and 21.66/0.57 seconds respectively. As most of the moisture is removed in this phase, it is very much clear that by increasing of basis weight, the drying time in the constant heating phase is increased. The average contact coefficients for the sheets, measured in this phase remained between 500 and 700 W/m^2- °C.

Effect Of Basis Weight In The Falling Rate Phase

In this phase the drying rates for the 45, 90, and 145 g/m^2 hardwood sheets, fall from 5 g/m^2 s to 0 g/m^2 s. It was observed the drying time increases when basis weight goes high from 45 to 90 g/m^2 but further increasing from 90 to 145 g/m^2 does not have any effect on drying time in this phase. The drying time observed for this phase was between 15 to 26 seconds. The value of contact coefficient also comes from 500 W/m^2- °C to 0 for the same sheets. So the effect of basis weight in this phase is not very distinct as only drying time increases for the 90 g/m^2 sheet.

EFFECT OF REFINING LEVEL

Figures 25 to 32 show the effect of refining on drying behavior for 90 g/m^2 and 145 g/m^2 HW sheets. The sheets were refined from 535 CSF to 275 CSF. The first region is reduced by refining, where the rapid evaporation takes place when the sheet first contacts the dryer and also appears to increase the fourth (or bound water region).

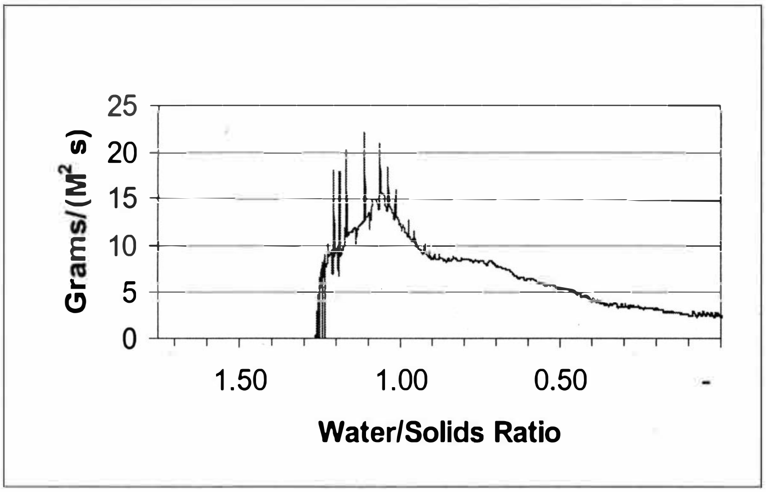

Figure 25. Drying rate versus water/solids ratio, BW 90 g/m^2, CSF 535, HW

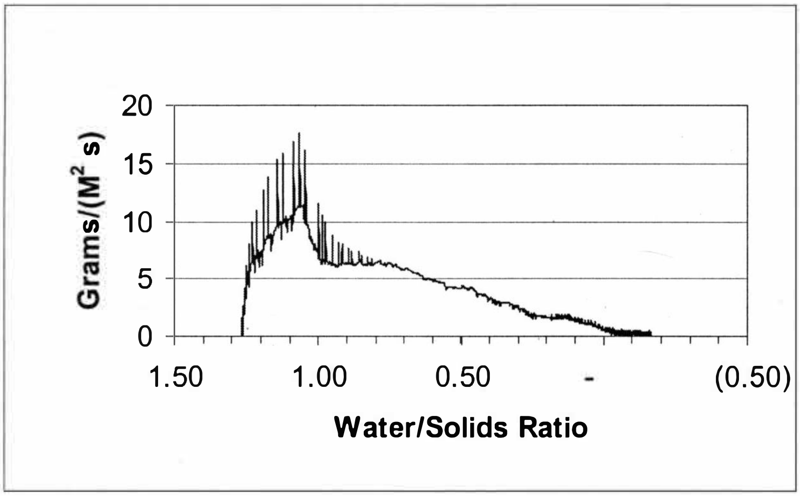

Figure 26. Drying rate versus water/solids ratio, BW 90 g/m^2, CSF 275, HW

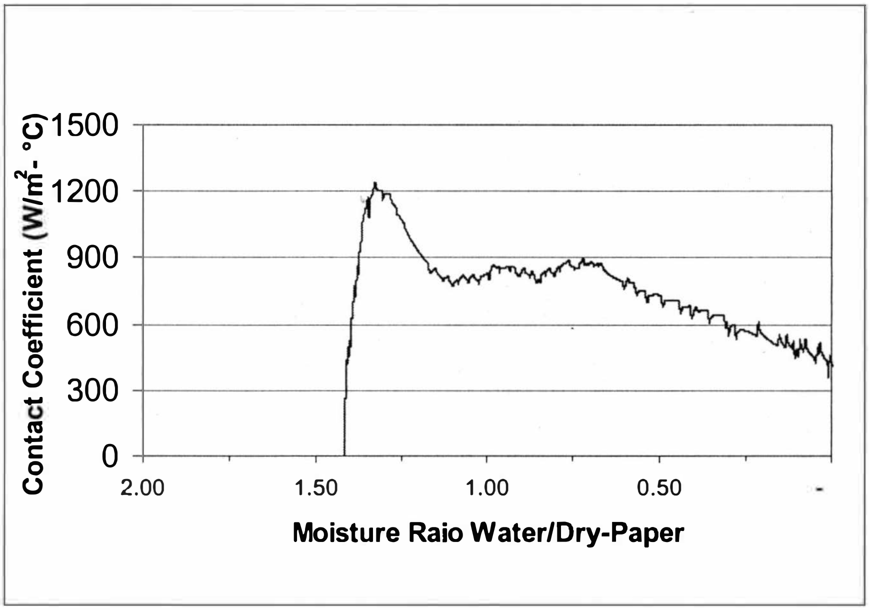

Figure 27. Paper-Shell Contact Coefficient versus Moisture ratio, Basis Weight 90 g/m^2, CSF 535, HW

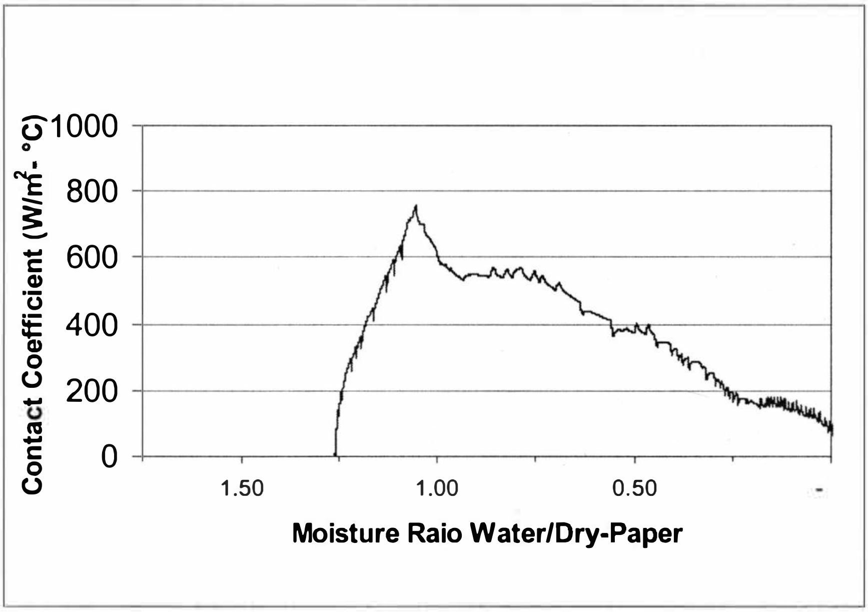

Figure 28. Paper-Shell Contact Coefficient versus Moisture ratio, Basis Weight 90 g/m^2, CSF 275, HW, 120 °C

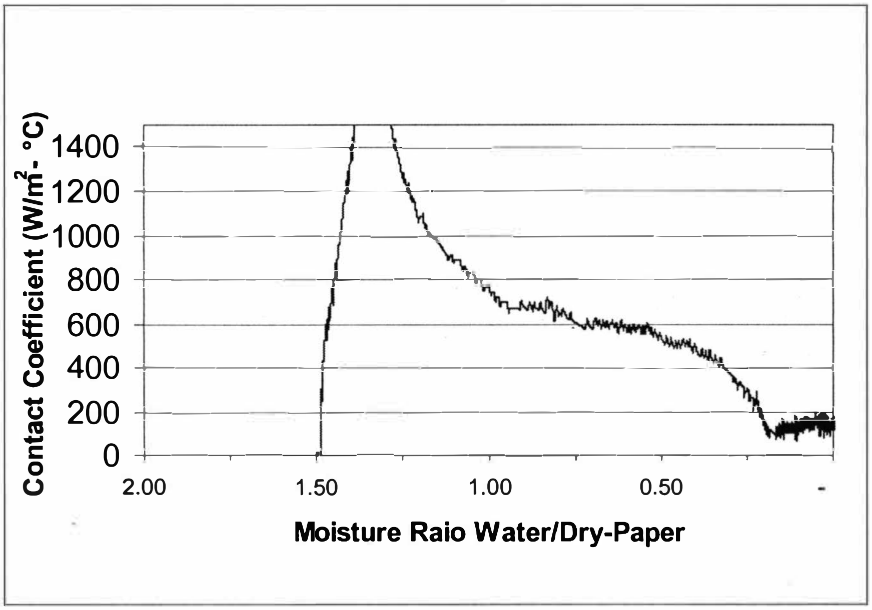

Figure 29. Paper-Shell Contact Coefficient versus Moisture ratio, Basis Weight 145 g/m², CSF 535, HW, 120 °C

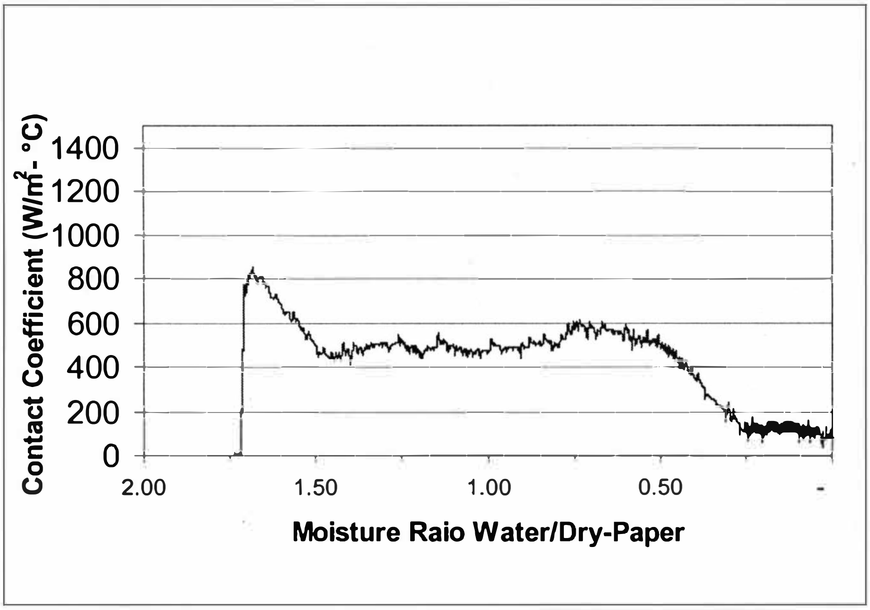

Figure 30. Paper-Shell Contact Coefficient versus Moisture ratio, Basis Weight 145 g/m², CSF 275, HW, 120 °C

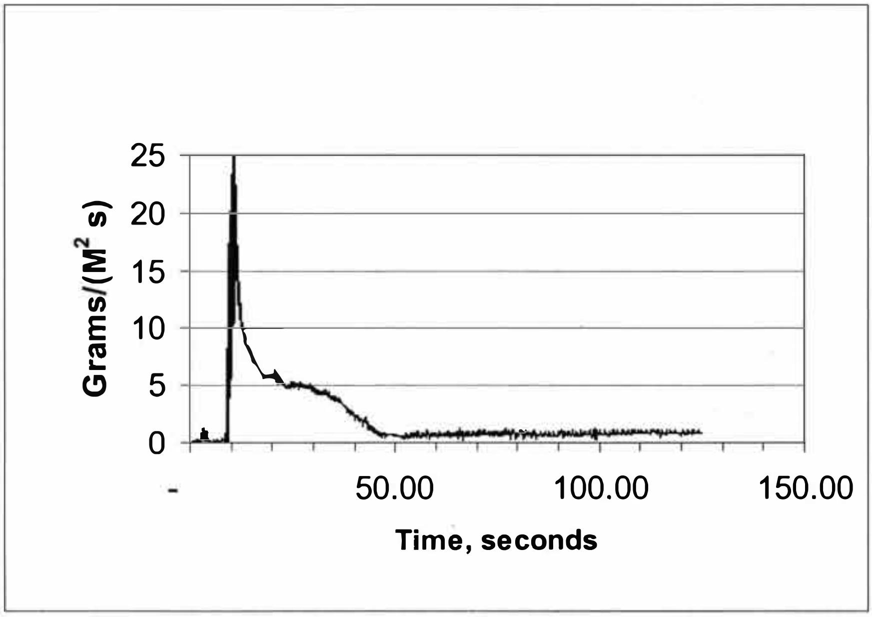

Figure 31. Drying rate versus time, Basis Weight 145 g/m^2, CSF 535, HW, 120 °C

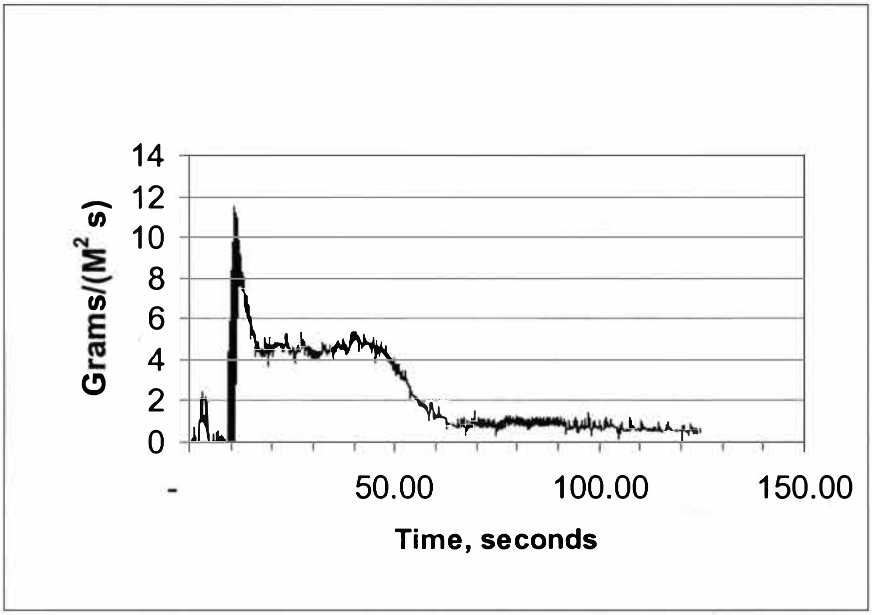

Figure 32. Drying rate versus time Basis Weight 145 g/m^2, CSF 275, HW, 120 °C

With increased refining level, less drying occurs in the initial drying phase and more in later phases. The constant drying area appears to last for a shorter period of time and the shift to the bound water section tends to occur at a later time. The total time consumed for the drying of the sheet increases slightly with the increasing refining for the 145 g/m^2 but remained around same for the 90 g/m^2. The table 18 summarizes the results for hardwood sheets with different refining level.

Table 18. Average / Standard deviation of the drying rates and contact coefficient for hardwood sheets of basis weight 90 and 145 g/m^2 with CSF 535 and 275

		AVERAGE / STANDARD DEVIATION		
	HW Sheets	HEATING PHASE	CONSTANT RATE PHASE	FALLING RATE PHASE
Drying rate (g/m^2.s)	90 g/m^2, 535 CSF	14.42 / 0.84	4.686 / 0.488	1.22 / 0.1
	90 g/m^2, 275 CSF	12.1 / 0.8	5.175 / 0.925	1.763 / 0.25
	145 g/m^2, 535 CSF	17.66 / 0.57	5.23 / 0.25	2.06 / 0.25
	145 g/m^2, 275 CSF	14.66 / 0.57	4.73 / 0.67	2.16 / 0.11
Contact Coef. (W/m^2- °C)	90 g/m^2, 535 CSF	1294.3/128.6	612.1/111.4	147.9 / 27.7
	90 g/m^2, 275 CSF	847.5 / 118.7	460/46.9	114.7 / 34.5
	145 g/m^2, 535 CSF	1480 / 52.8	513.3/35.1	195 / 27.8
	145 g/m^2, 275 CSF	1096.7 / 85.1	513 / 11.55	257 / 15.72

Effect Of Refining Level In The Heating Phase

As mentioned in Table 18 and also shown in figures 25 to 32, the effect of refining level is clearly noticed on the drying rate in the heating phase. The maximum drying rate goes down from 14.30 g/m^2 s to 12 g/m^2 s for the 90 g/m^2 hardwood sheets with the refining level changes from 535 to 275 CSF. Figures 31 and 32 show the maximum drying rate for the 145 g/m^2 sheets with 535 and 275 CSF are 17.5 g/m^2 s and 14.7 g/m^2 s respectively. Figures show the effect of refining level on the drying rate and on the contact coefficient elapsed for the 90 g/m^2 and 145 g/m^2 sheets.

The effect of refining level on the contact coefficient is also very much distinct. In this phase, maximum contact coefficient measured for 90 g/m^2 sheets with 535 and 275 CSF are 1290 W/m^2- °C and 847 W/m^2- °C respectively and for 145 g/m^2 sheets with 535 and 275 CSF, the maximum contact coefficient measured are 1490 W/m^2- °C and 1100 W/m^2- °C respectively.

Effect Of Refining Level In The Constant Drying Phase

In this phase the drying rates measured for 90 g/m^2 hardwood sheets with 535 CSF and 275 CSF were around same, between 4 and 6 g/m^2 s but remain constant for more time for the sheets of more refining level. Drying time increased very slightly with the refining level in this phase. With more refining level, less drying occurs in the first phase and most of the drying take place in the later phases. The values of contact coefficient remained around same for the sheets of different refining level, measured between 500 to 600 W/m^2- °C.

Effect Of Refining Level In The Falling Rate Phase

In this phase the drying rates increases slightly with the increasing of refining level for the 90 and 145 g/m^2 hardwood sheets, measured between 1 g/m^2s to 2 g/m^2s. The drying time for this phase was observed similar for the sheets with refining level. The value of contact coefficient was more for the sheets with 275 CSF than sheets with 535 CSF of 145 g/m^2 but it was around same for 90 g/m^2 sheets.

EFFECT OF HARDWOOD VERSUS SOFTWOOD

Figures 33 to 38 show the effect for hardwood and softwood pulps on various drying properties. These pulps were refined to around 520 and 260 CSF and made into around 90 g/m^2 sheets.

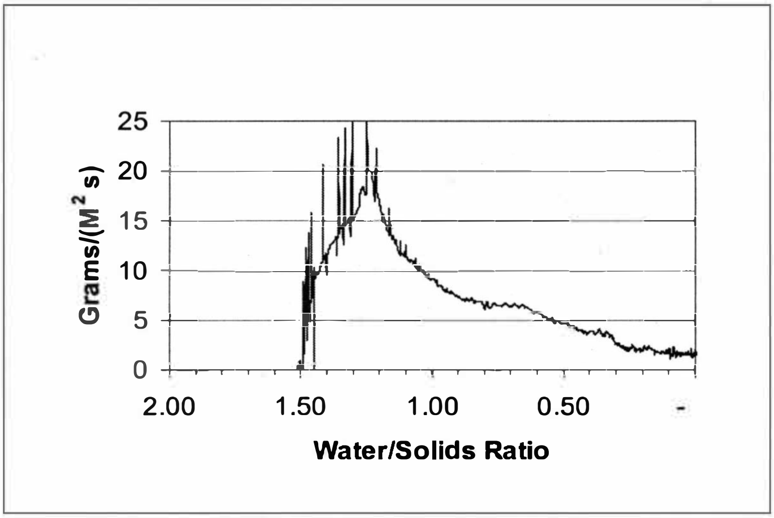

Figure 33. Drying rate versus water/solids ratio, BW 95 g/m^2, CSF 510, SW

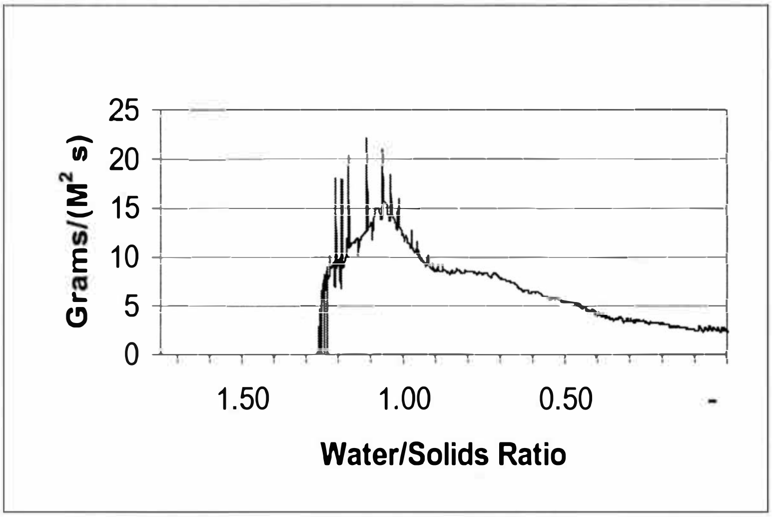

Figure 34. Drying rate versus water/solids ratio, BW 90 g/m^2, CSF 535, HW

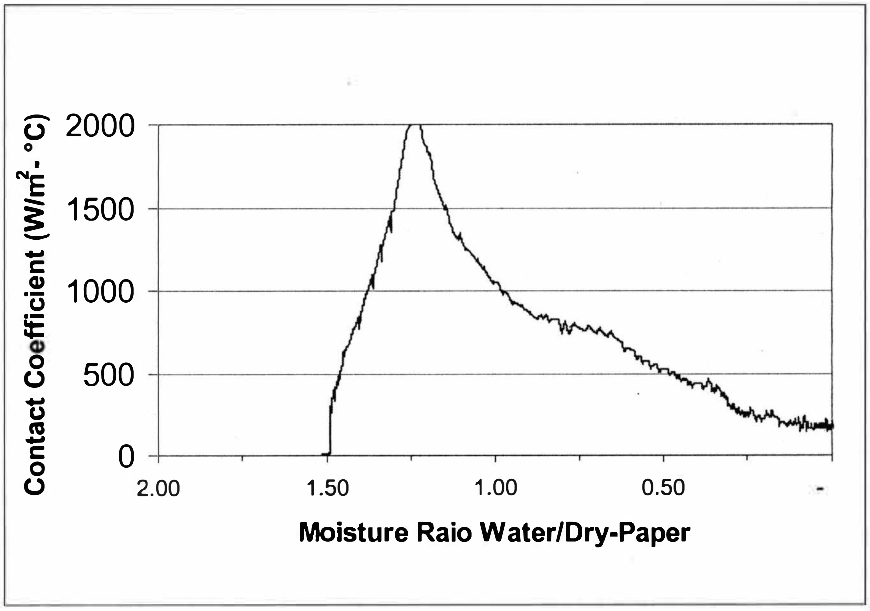

Figure 35. Paper-Shell Contact Coefficient versus Moisture ratio, Basis Weight 95 g/m^2, CSF 510, SW

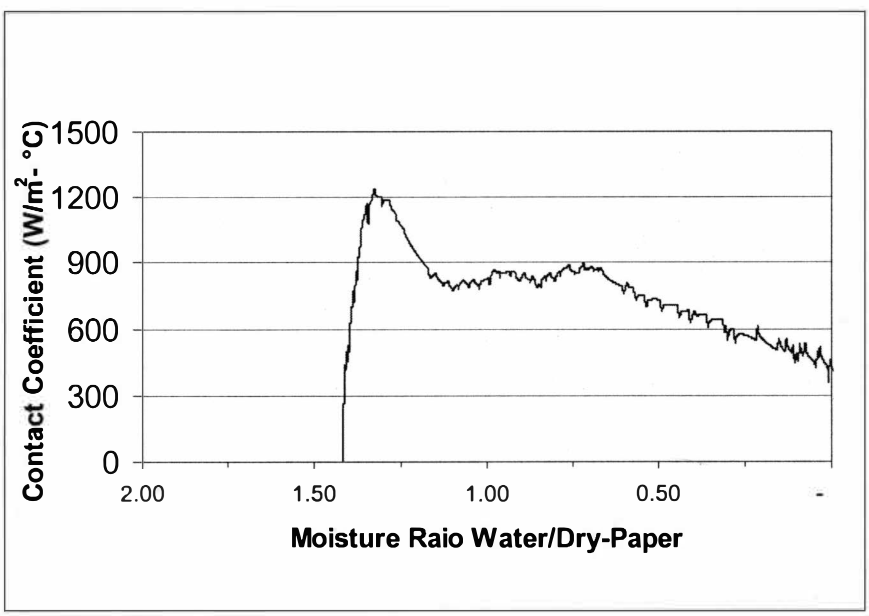

Figure 36. Paper-Shell Contact Coefficient versus Moisture ratio, Basis Weight 90 g/m^2, CSF 535, HW

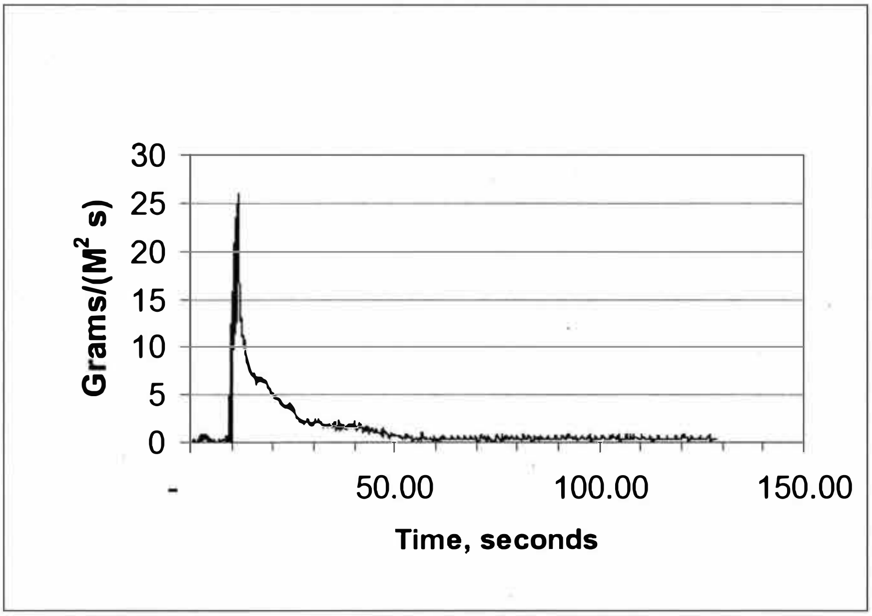

Figure 37. Drying rate versus time, Basis Weight 95 g/m^2, CSF 510, SW

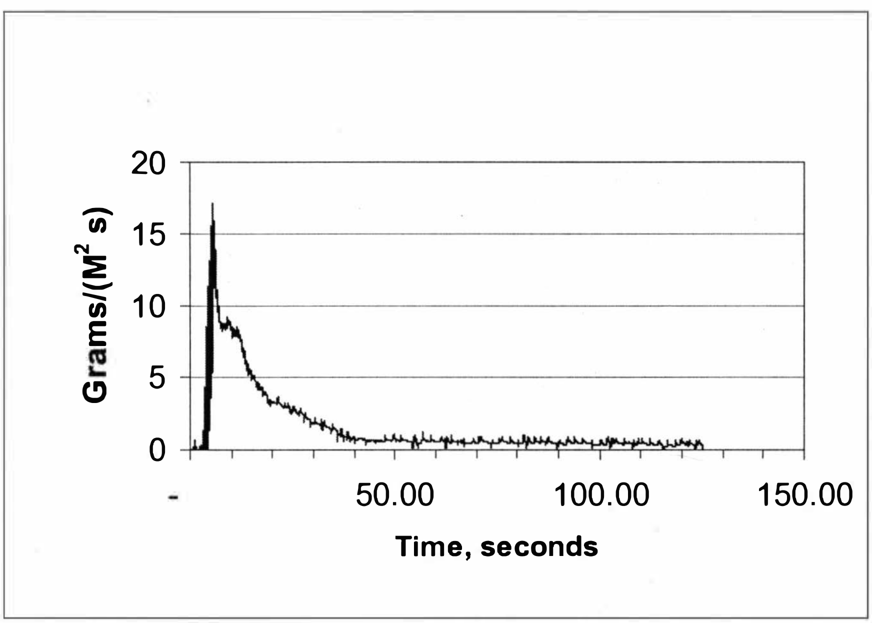

Figure 38. Drying rate versus time, Basis Weight 90 g/m^2, CSF 535, HW, 120 °C

The effect of softwood versus hardwood seems to be very similar to that of refining. The softwood sheet dries very rapidly in the initial phase when the moisture ratio is high and the later phase dries very slowly so contributes a little to the overall drying.

Table 19. The observed drying rates and contact coefficient for each phase for the sheets of 90 g/m^2 with refining level around 500 and 260 of both hardwood and softwood pulp.

		AVERAGE / STANDARD DEVIATION		
	90 g/m^2 Sheets	HEATING PHASE	CONSTANT RATE PHASE	FALLING RATE PHASE
Drying rate (g/m^2.s)	HW, 535 csf	14.42 / 0.84	4.68 / 0.48	1.22 / 0.1
	SW, 510 csf	21.66 / 1.15	4.93 / 0.20	1.36 / 0.05
	HW 260 csf	12.05 / 1.256	5.17 / 0.92	1.763 / 0.25
	SW, 258 csf	15.33 / 1.52	4.9 / 1.3	2.2 / 0.3
Contact Coef. (W/m^2- °C)	HW, 535 csf	1294.3 / 128.6	612.1 / 111.4	147.9 / 27.7
	SW, 510 csf	1940 / 65	506 / 27.5	135 / 5.0
	HW 260 csf	847.5 / 118.7	460 / 46.9	114.7 / 34.5
	SW, 258 csf	1420.1 / 72.1	548.3 / 44.8	166.7 / 47.3

Above table and figures show the effect of HW or SW on the drying rate and total drying time elapsed for the 90 g/m^2 sheets. As figures 33 and 34 shows the maximum drying rate for the 90 g/m^2 SW sheet and for the 90 g/m^2 HW sheet, are around 22 $g/m^2.s$ and 14 $g/m^2.s$, the calculated average/standard deviation of the drying rate are 21.66/1.15 and 14.42/0.84 $g/m^2.s$ respectively for the heating phase. Maximum contact coefficient measured for the 90 g/m^2 SW sheet was 2000 W/m^2- °C and for the 90 g/m^2 HW sheet was 1200 W/m^2- °C.

It can be observed from the table 19 that from changing the pulp from hardwood to softwood the drying rate and the contact coefficient goes very high but the drying time remains almost same in the first phase.

For the constant rate phase and the falling rate phase the drying rate and the contact coefficient were in the same range but the drying time was observed more for the softwood sheets than the hardwood sheets.

CHAPTER VI

CONCLUSIONS

Using JMP software developed by SAS INSTITUTE INC., Gary, NJ, presented in the Appendix C performed the statistical analysis on the various data obtained by experimental work.

The Statistical analysis is based on linear model. The assumed true model for a typical observation, y_i is

$$y_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4$$

Where

y_i is the response (drying rate, contact coefficients)

x_i functions of the data (basis wt, refining level, hw/sw, initial moisture content)

β_j are unknown parameter to be estimated

i indexes the observation

Response variables are the drying rates and the contact coefficients in the heating phase, constant phase and falling rate phase. They were observed from the results, got from the experimental work.

Functions are the basis weight, refining level, fiber (hardwood or softwood) and the initial moisture content.

Based on statistical analysis the following conclusions can be drawn:

1. In the Heating phase, the drying rate and the contact coefficient between the paper web and metal shell were significantly affected by the basis weight of the sheet. This is supported by the linear model which shows that drying rate and contact

coefficient are dependent on the basis weight in this phase with F ratio of 39.89 and 20.37 and prob>F of 0.0001 and 0.0002 respectively.

2. In the Heating phase, the refining level of the sheet significantly affected the drying rate and the contact coefficient between the paper web and metal shell. This is supported by the linear model, which shows that drying rate and contact coefficient are dependent on the refining level in this phase.
3. The drying rate and the contact coefficient between the paper web and metal shell are also clearly affected by the fiber type (HW/SW) in the heating phase; this is also proved by the statistical analysis.
4. The initial moisture content in the sheet did not statistically affect the drying rate or the contact coefficient.
5. In the constant rate phase, none of the direct variables (basis weight, refining level, type of wood and initial moisture content) affected either the drying rate or the contact coefficient significantly.
6. In the falling rate phase, the direct variables (basis weight, refining level, type of wood and initial moisture content) have no significant effect either on the drying rate or on the contact coefficient.
7. Statistical analysis also shows that in the falling rate phase, the drying rate and the contact coefficient were affected by the initial moisture content variable. This is difficult to understand why the drying rate and contact coefficient were increased in the later phase with initial moisture content.

CHAPTER VII

RECOMMENDATIONS FOR FURTHER STUDY

The following areas are recommended for future work on this study:

1. In the falling rate phase, the effect of initial moisture content on the drying rate and contact coefficient were unpredicted as they increased with increasing of initial moisture content, further study is needed to understand this behavior.

2. The effect of initial shell temperature and the pressure applied on the paper web can be significant on the drying rate and the contact coefficient.

3. The drying fabric tension can be another variable which can affect the drying behavior.

4. There can be more experimental work with the different refining level as the all results were not in the manner as expected. The drying time should be high when the sheets are more refined but was not as the statistical analysis suggests.

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APPENDICES

APPENDIX A

EQUIPMENT

EQUIPMENT

Thermocouple: Type E thermocouples from Modtherm Corporation, PO 412, Huntsville, AL 35804.

TC-E0802GZ 0.002 inserted into paper

TC-E0803GZ 0.003 inserted into steel shell

Data Acquisition Board: CIO-DAS-TC, ASI version from ComputerBoards, Inc. 16 Commerce Blvd, Middleboro, A 02346, note PCI version of this board is not suitable.

APPENDIX B

DATA ACQUISITION AND ANALYSIS PROGRAM

DATA ACQUISITION AND ANALYSIS PROGRAM

The data acquisition and analysis program is based on the Explicit method of Heat Transfer Analysis. One of the features of this program is the calculation of the Fourier number Fo = alpha * dt/dx^2). Here alpha is the thermal and is equal to $k/\rho C_p$, k is the thermal conductivity, ρ is the density and C_p is the heat capacity. For the Explicit method to be stable, it must be less than ½. The value of the Fourier is calculated and shown by the program.

The program is shown below.

Program:

```
Sub GetTemperature()
Dim Temparray() As Single
Const max As Integer = 10000 'number of data points'
Const nodes as Integer = 25 'number of nodes in shell' Calculated based on Basis Weight
HFlos = 165 'Energy lost due to heating fabric'
HPC = 1#  'Fraction of heat transfer to paper used for drying
Dim Fo As Single
Dim k As Single
Dim dt As Single
Dim dx As Single
Dim x As Single
Dim Cp As Single
Dim thi As Single
Dim tsi As Single
Dim TimeStart As Single
```

```
Dim TimeEnd As Single
Dim u As Integer
Dim v As Integer
Dim t As Single
Dim rho As Single
Dim alpha As Single
Dim step As Single
Dim i As Integer
Dim j As Integer
Dim Jave As Integer
Dim n As Integer
Dim Temp As Single
Dim TimeII As Single
Dim count As Integer
Dim Tem(1 To max, 1 To 4)
Dim Htem (1 To max, 1 To 11)
Dim Array1 (1 To max, 1 To 4) As Single
Dim sum1 As Single
Dim sum2 As Single
ReDim Temparray (1 To max, 1 to 4)
Dim Temp2() As Single
Dim Qflux (1 To (max + 10), 3) As Single
Dim q As Single
Dim TemA (max + 1, nodes) As Single
Dim Temp1 (nodes, max +1) As Single
```

```
Dim dweight As Single
Dim wweight As Single
Dim area As Single
Dim DR As Single
n = nodes
'initialize board
        ProgStat% = cbTIn (0, 0, Celsius, TempI, FILTER)
        ProgStat% = cbTIn (0, 1, Celsius, TempII, FILTER)
        ProgStat% = cbTIn (0, 2, Celsius, TempIII, FILTER)
'set initial time and measure temperature
'Temperature TempI          = Heater
'Temperature TempII         = Shell
'Temperature TempIII        = Paper
TimeStart      = Timer
        For count =1 To max Step 1
        ProgStat% = cbTIn (0, 0, Celsius, TempI, FILTER)
        ProgStat% = cbTIn (0, 1, Celsius, TempII, FILTER)
        ProgStat% = cbTIn (0, 2, Celsius, TempIII, FILTER)
        Temparray (count, 1) = TempI
        Temparray (count, 2) = TempII
        Temparray (count, 4) = TempIII
Next count
TimeEnd = Timer
'Start Heat flux routine here'
Set Boundary conditions at first data point
```

```
tsi = Temparray (1,2)
thi = Temparray (1,1)
'calculate delta time
t = (TimeEnd – TimeStart)
dt = t/max
'Calculate Constants
ktemp = 273.15 + (tsi +thi) /2
k = 14.9 + 0.017 * (ktemp – 300.001) 'stainless 304'
rho = 7900
Cp = 477 +0.38 * (ktemp – 300.001)
x = 0.0127
dx = x/ (n-1)
alpha = k/(rho *Cp)
'check constants
        Fo = alpha * dt / dx^2
        MsgBox Fo,, "Fo must be less than 0.5"
'Create Time Array
        For i = 1 To max
        Temparray( i, 3) = i *dt
        Next i
'average temperatures
        For i = 1 To 10
        Tem (i, 1) = Temparray (i, 1)
        Tem (i, 2) = Temparray (i, 2)
        Tem (i, 3) = Temparray (i, 3)
```

```
        Tem (i, 4) = Temparray (i, 4)
        Next i
        For I =11 to max -11
        For j = -5 To 5
        Tem (i, 1) = Temparray (i +j, 1) / 11 + Tem (i, 1)
        Tem (i, 2) = Temparray (i +j, 2) / 11 + Tem (i, 2)
        Tem (i, 3) = Temparray (i +j, 3) / 11 + Tem (i, 3)
        Tem (i, 4) = Temparray (i +j, 4) / 11 + Tem (i, 4)
        Next j
        Next i
'Write temperature and time data to spread sheet
        Worksheets("sheet1"). Select
        With Range ("c15:f10015)
.Value = Tem
End with
'Set initial conditions
'Dimensions as distance and time
        TemA (1, 1) = tsi
        Step = (thi – tsi) /(n-1)
        For i = 1 To n-1
        TemA ( 1, i +1) = tsi + i * step
        Next i
        Determine Temp distribution in plate at each time t = p*dt(p>1)
        'use thermocouples readings to get the temp at the front and
        'back surfaces. Use numerical techniques to determine internal
```

```
        'Temp distribution. Calculate heat flux and store in array'
'Set Boundary Conditions
        For i = 1 To (max -1)
        TemA (i, 1) = Tem(i + 1, 2)
        TemA (i, n) = Tem(i + 1, 1)
        Next i
For i = 1 To (max -1)
 For j = 2 To n-1
  TemA ( i +1, j) = (Fo * (TemA (i, j -1) + TemA(i, j + 1))) + ((1 -2 * Fo) *
TemA(i,j))
 Next j
Next i
For i = 1 To max -2
' heat flux
        Qflux (i, 1) = 1* k*(TemA (i, 2) – TemA (i, 1))/ dx
' heat flux including temperature change
Qflux (i, 2) = -1 * ((rho * dx * Cp) / (2* dt) * (TemA (i +1, 1) – TemA (i, 1))) + Qflux (i, 1)


'Total heat transferred w/m2
        Qflux(i + 1, 3) = Qflux (i, 2) *dt + Qflux(i, 3)
  Next i
' Write heat fluxes to worksheet Qflux is basic heat flux, Qflux2 = is corrected heat
flux, and Qflux3 is total energy transferred
  Worksheets ("sheet1"). Select
```

```
 With Range ("z14:ax10015")
         .Value = TemA
End With
With Range ("g14:i10014")
  .Value = Qflux
End With

'Calculation of Paper Shell contact Coefficient
'Entering Sheet Data
"Input the date
'Input the run number
         Temp = InputBox ("Enter run number as #")
         rnumber = CSng (Temp)
'Input the wet weight of the paper
         Temp = InputBox ("Enter the weight of wet paper in grams")
         wweight = CSng (Temp)
         iwweight = wweight
'Input the dry weight of the paper
         Temp = InputBox ("Enter the weight of dry paper in grams")
         Dweight = Csng (Temp)
'Input the sheet area
         Temp = InputBox ("Enter the area of the paper in sq meters")
         area = CSng (Temp)
Range ("a2") = "run number"
Range ("a2").Value = rnumber
```

```
Range (“b2”) = “DATE”
Range (“b3”) = Date
Range (“c2”) = “wet weight”
Range (“c3”).Value = wweight
Range (“d2”) = “dry weight”
Range (“d3”).Value = dweight
Range (“e2”) = “area”
Range (“e3”).Value = area
Bweight = dweight / area
Range (“f2”) = “Basis Weight g/m2”
Range (“f3”).Value = Bweight
‘ Input Target Basis weight
Temp = InputBox (“Enter target basis weight”)
TBW = CSng (Temp)
Range (“f5).Value = TBW
“Input CSF
Temp = InputBox (“Enter the refining level in CSF”)
CSF = CSng (Temp)
Range (“g2”) = “CSF”
Range (“g3”).Value = CSF
‘Input Fiber Type
Temp = InputBox (“Enter the fiber type 1 =HW, 2=SW”)
Fiber = CSng(Temp)
Range (“h2”) = “Fiber Type, HW =1 and SW =2”
Range (“h3”) = Fiber
```

```
For i =2 To max -1
If (Tem (i, 2) - Tem (i, 4)) = 0 # Then
Htem (i, 1) = 0#
Else: Htem( i, 1) = Qflux( i, 2) / Tem (i, 2) - Tem (i, 2) + 0.00000000001)
End If
'Calculation of Sheet Moisture Content
Hlos = -0.06732 * TBW + 15.35
Htem (i, 2) = (wweight – dweight) / dweight
dryR = (((( HPC * Qflux(i, 2) – Hlos * Tem(i, 4)) * dt – Hflos * (Tem (i, 4) – Tem(i -1,4))) *
area) – (dweight * (1.33 + Htem (i, 2) * 4.184) * (Tem(i, 4) – Tem(i -1,4)))) / 2508 – 2.45 *
Tem(i,4))
If dryR < 0 # Then dryR = 0#
        Wweight = wweight – dryR
        Htem (i, 3) = dryR / (dt * area)
'Htem (i, 3) g/m2
'

'Paper Balance
' Paper Balance Based on Calculated Heat Flux and Temperature of Paper
 Htem (i, 4) = ((dweight * (1.33 + Htem (i, 2) * 4.184)) * (Tem (i, 4) – Tem (i – 1, 4))
 +    dryR * (2508 – 2.45 * (Tem(i, 4))) / area
 Htem (i, 5) = Htem (i – 1, 5) + Htem (i, 4)
' Paper Balance based on wet and dry weights and temperature of the paper
' Assume that the vaporization occurs at 295 K and the vapor leaves at paper
temperature
```

```
 Htem (i, 6) = (((Tem (i, 4) – Tem(1, 4)) * (dweight * 1.33) + (iwweight – dweight) *
2449 + ((wweight – dweight) * (Tem (i, 4) – Tem (1, 4)) * 2.09))) / area
'Energy Balances
'Steel Balance
' Htem (i, 7) = 0.0127 * 7900 * 477 * (TemA (11, 1) + TemA (11, 2) – TemA(i, 1) –
TemA (i, 2)) /2#


'Ratios
' Paper (Htem (i, 9), Htem (i, 10) and steel Htem (i, 11))
Htem (i, 9) = Htem (i, 5) / Qflux (i, 3) + 10^-20)
Htem (i, 10) = Htem (i, 6) / (Qflux (i, 3) + 10^-20)
Htem (i, 11) = Htem (i, 7) / Qflux (i, 3) + 10^-20 )
Next i
'write data
 With Range ("K15:u10015")
 .Value = Htem
 End With
End Sub
```

APPENDIX C

STATISTICAL ANALYSIS

The JMP software developed by SAS Institute Inc., Gary NC, was used for doing statistical analysis. The results obtained from the experiments were entered and then the analysis was performed.

To begin a statistical analysis, 3 steps were followed.

1. Assigned modeling types (Continuous, Ordinal and Nominal) to data table columns. For Continuous columns, the numeric value is used directly. An ordinal value is not used directly, but only as a name. For the nominal type, the values are treated as unordered categories, or names.
2. Selected columns to play variable roles. X or Y roles can be chosen for the variable in the analysis depending upon the treatment by JMP. A column assigned the role of Y is a response or dependent variable. An X column is a factor variable that fits, predicts, or groups a response.
3. Launched an analysis platform.

A linear combination of X (As 80 -90 % responses achieved) by least squares was used to analyze the data. Continuous responses were reported with leverage plots, least squares means, contrasts and output formulas.

STATISTICAL TABLES

SUMMARY OF FIT TABLE

The Summary of Fit table shows the numeric summaries of the response for a variable. Comparing Summary of Fit tables lets you see the improvement of one model over another as indicated by a larger Rsquare value and smaller Root Mean Square Error.

Rsquare:

Rsquare measures the proportion of the total variation accounted for by the model. The remaining variation is attributed to random error. Rsquare is 1 if the model fits perfectly. An Rsquare of 0 means that the fit is no better than the mean. Using quantities from the corresponding analysis of variance table, the Rsquare for any interval response fit is always calculated as:

Rsquare = Sum of squares for model / Sum of squares for C total

Rsquare Adj:

Rsquare Adj adjusts Rsquare to make it more comparable over models with different numbers of parameters by using the degrees of freedom in its computation. It is a ratio of mean squares instead of sums of squares and is calculated as

Rsquare Adj = 1 – (Mean square for error / Mean square for C total)

where mean square for Error is found in the Analysis of Variance table and the mean square for C Total can be computed as the C Total sum of squares divided by its respective degrees of freedom.

Root Mean Square Error:

Root Mean Square Error estimates the standard deviation of the random error. It is the square root of the mean square for Error found in the corresponding Analysis of Variance table.

Mean of Response:

Mean of Response is the sample mean (arithmetic average) of the response variable. This is the predicted response when no model effects are specified.

Observations:

Observations is the number of observations used in estimating the fit. If weights are used, this is the sum of the weights.

EFFECT TESTS TABLE

The Effect Tests in the Effect Test Table are joint tests that all the parameters making up an individual effect are zero. If an effect has only one parameter, as is the case with simple regressors, then the tests are no different from the t tests in the Parameter Estimates table.

Source:

Source lists the names of the effects in the model.

NParm:

Nparm is the number of parameters associated with the effect.

DF:

DF is the degrees of freedom for the effect test. Ordinarily Nparm and DF are the same. They are different if there are linear combinations found among the regressors such that an effect cannot be tested to its fullest extent. Sometimes the DF will even be zero, indicating that no part of the effect is testable. Whenever DF is less than Nparm, the note Lost DF's appears to the right of the line in the report.

SS:

Sum of Squares is the sum of squares for the hypothesis that the listed effect is zero.

F Ratio:

F Ratio is the F statistic for testing that the effect is zero. It is formed as the ratio of the mean square for the effect divided by the mean square for Error. The mean square for the effect is the Sum of Squares for the effect divided by its degrees of freedom. In situations where a subsequent term is specified to be an error term, the mean square for this error term is used instead of Mean Square for Error as the denominator of the F Ratio. Effects designated as error terms are marked with the message {Error Effect} on the right. This specification is used in split-plot and repeated-measure models where there are different observational units for different layers of the model.

Prob > F:

Prob > F is the observed significance probability for the F Ratio. It is the probability that, given that the hypothesis is true, that a larger F statistic would occur due to random error. If the value is less than .0005, then it appears as .0000 and represents a probability that is conceptually zero.

ANALYSIS OF VARIANCE TABLE

The Analysis of Variance table partitions the total variation of a sample into components. The components are used to compute an F ratio that evaluates the effectiveness of the model. If the probability associated with the F ratio is small, then the model is considered a better statistical fit for the data than the response mean alone.

Source:

Source lists the three sources of variation called C Total, Model, and Error.

Degrees of Freedom:

DF records the associated degrees of freedom for each source of variation. A degree of freedom is subtracted from the total number of non-missing values for each parameter estimate used in a model computation.

The computation of the total sample variation (C Total) uses an estimate of the mean, so one degree of freedom is subtracted from the total. The total degrees of freedom are partitioned into the Model and Error terms.

For the Model DF, k-1 degrees of freedom from the total are used to compute the variation attributed to the analysis of variance model for a factor with k levels. The Error degrees of freedom are the difference between the total DF and Model DF.

Sum of Squares:

Sum of Squares records an associated sum of squares (SS for short) for each source of variation. The total (C Total) sum of squared distances of each response from the overall sample mean. That is the sum of squares for the base model (or simple mean model) used for comparison with all other models.

The sum of squared distances from each point to its respective group mean. This is the remaining unexplained Error (residual) SS after fitting the analysis of variance model.

The total SS less the error SS gives the sum of squares attributed to the Model.

Mean Square:

Mean Square is a sum of squares divided by its associated degrees of freedom. The F ratio for a statistical test is computed as the ratio of mean squares.

The Model mean square estimates the variance, but only under the hypothesis that the group means are equal.

The Error mean square estimates the variance of the error term independently of the model mean square and is unconditioned by any model hypothesis.

F Ratio:

F Ratio is the model mean square divided by the error mean square. If the hypothesis is true that all the regression parameters (except the intercept) are zero, then the mean square for error and the mean square for model both estimate the error variance, and their ratio has an F distribution. If there is a significant effect in the model, the F Ratio is higher than expected by chance alone.

Prob > F:

Prob > F is the observed significance probability (P-value) of obtaining a greater F value by chance alone if the specified model fits no better than the overall response mean. Observed significance probabilities of .05 or less are often considered evidence of a regression effect.

LEAST SQUARES MEANS TABLE:

Least Squares Means are the statistics that are compared when effects are tested. They are the predicted values for the response across the levels of some effect, given that all the other effects in the model are held at some "neutral" value. They may not reflect typical real-world values of the response if the values that the factors are set to do not reflect prevalent combinations of values in the real world. They are mainly used for the purpose of comparison in experimental situations. A Least Squares Means table is produced for all categorical effects in the model. For main effects, the sample means are also reported.

Level:

Level lists the names of each categorical level.

Least Sq Mean:

Least Sq Mean lists the least squares mean for each level of the categorical variable.

Std Error:

Std Error lists the standard error for each level of the categorical variable.

Mean:

Mean lists the response sample mean for each level of the categorical variable. This will be different from the least squares mean if the values of other effects in the model do not balance out across this effect.

PARAMETER ESTIMATE TABLE:

The Parameter Estimates table lists the estimates and standard errors for each parameter in the model. The t ratio and observed probability for the t test are given that compare each parameter to zero. The terms in the Parameter Estimates table for a linear fit are the intercept and the single X variable. For a polynomial fit of order k, there is an estimate for the model intercept and a parameter estimate for each of the k powers of the X variable.

Term:

Term names the estimated parameter. The first parameter is always the intercept. Simple regressors show up as the name of the data table column. Regressors that are dummy indicator variables constructed from nominal effects are labeled with the names of the levels in brackets. The dummy variables are coded as 1 except for the last level, which is coded as -1 across all the other dummy variables for that effect.

Estimate:

Estimate lists the parameter estimates for each term. They are the coefficients of the linear model and are determined by least squares.

Std Error:

Std Error is the standard error, an estimate of the standard deviation of the distribution of the parameter estimate. It is used to construct t tests and confidence intervals for the parameter.

t Ratio:

t Ratio lists the test statistics for the hypotheses that each parameter is zero. It is formed by the ratio of the parameter estimate to its standard error. If the hypothesis is true, then this statistic has a Student's t distribution. Looking for a t ratio greater than 2 in absolute value is a common rule-of-thumb for judging significance because it approximates the .05 significance level.

Prob > |t|:

Prob>|t| lists the observed significance probability calculated from each t ratio. It is the probability of getting by chance alone a t ratio greater (in absolute value) than the computed value, given that the hypothesis is true. Often, a value below .05 (or sometimes .01) is interpreted as evidence that the parameter is significantly different from zero.

LEVERAGE PLOT

Whole Model:

The popup menu next to the Leverage Plot offers whole model Power Details and the Press statistic .See also: Confidence Curves to assess significance Leverage Plots for EffectsPlot Dynamics The Whole-Model leverage plot is a plot of the observed response versus the predicted one. This is a special case of a general leverage plot, which is a point- by-point display of how the hypothesis sums-of-squares is composed. The Whole-Model hypothesis is that all the parameters except the intercept are zero, i.e. you can fit just as well by the mean alone, without any effects in the model. The distance from a point to the sloped 45 degree line shows the actual residual. The distance from the point to the horizontal line at the mean shows what the residual error would be if all effects were removed from the model. This is a graphical display of the test done in the Analysis of Variance report.

Leverage Plot for an Effect in the Model:

The leverage plot is a point-by- point display of how the hypothesis sums-of-squares is composed. There is a sloped line representing the fitted model, and a horizontal line representing the model under constraint, i.e. without the particular effect in the model. The distance from a point to the line of fit shows the actual residual. The distance from the point to the horizontal line of the mean shows what the residual error would be if the effect were removed from the model (if its parameters were constrained to the hypothesized value of zero). Points farther out from the middle of the X axis have an opportunity to exert more leverage on the test.

Leverage Plot Interpretation:

The leverage plots are shown with confidence curves. These indicate whether the test is significant at the .05 level by showing a confidence region for the line of fit. If the confidence region between the curves contains the horizontal line, then the effect is not significant. If the curves cross the line, the effect is significant.

Leverage Plot for an Effect in the Model:

The leverage plot is a point-by- point display of how the hypothesis sums-of-squares is composed. There is a sloped line representing the fitted model, and a horizontal line representing the model under constraint, i.e. without the particular effect in the model. The distance from a point to the line of fit shows the actual residual. The distance from the point to the horizontal line of the mean shows what the residual error would be if the effect were removed from the model (if its parameters were constrained to the hypothesized value of zero). Points farther out from the middle of the X axis have an opportunity to exert more leverage on the test.

STATISTICAL ANALYSIS

RESPONSE: DRYING RATE (HEATING PHASE)

Summary of Fit:

Rsquare	0.86
Rsquare Adj	0.83
Root Mean Square Error	1.27
Mean of Response	15.11
Observations (or Sum Wgts)	26

Effect Test:

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
BW	1	1	64.07	39.89	< 0.0001
CSF	1	1	39.87	24.83	< 0.0001
HW / SW	1	1	113.87	70.90	< 0.0001
Ini. w/s ratio	1	1	0.32	0.19	0.66

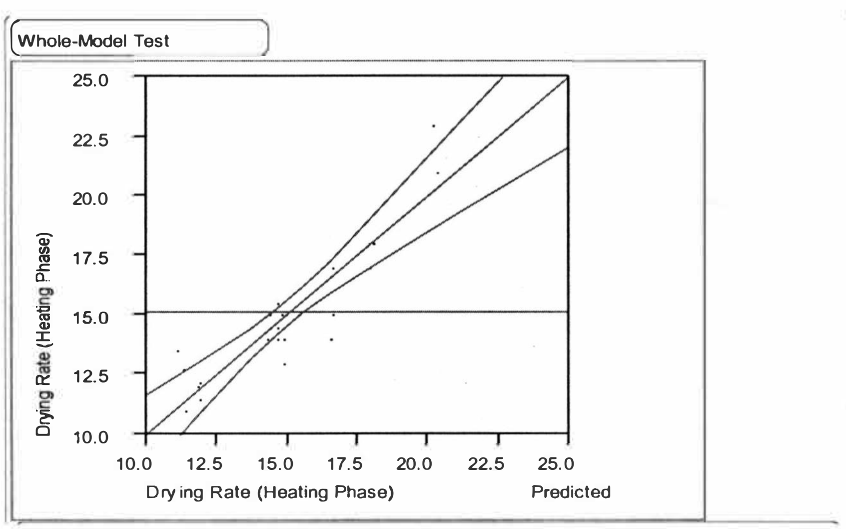

Figure 39. Whole Model Test for the drying rate (heating phase)

Analysis of Variance (whole model test):

Source	DF	Sum of Squares	Mean Squares	F Ratio
Model	4	205.08	51.27	31.92
Error	21	33.73	1.60	Prob >F
C Total	25	238.80		< 0.0001

Figure 40 shows the effect of HW/SW on the drying rate in the heating phase.

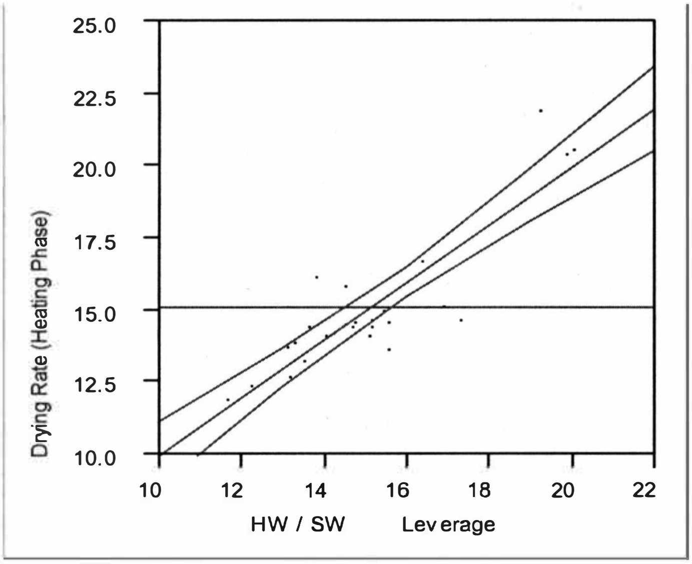

Figure 40. Effect of HW/SW on the drying rate (heating phase)

Effect Test (Drying rate versus HW / SW Leverage):

Sum of squares	F Ratio	DF	Prob > F
113.87	70.90	1	< 0.0001

Least Square Means (Drying rate versus HW / SW Leverage):

Level	Least Sq Means	Std Error	Mean
HW	13.73	0.298	14.09
SW	19.71	0.600	18.50

Figure 41 shows the effect of basis weight on the drying rate (heating phase)

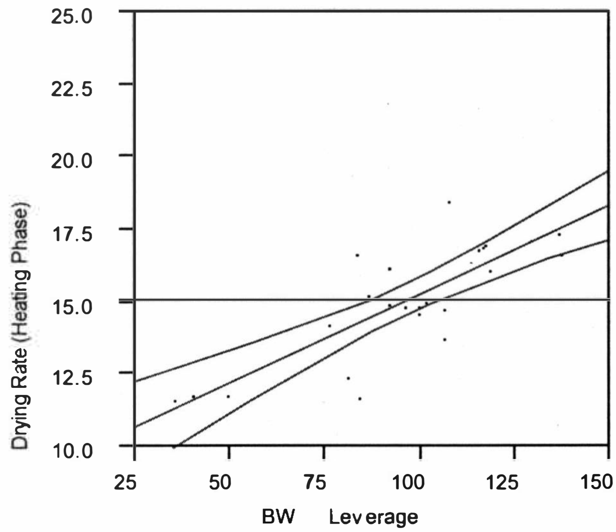

Figure 41. Effect of BW on the drying rate (heating phase)

Effect Test (Drying rate in heating phase versus BW Leverage):

Sum of squares	F Ratio	DF	Prob > F
64.06	39.89	1	< 0.0001

Figure 42 shows the effect of refining level on the drying rate (heating phase).

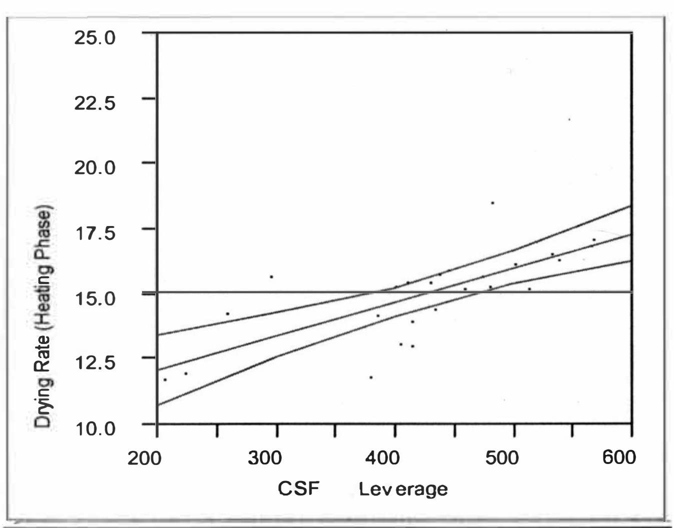

Figure 42. Effect of Refining level (CSF) on the drying rate (heating phase)

Effect Test (Drying rate in heating phase versus CSF Leverage):

Sum of squares	F Ratio	DF	Prob > F
39.87	24.83	1	< 0.0001

Figure 43 shows the effect of Initial moisture content (initial water/solids ratio) on the drying rate (heating phase).

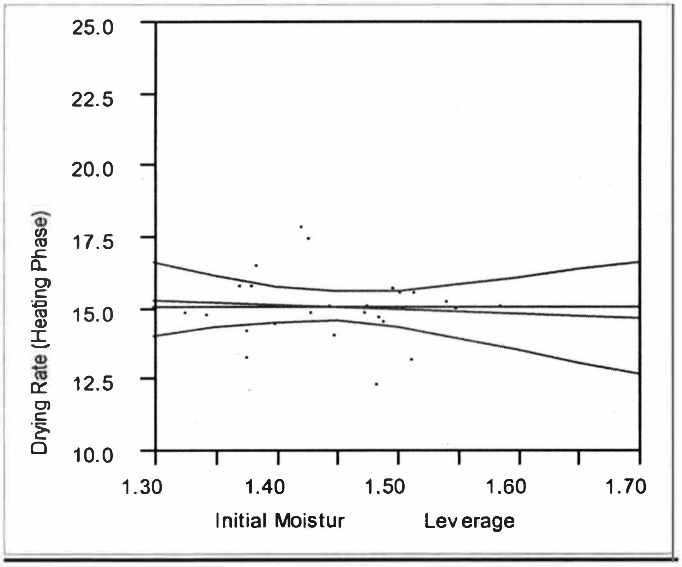

Figure 43. Effect of Initial Moisture content (CSF) on the drying rate (heating phase)

Effect Test (Drying rate in heating phase versus CSF Leverage):

Sum of squares	F Ratio	DF	Prob > F
0.32	0.19	1	0.66

RESPONSE: DRYING RATE (CONSTANT PHASE)

Summary of Fit

Rsquare	0.005
Rsquare Adj	- 0.183
Root Mean Square Error	0.686
Mean of Response	4.957
Observations (or Sum Wgts)	26

Effect Test

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
BW	1	1	0.021	0.045	0.833
CSF	1	1	39.87	24.83	0.797
HW / SW	1	1	113.87	70.90	0.999
Ini. w/s ratio	1	1	0.32	0.19	0.922

Figure 44 shows the Whole Model Test for the drying rate (constant phase).

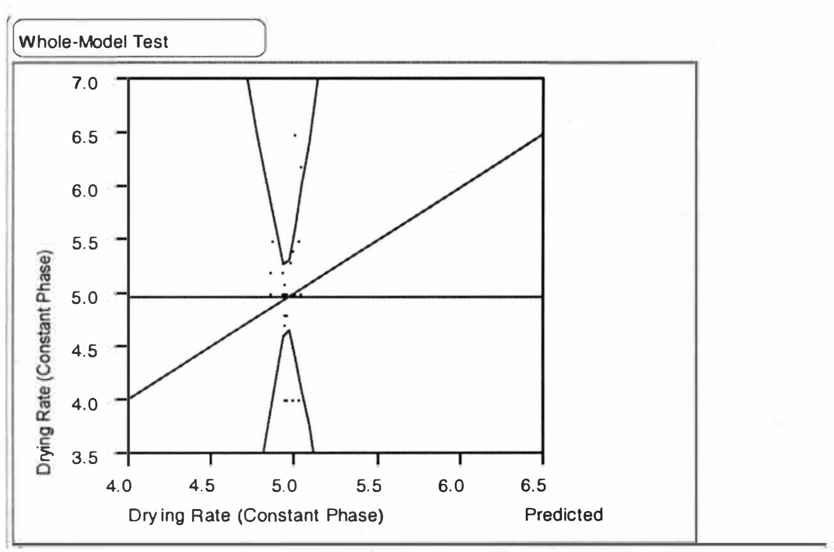

Figure 44. Whole Model Test for the drying rate (constant phase)

Analysis of Variance (whole model test):

Source	DF	Sum of Squares	Mean Squares	F Ratio
Model	4	0.059	0.014	0.031
Error	21	9.884	0.470	Prob >F
C Total	25	9.943		0.9979

Figure 45 shows the effect of HW/SW on the drying rate in the constant phase.

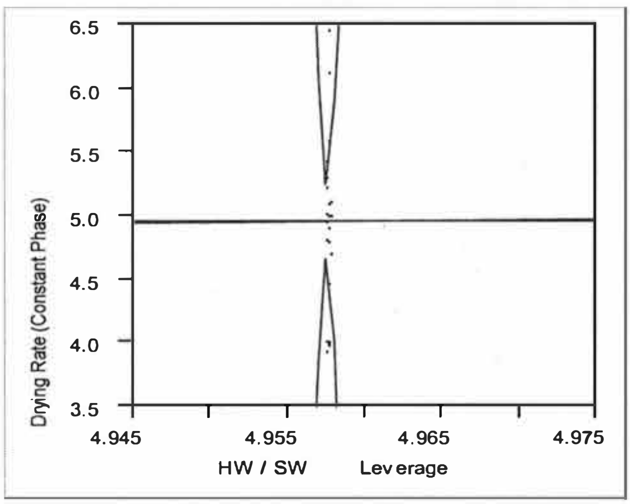

Figure 45. Effect of HW/SW on the drying rate (constant phase)

Effect Test (Drying rate in constant phase versus HW / SW Leverage)

Sum of squares	F Ratio	DF	Prob > F
0.00000003	0.00	1	0.9994

Least Square Means (Drying rate in constant phase versus HW / SW Leverage)

Level	Least Sq Means	Std Error	Mean
HW	4.96	0.161	4.95
SW	4.96	0.325	4.96

Figure 46 shows the effect of basis weight on the drying rate (constant phase)

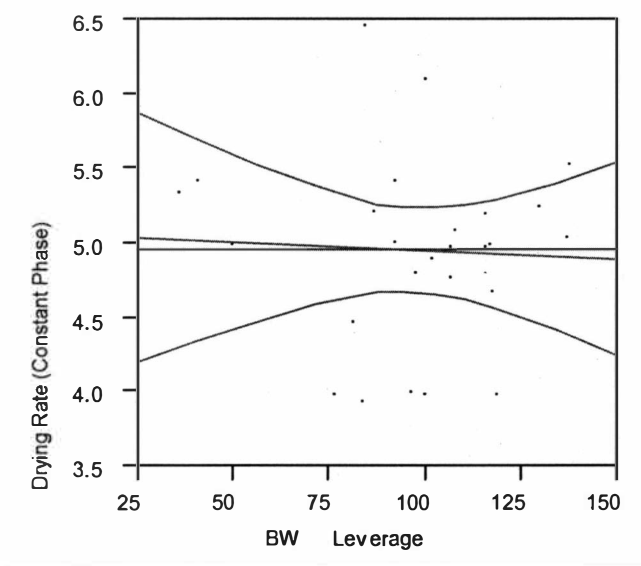

Figure 46. Effect of BW on the drying rate (constant phase)

<u>Effect Test (Drying rate in constant phase versus BW Leverage):</u>

Sum of squares	F Ratio	DF	Prob > F
0.021	0.045	1	0.833

Figure 47 shows the effect of refining level on the drying rate (constant phase).

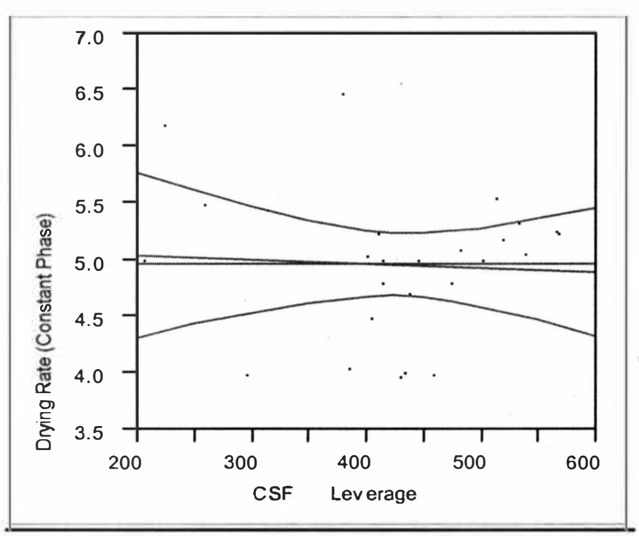

Figure 47. Effect of Refining level (CSF) on the drying rate (constant phase)

Effect Test (Drying rate in constant phase versus CSF Leverage):

Sum of squares	F Ratio	DF	Prob > F
39.87	24.83	1	< 0.0001

Figure 48 shows the effect of Initial moisture content (initial water/solids ratio) on the drying rate (constant).

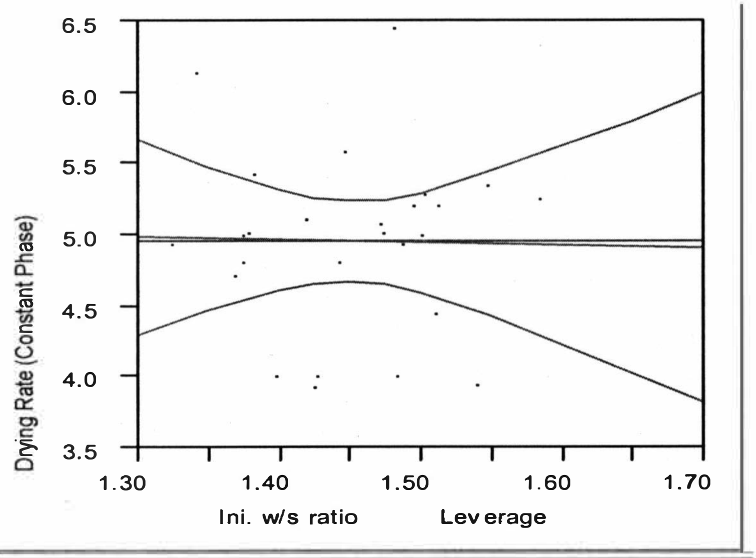

Figure 48. Effect of Initial Moisture content (CSF) on the drying rate (constant phase)

Effect Test (Drying rate in constant phase versus CSF Leverage):

Sum of squares	F Ratio	DF	Prob > F
0.004	0.0097	1	0.92

RESPONSE: DRYING RATE (FALLING RATE PHASE)

Summary of Fit:

Rsquare	0.75
Rsquare Adj	0.70
Root Mean Square Error	0.23
Mean of Response	1.67
Observations (or Sum Wgts)	26

Effect Test:

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
BW	1	1	0.20	3.78	0.06
CSF	1	1	0.12	2.43	0.13
HW / SW	1	1	0.05	0.93	0.34
Ini. w/s ratio	1	1	0.65	12.31	0.002

Figure 49 shows the Whole Model Test for the drying rate (falling rate phase).

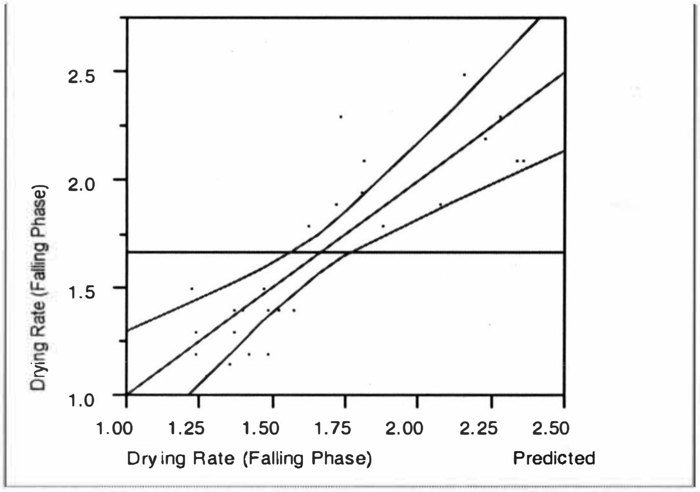

Figure 49. Whole Model Test for the drying rate (falling rate phase)

Analysis of Variance (whole model test):

Source	DF	Sum of Squares	Mean Squares	F Ratio
Model	4	3.38	0.84	15.93
Error	21	1.11	0.05	Prob >F
C Total	25	4.49		< 0.0001

Figure 50 shows the effect of HW/SW on the drying rate in the falling rate phase.

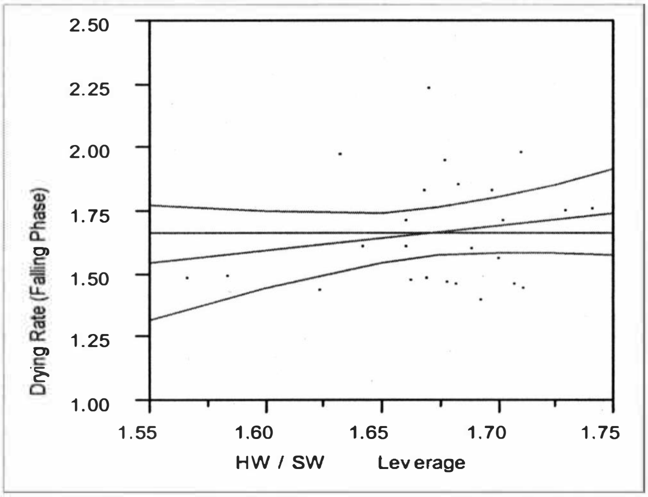

Figure 50. Effect of HW/SW on the drying rate (constant phase)

Effect Test (Drying rate in falling rate phase versus HW / SW Leverage):

Sum of squares	F Ratio	DF	Prob > F
0.049	0.94	1	0.3434

Least Square Means (Drying rate in falling rate phase versus HW / SW Leverage):

Level	Least Sq Means	Std Error	Mean
HW	1.69	0.054	1.63
SW	1.57	0.109	1.78

Figure 51 shows the effect of basis weight on the drying rate (falling rate phase)

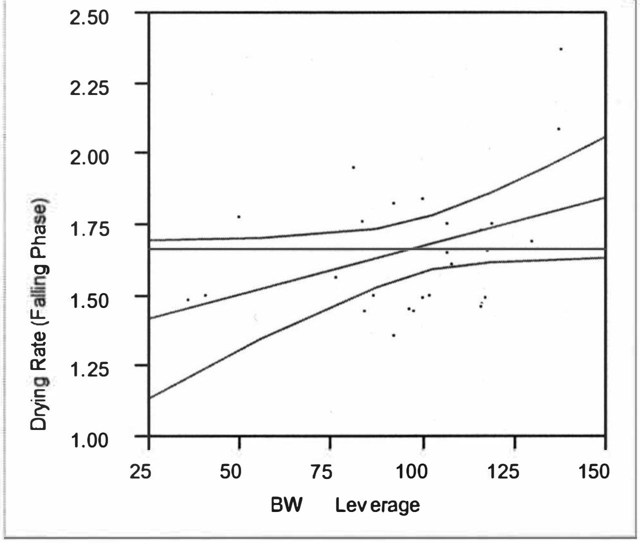

Figure 51. Effect of BW on the drying rate (falling rate phase)

<u>Effect Test (Drying rate in falling rate phase versus BW Leverage):</u>

Sum of squares	F Ratio	DF	Prob > F
0.20	3.77	1	0.065

Figure 52 shows the effect of refining level on the drying rate (falling rate phase).

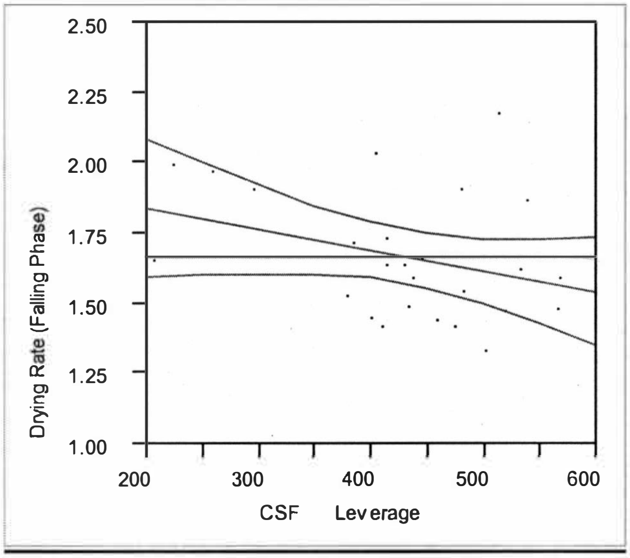

Figure 52. Effect of Refining level (CSF) on the drying rate (falling rate phase)

Effect Test (Drying rate in falling rate phase versus CSF Leverage):

Sum of squares	F Ratio	DF	Prob > F
0.13	2.43	1	0.13

Figure 53 shows the effect of Initial moisture content (initial water/solids ratio) on the drying rate (falling rate phase).

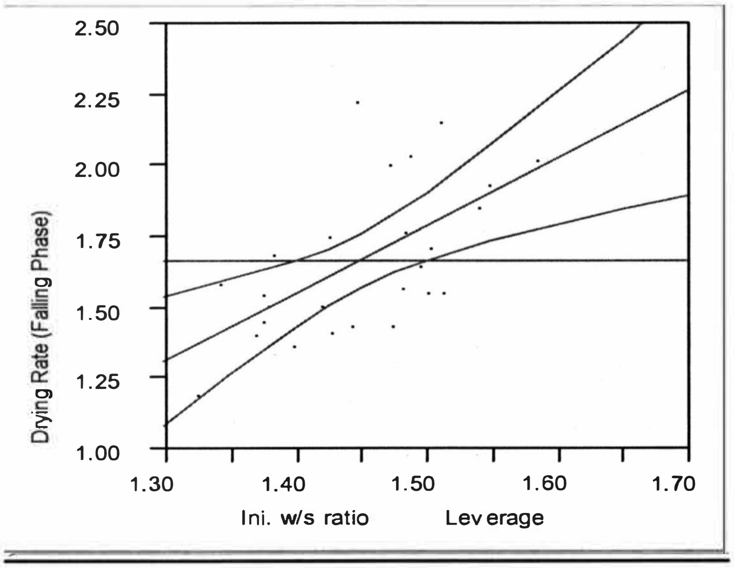

Figure 53. Effect of Initial Moisture content (CSF) on the drying rate (falling rate phase)

Effect Test (Drying rate in constant phase versus CSF Leverage):

Sum of squares	F Ratio	DF	Prob > F
0.65	12.31	1	0.0021

RESPONSE: CONTACT COEFFICIENT (HEATING PHASE)

Summary of Fit:

Rsquare	0.93
Rsquare Adj	0.91
Root Mean Square Error	92.82
Mean of Response	1309.615
Observations (or Sum Wgts)	26

Effect Test:

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
BW	1	1	900955.86	104.58	< 0.0001
CSF	1	1	966699.33	112.22	< 0.0001
HW / SW	1	1	60147.83	6.98	0.0152
Ini. w/s ratio	1	1	175528.43	20.38	0.0002

Figure 54 shows the Whole Model Test for the contact coefficient (heating phase).

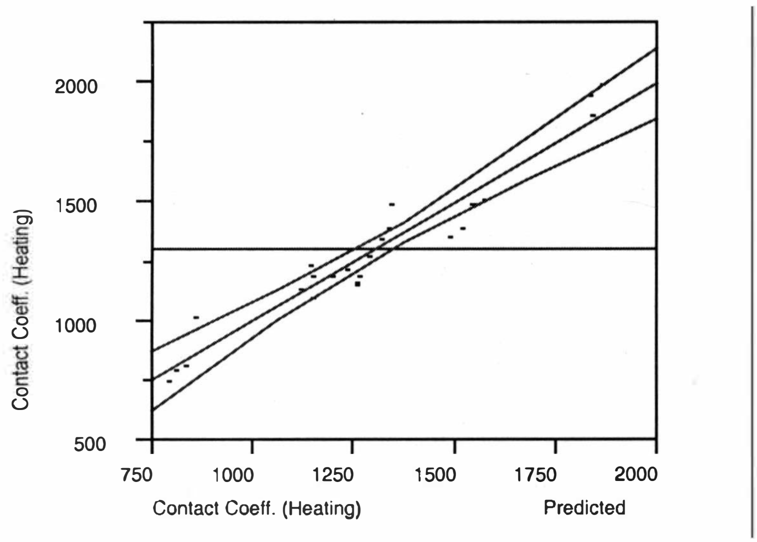

Figure 54. Whole Model Test for the contact coefficient (heating phase)

Analysis of Variance (whole model test):

Source	DF	Sum of Squares	Mean Squares	F Ratio
Model	4	2262388.8	565597	65.6551
Error	21	180908.1	8615	Prob >F
C Total	25	2443296.2		< 0.0001

Figure 55 shows the effect of HW/SW on the contact coefficient in the heating phase.

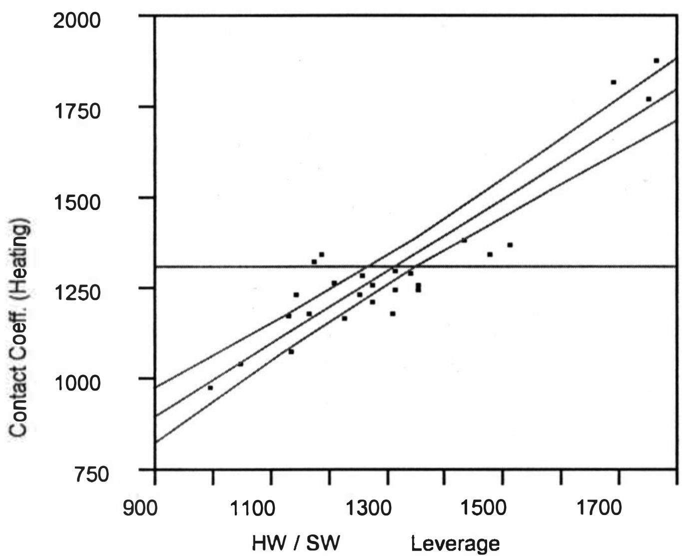

Figure 55. Effect of HW/SW on the contact coefficient (heating phase)

Effect Test (contact coefficient versus HW / SW Leverage):

Sum of squares	F Ratio	DF	Prob > F
966699.3	112.21	1	< 0.0001

Least Square Means (contact coefficient versus HW / SW Leverage):

Level	Least Sq Means	Std Error	Mean
HW	1182.37	21.80	1198.5
SW	1733.76	43.98	1680.0

Figure 56 shows the effect of basis weight on the contact coefficient (heating phase)

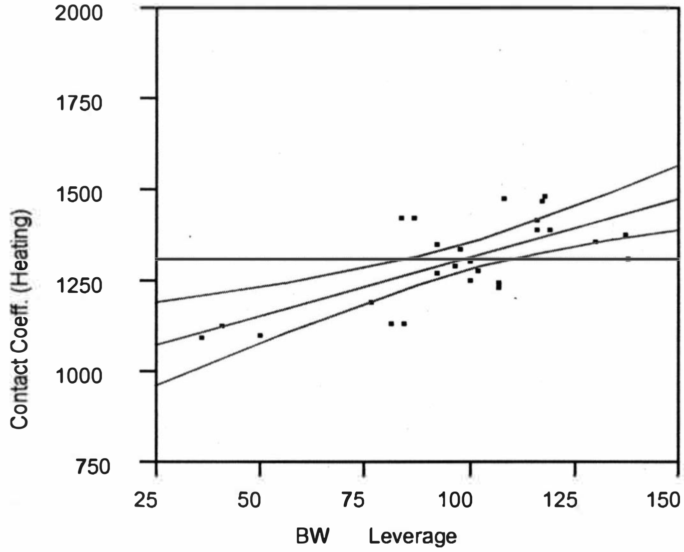

Figure 56. Effect of BW on the contact coefficient (heating phase)

<u>Effect Test (contact coefficient in heating phase versus BW Leverage):</u>

Sum of squares	F Ratio	DF	Prob > F
175528.4	20.37	1	< 0.0002

Figure 57 shows the effect of refining level on the contact coefficient (heating phase).

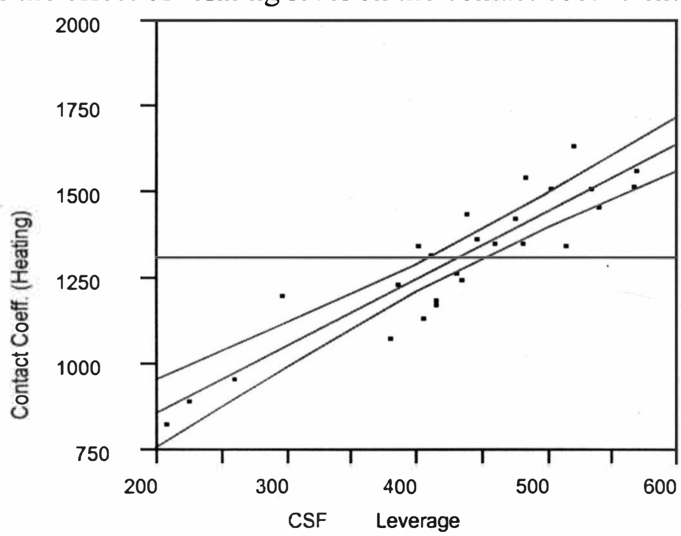

Figure 57. Effect of Refining level (CSF) on the contact coefficient (heating phase)

Effect Test (contact coefficient in heating phase versus CSF Leverage):

Sum of squares	F Ratio	DF	Prob > F
900955.8	104.58	1	< 0.0001

Figure 58 shows the effect of Initial moisture content (initial water/solids ratio) on the contact coefficient (heating phase).

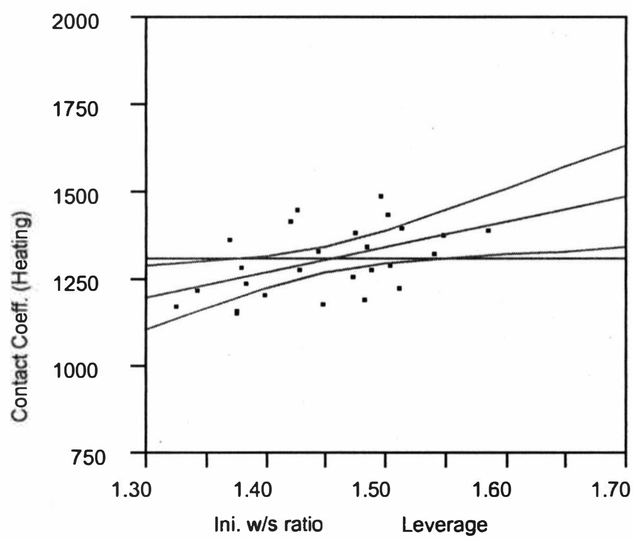

Figure 58. Effect of Initial Moisture content (CSF) on the contact coefficient (heating phase)

Effect Test (contact coefficient in heating phase versus CSF Leverage):

Sum of squares	F Ratio	DF	Prob > F
60147.8	6.98	1	0.015

RESPONSE: CONTACT COEFFICIENT (CONSTANT PHASE)

Summary of Fit:

Rsquare	0.356
Rsquare Adj	0.234
Root Mean Square Error	65.25
Mean of Response	543.84
Observations (or Sum Wgts)	26

Effect Test:

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
BW	1	1	27184.5	6.38	0.019
CSF	1	1	6028.3	1.42	0.247
HW / SW	1	1	9845.5	2.31	0.143
Ini. w/s ratio	1	1	18439.8	4.33	0.049

Figure 59 shows the Whole Model Test for the contact coefficient (constant phase).

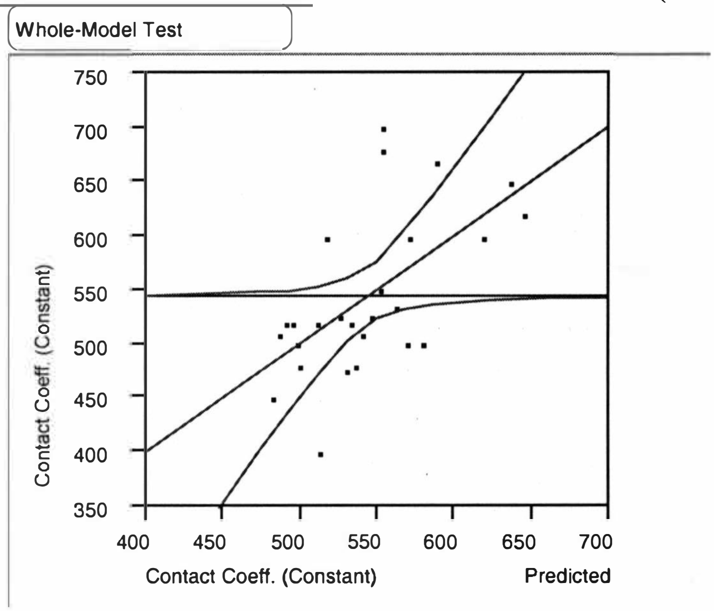

Figure 59. Whole Model Test for the contact coefficient (constant phase)

Analysis of Variance (whole model test):

Source	DF	Sum of Squares	Mean Squares	F Ratio
Model	4	49499.5	12374.9	2.90
Error	21	89415.8	4257.9	Prob >F
C Total	25	138915.3		0.046

Figure 60 shows the effect of HW/SW on the contact coefficient in the constant phase.

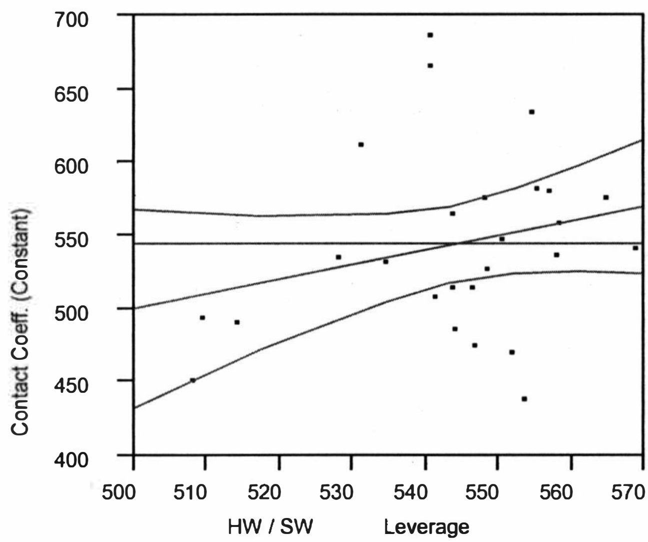

Figure 60. Effect of HW/SW on the contact coefficient (constant phase)

Effect Test (Drying rate in constant phase versus HW / SW Leverage):

Sum of squares	F Ratio	DF	Prob > F
6028.29	1.42	1	0.2474

Least Square Means (Contact coefficient in constant phase versus HW / SW Leverage):

Level	Least Sq Means	Std Error	Mean
HW	553.89	15.33	548.75
SW	510.35	30.92	527.50

Figure 61 shows the effect of basis weight on the contact coefficient (constant phase)

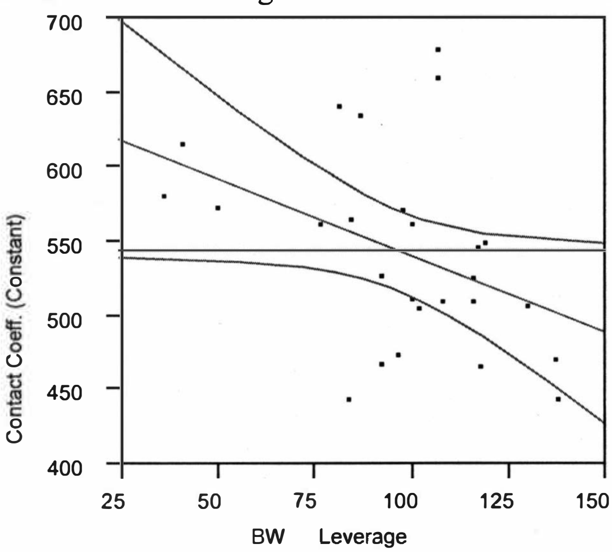

Figure 61. Effect of BW on the contact coefficient (constant phase)

Effect Test (Drying rate in constant phase versus BW Leverage):

Sum of squares	F Ratio	DF	Prob > F
18439.7	4.33	1	0.049

Figure 62 shows the effect of refining level on the contact coefficient (constant phase).

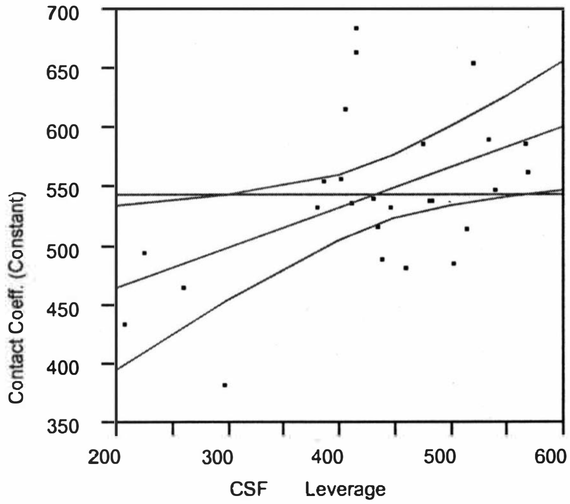

Figure 62. Effect of Refining level (CSF) on the contact coefficient (constant phase)

Effect Test (contact coefficient in constant phase versus CSF Leverage):

Sum of squares	F Ratio	DF	Prob > F
27184.5	6.38	1	0.0196

Figure 63 shows the effect of Initial moisture content (initial water/solids ratio) on the contact coefficient (constant rate phase).

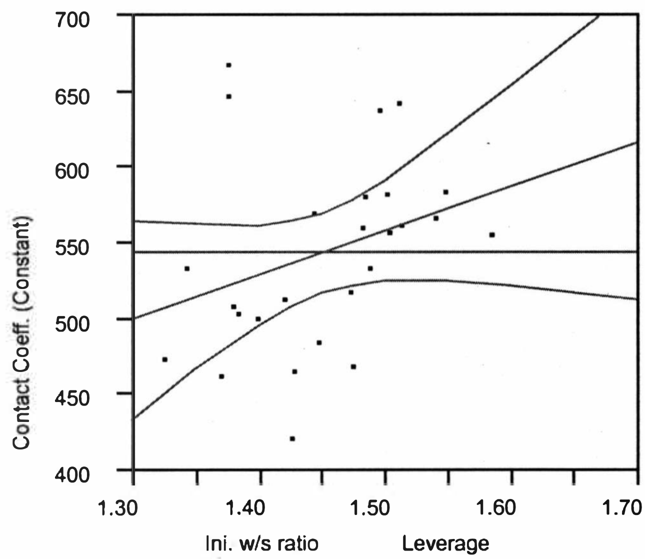

Figure 63, Effect of Initial Moisture content (CSF)

on the contact coefficient (constant phase)

<u>Effect Test (contact coefficient in constant phase versus CSF Leverage):</u>

Sum of squares	F Ratio	DF	Prob > F
9845.5	2.31	1	0.1433

RESPONSE: CONTACT COEFFICIENT (FALLING RATE PHASE)

Summary of Fit:

Rsquare	0.60
Rsquare Adj	0.52
Root Mean Square Error	33.53
Mean of Response	164.42
Observations (or Sum Wgts)	26

Effect Test:

Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
BW	1	1	2374.7	2.11	0.1609
CSF	1	1	5783.2	5.14	0.0340
HW / SW	1	1	7340.7	6.52	0.0184
Ini. w/s ratio	1	1	17857.9	15.89	0.0007

Figure 64 shows the Whole Model Test for the contact coefficient (falling rate phase).

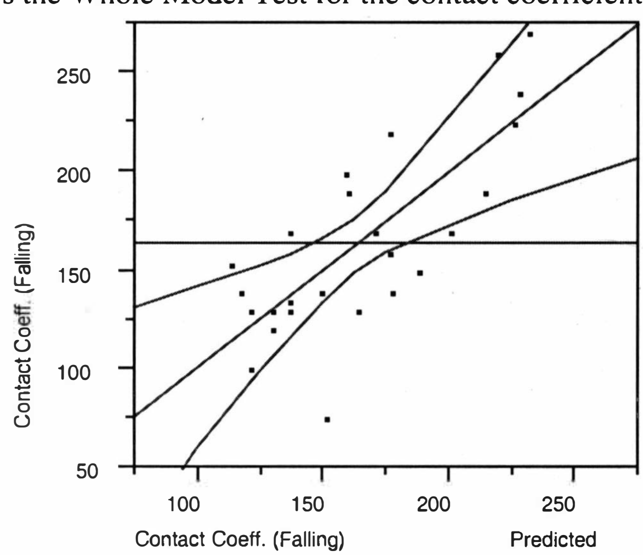

Figure 64. Whole Model Test for the contact coefficient (falling rate phase)

Analysis of Variance (whole model test):

Source	DF	Sum of Squares	Mean Squares	F Ratio
Model	4	34740.8	8685.2	7.73
Error	21	23607.5	1124.1	Prob >F
C Total	25	58348.3		0.0005

Figure 65 shows the effect of HW/SW on the contact coefficient in the falling rate phase.

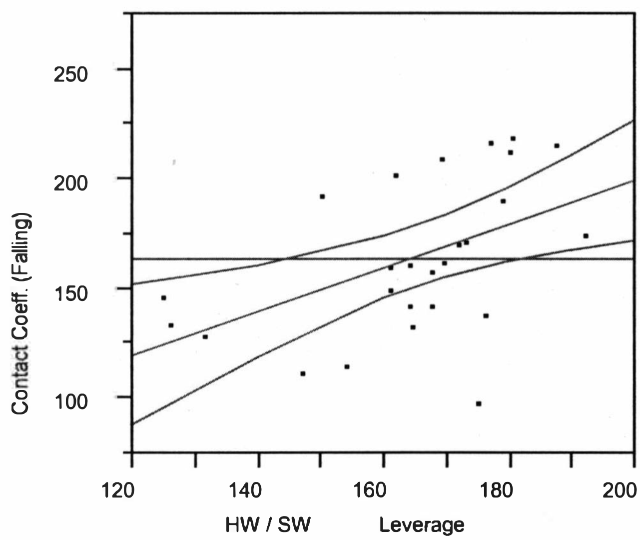

Figure 65. Effect of HW/SW on the contact coefficient (constant phase)

Effect Test (contact coefficient in falling rate phase versus HW / SW Leverage):

Sum of squares	F Ratio	DF	Prob > F
7340.7	6.53	1	0.0184

Least Square Means (Drying rate in falling rate phase versus HW / SW Leverage):

Level	Least Sq Means	Std Error	Mean
HW	175.51	7.88	168.5
SW	127.46	15.89	150.8

Figure 66 shows the effect of basis weight on the contact coefficient (falling rate phase).

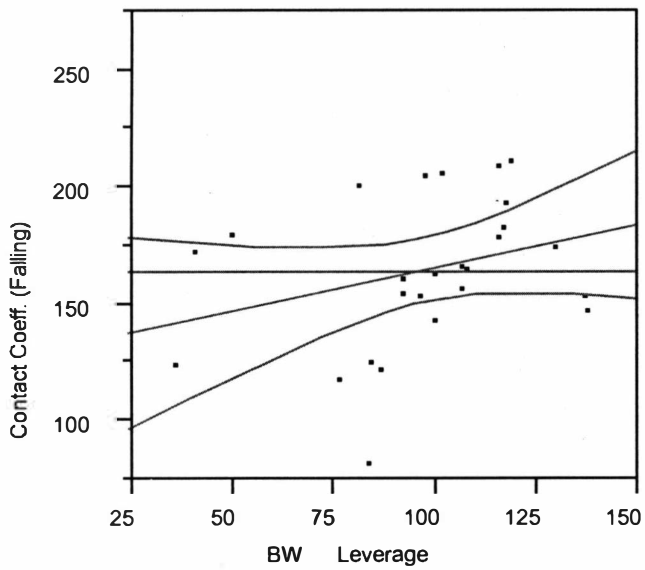

Figure 66. Effect of BW on the contact coefficient (falling rate phase)

Figure 67 shows the effect of refining level on the contact coefficient (falling rate phase).

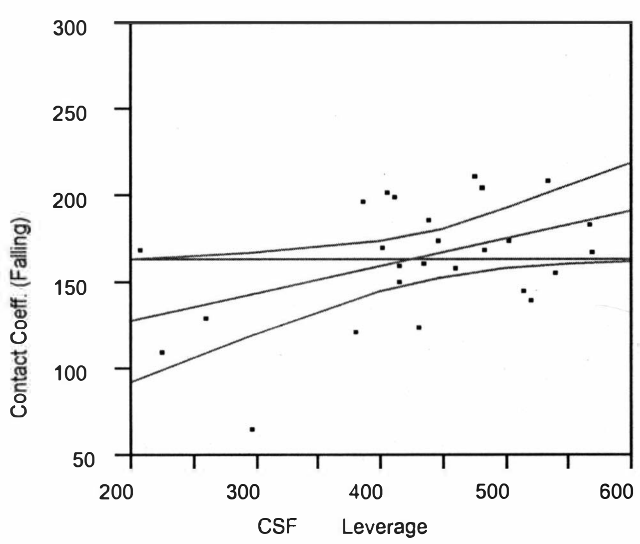

Figure 67. Effect of refining level on the contact coefficient (falling rate phase)

Figure 68 shows the effect of Initial moisture content (initial water/solids ratio) on the contact coefficient (falling rate phase).

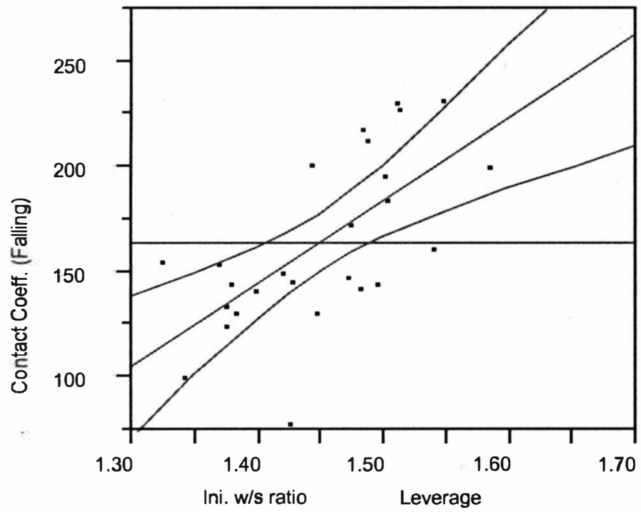

Figure 68. Effect of Initial Moisture content (CSF) on the contact coefficient