ML Sultan Technikon, Natal

THE DEVELOPMENT AND EVALUATION OF AN ON-LINE SUGAR PURITY METER FOR USE IN A LOW GRADE CONTINUOUS CENTRIFUGAL

Lynettra Govender

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Lynettra Govender

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Abstract

There are two process operations in the sugar factory that directly affect the recovery of sugar from evaporated syrup, namely crystallisation (boiling) and centrifugal operation. Successful automation of the vacuum pans (boiling) has been implemented using brix (total dissolved solids) control, but to date on-line measurement of continuous centrifugal performance has not been successfully accomplished in South Africa. The purpose of this investigation was to continue the preliminary work performed by Tongaat Hulett Sugar in developing a purity meter for the measurement of sugar purity (sucrose content) in a continuous centrifugal. This instrument would provide the centrifugal operator with a reliable tool to perform on-line measurement of sugar purity and would also facilitate the automation of the centrifugal.

This investigation was approached by initially developing a laboratory purity meter and then using this experience to develop a meter for the factory continuous centrifugal. The laboratory purity meter was developed utilising the measurement reflected light intensity for the prediction of sugar purity. The technique involved the focusing of a light source onto the surface of sugar crystals and then measuring the reflected light intensity with a light detector. The higher the reflected light intensity measured, the higher the sugar purity.

Preliminary laboratory trials involved the selection of the light source and sensor. The selection criteria for the light source and sensor were:

a) the achievement of a reliable and repeatable relationship between sugar purity and measured reflected light intensity, and
b) a light source and sensor that can withstand the environmental conditions of the sugar mill.

Four light sources were tested viz. incandescent lamp (12W and 35 W), red LED (12 candela), and a strobe light (35W strobe at 4 Hz). As part of the continuation of earlier trials by Tongaat Hulett Sugar, the light detector used for the light selection trials was the photodiode. Two lamps were selected. The

12- candela red LED and the 35W incandescent lamps both provided a repeatable, highly linear relationship between laboratory analysed sugar purity and measured reflected light intensity.

The light detector selection trials involved the testing of the light dependent resistor (LDR) and the photodiode sensors to check if better results could be produced for the selected light sources. Results showed both the LDR and the photodiode sensors were able to successfully predict sugar purity. The relationship between sugar purity and measured reflected light intensity was linear and repeatable. The light sensor selection trials were performed at ambient temperatures.

Attempts were made to replicate the environmental conditions of the continuous centrifugal. As a result high temperatures (60 to 70°C), the spinning motion of the sugar samples, steam and vibration effects on the light reflectance measurement were tested. The following results apply to both the red LED and the 35W incandescent lamps.

- For the temperature tolerance testing the two light detectors were tested viz. the photodiode and the LDR (light dependent resistor). The LDR was selected for its ability to provide a steady output at the specified temperature range of 60 to 70°C. The photodiode output was unstable in this temperature range.
- Sugar crystal movement (spinning) had no significant effect on the reflected light intensity measurement.
- There was no significant effect of steam on the reflected light intensity measurement.
- The effect of vibration could not be tested, however this factor was taken into consideration when building the purity meter prototype.

The success of the laboratory trials led to the construction of the factory purity meter prototype. Both the red LED and the 35W incandescent lamps were tried in the factory. The following results were obtained for the factory trials:

For the red LED trials, the relationship between sugar purity and reflected light intensity measurement remained linear in the continuous centrifugal.

Calibration of the purity meter had to be performed with the purity meter installed in the continuous centrifugal as the laboratory calibration did not apply. It was discovered that the range in which the purity meter operated in the centrifugal and the laboratory rig varied. This was attributed to different environmental conditions that the laboratory meter was unable to accommodate. Correlation coefficient values in the region of 0.97 were achieved for the red LED factory trials.

The effect of varying massecuite quality was tested and it was found that although the relationship between sugar purity and measured light intensity remained linear, the gradient of the curves changed with changing massecuite quality. It was concluded that the calibration of the purity meter had to be conducted daily. Modifications made to improve the purity meter prototype performance included the shortening of the light source and detector tubes to reduce molasses fouling of the tubes. A cleaning period of once per week was achieved. The electronics were remotely panel mounted after short- circuiting occurred due to water ingress when the electronics were initially mounted on top of the centrifugal monitor casing.

The following are results obtained from the incandescent lamp trials:
The experiences from the red LED trials led to a more informed approach to the incandescent light trials. The purity meter electronics were modified to operate in a range of 70 to 99%. This allowed operators to have a direct correlation of sugar purity in the continuous centrifugal. The results obtained from the incandescent lamp trials were similar to those experienced with the red LED trials. The relationship between sugar purity and measured reflected light intensity was linear, the purity meter had to be calibrated while installed in the continuous centrifugal and had to be calibrated daily due to the changing quality of the massecuite. Correlation coefficient values in the region of 0.94 were achieved.

The objective of this investigation, to provide the centrifugal operator with a reliable measure of sugar purity, was adequately achieved with both light sources. The results from the red LED trials were however better than those achieved from the incandescent lamp trials. Correlation coefficient values

achieved with the incandescent lamp in the laboratory ($r=0.99$) deteriorated when tested in the factory ($r^2 = 0.94$). Lamp deterioration was the reason for this phenomenon. The red LED maintained the good linear relationship of approximately $r= 0.97$ in both the laboratory and the factory trials. In light of these findings it was believed that the red LED would be the better choice for the light source for use in the detection of sugar purity in a continuous centrifugal.

The purity meter although capable of providing a reliable measure of sugar purity cannot totally replace daily laboratory analyses. This is proven by the fact that the meter requires daily calibration. The meter will however assist in significantly reducing the number of laboratory analyses performed and in reducing the loss of sucrose to molasses.

Preface

I hereby declare that this entire dissertation is my own work, unless stated otherwise in the text, and that it has not been submitted, in whole or in part, for a degree to any other University or Institution.

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Table of Contents

Page

List of tables xii

List of figures xiii

Glossary xviii

Chapter 1: INTRODUCTION **1-1**

1.1 Background to sugar production **1-1**

1.2 Objectives of the investigation. **1-10**

1.3 Approaches to investigation. **1-11**

Chapter 2: LITERATURE REVIEW 2-1

2.1 The structure and colour characteristics of raw sugar 2-1

2.1.1 The structure of raw sugar 2-1

2.1.2 Colour characteristics of raw sugar 2-4

2.1.2.1 Sugar cane plant derived colour 2-6

2.1.2.2 Factory produced colour 2-7

2.1.2.3 Measurement of colour 2-8

2.2 Present methods of determining purity **2-10**

2.2.1 Pol 2-11

2.2.2 Brix 2-13

2.3 Other methods used to determine sugar purity. **2-16**

2.3.1 The measurement of light wavelength or frequency 2-17

2.3.2 The measurement of reflected light intensity off the surface of sugar crystals 2-21

2.3.3 Wavelength versus intensity measurement. 2-25

Chapter 3: CONTINUOUS CENTRIFUGAL OPERATION 3-1

3.1 Continuous centrifugals in the sugar industry 3-1
3.2 Present continuous centrifugal control 3-5
3.3 C-Sugar purity control 3-6
3.4 Proposed method of continuous centrifugal control 3-7

Chapter 4: DEVELOPMENT OF THE LABORATORY PURITY METER 4-1

4.1 Geometric design 4-2
4.2 Selection of the light source 4-4
4.2.1 Aim of the experiment 4-4
4.2.2 Experimental method and equipment 4-4
4.2.2.1 Light sources 4-4
4.2.2.2 Light detector 4-9
4.2.2.3 Sugar sampling and analyses 4-11
4.2.2.4 Sample preparation 4-12
4.2.2.5 Data collation and analyses 4-12
4.2.3 Experimental results and discussion 4-13
4.2.3.1 Strobe light 4-13
4.2.3.2 Incandescent light (12 W) 4-18
4.2.3.3 Incandescent light (35 W) 4-20
4.2.3.4 Red light emitting diode (LED) 4-21
4.2.4 Conclusions 4-22
4.3 Selection of the light detector/sensor 4-24
4.3.1 Aim of the experiment 4-24
4.3.2 Experimental method and equipment 4-24
4.3.3 Experimental results and discussion 4-26
4.3.4 Conclusions 4-28

4.4 Testing of centrifugal environmental conditions 4-29
4.4.1 Temperature tolerance testing of the light sensor/detector 4-29
4.4.1.1 Aim of the experiment 4-29
4.4.1.2 Experimental method and equipment 4-29
4.4.1.3 Experimental results and discussion 4-30
4.4.1.4 Conclusions 4-31

4.4.2 Effect of sugar crystal movement on the light reflectance intensity measurement 4-32
4.4.2.1 Aim of experiment 4-32
4.4.2.2 Experimental method and equipment 4-32
4.4.2.3 Experimental results and discussion 4-33
4.4.2.4 Conclusions 4-36
4.4.3 The Effect of steam addition on the measurement of reflected light 4-37
4.4.3.1 Aim of the experiment 4-37
4.4.3.2 Experimental method and equipment 4-37
4.4.3.3 Experimental results and discussion 4-38
4.4.3.4 Conclusions 4-39
4.4.4 Efforts to accommodate the effect of vibration. 4-41
4.5 Conclusions of the laboratory trials 4-42

Chapter 5: DEVELOPMENT OF THE FACTORY PURITY METER. 5-1

5.1 Red LED factory trials 5-2
5.1.1 Aim of the experiment 5-2
5.1.2 Experimental method and equipment 5-2
5.1.3 Experimental results and discussion 5-7
5.1.3.1 Purity meter operations 5-7
5.1.3.2 A comparison between laboratory and factory trials. 5-10

5.1.3.3 The relationship between the measured light reflectance and sugar purity in the continuous centrifugal. 5-12
5.1.4 Conclusions 5-15
5.2 Incandescent light - Factory trials 5-17
5.2.1 Aim of the experiment 5-17
5.2.2 Experimental method and equipment 5-17
5.2.3 Experimental results and discussion 5-17
5.2.3.1 Purity meter operations 5-17
5.2.3.2 The relationship between measured light reflectance and sugar purity in the continuous centrifugal. 5-20
5.2.4 Conclusions 5-23
5.3 CONCLUSIONS FOR THE FACTORY TRIALS 5-24

Chapter 6: CONCLUSIONS AND RECOMMENDATIONS 6-1

REFERENCES R-1

APPENDICIES

APPENDIX A :Experimental Procedure A-1
A1.1 Procedure for purity determination of magma (C-Sugar).

APPENDIX B: Strobe light trials B-1

APPENDIX C: Incandescent light(12W) C-1

APPENDIX D: Incandescent light (35W) D-1

APPENDIX E: Red LED light data E-1

List of Tables

Table Number	**Table Description**	**Page**
Table 1.1	Typical massecuite, sugar and molasses purities.	1-8
Table 4.1	Overall strobe light test results	4-17
Table 4.2	Overall incandescent light (12w) test results	4-19
Table 5.1	Regression analyses and correlation coefficients generated on separate days (red LED).	5-15
Table 5.2	Regression analysis and correlation coefficients generated on separate days (incandescent lamp)	5-22
Table D.1	Raw data for the incandescent lamp and LDR trials.	D-2
Table D.2	Incandescent motion trials raw data	D-2
Table D.3	Incandescent steam simulation trials - raw data	D-3
Table E.1	Raw data for the motion trials	E-2
Table E.2	Raw data for the steam simulation trials	E-2

List of Figures

Figure Number	Figure Description	Page
Figure 1.1	Simplified flow diagram of the sugar production process from sugar cane to raw sugar.	1-4
Figure 1.2	The three boiling system.	1-5
Figure 2.1	The molecular structure of sucrose [(Moeller *et al* (1984)]	2-2
Figure 2.2	The molecular structure of glucose [Moeller *et al* (1984)]	2-3
Figure 2.3	The molecular structure of fructose [Moeller *et al* (1984)]	2-3
Figure 2.4	Refraction of light.	2-14
Figure 2.5	Measuring refractive index by refractometer trough	2-15
Figure 2.6	Diagram of a light wave	2-18
Figure 2.7	Diffraction grating	2-20
Figure 3.1	Diagram of a typical continuous centrifugal	3-3
Figure 3.2	Movement of massecuite on the centrifugal screen.	3-4
Figure 4.1	Laboratory purity meter rig	4-3
Figure 4.2	Incandescent light – Electrical set-up	4-6
Figure 4.3	Strobe light – Electrical set-up.	4-7
Figure 4.4	Red light emitting diode– Electrical set-up	4-9
Figure 4.5	Light detector– photodiode	4-10
Figure 4.6	Strobe light: the relationship between sugar purity and reflected light intensity, using a blue filter.	4-15
Figure 4.7	Strobe light: the relationship between sugar purity and reflected light intensity, using a blue and brown filter.	4-16
Figure 4.8	Incandescent light(12W): the relationship between sugar purity and reflected light intensity , using an orange filter.	4-20
Figure 4.9	Relationship between sugar purity and reflected light, using incandescent light of 35 W.	4-21

Figure 4.10	Relationship between sugar purity and reflected light, using a red LED at 12 candela.	4-22
Figure 4.11	Light detector (LDR)	4-25
Figure 4.12	Relationship between sugar purity and reflected light, using incandescent lamp and a LDR	4-27
Figure 4.13	Relationship between sugar purity and reflected light, using a red led and a LDR	4-27
Figure 4.14	Relationship between the photodiode output and increasing temperature.	4-30
Figure 4.15	Relationship between the LDR output and increasing temperature.	4-30
Figure 4.16	Laboratory set-up for the motion trials.	4-33
Figure 4.17	Motion trials: Incandescent light source and the LDR	4-34
Figure 4.18	Motion trials: Red LED and a LDR	4-35
Figure 4.19	Steam trials: Simulation of the steam effect on the reflectance measurement, using a 35W incandescent lamp and a LDR.	4-38
Figure 4.20	Steam trials: Simulation of the steam effect on the reflectance measurement, using a red LED and a LDR	4-39
Figure 5.1	Purity meter prototype	5-3
Figure 5.2	Purity meter set-up on the centrifugal	5-4
Figure 5.3	Light and light detector processing.	5-5
Figure 5.4	Red LED light source and detector tube distance to continuous centrifugal basket.	5-9
Figure 5.5	Relationship between the laboratory calibration and the centrifugal reflectance measurements.	5-10
Figure 5.6	Typical calibration curve for the continuous centrifugal	5-13
Figure 5.7	Calibration curves generated on separate days (red Led trials).	5-14
Figure 5.8	Incandescent lamp and detector tube distance to the continuous centrifugal basket.	5-18
Figure 5.9	Relationship between purity meter measurements and laboratory purity analysis.	5-21

Figure 5.10	The effect of changing massecuite quality on the purity meter measurement.	5-22
Figure B.1	Relationship between sugar purity and reflected light at a 18 cm sample distance	B-1
Figure B.2	Relationship between sugar purity and reflected light at a 12 cm sample distance	B-1
Figure B.3	Relationship between sugar purity and reflected light at a 7 cm sample distance	B-2
Figure B.4	Relationship between sugar purity and reflected light , using a blue filter	B-2
Figure B.5	Relationship between sugar purity and reflected light , using a brown filter	B-3
Figure B.6	Relationship between sugar purity and reflected light , using a green filter	B-3
Figure B.7	Relationship between sugar purity and reflected light , using an orange filter	B-4
Figure B.8	Relationship between sugar purity and reflected light , using a yellow filter	B-4
Figure B.9	Relationship between sugar purity and reflected light, using a blue and brown filter	B-5
Figure B.10	Relationship between sugar purity and reflected light , using a blue and yellow filter	B-5
Figure B.11	Relationship between sugar purity and reflected light , using blue and green filters	B-6
Figure B.12	Relationship between sugar purity and reflected light , using a green and yellow filters	B-6
Figure B.13	Relationship between sugar purity and reflected light , using green and orange filters	B-7
Figure B.14	Relationship between sugar purity and reflected light , using an orange brown filter	B-7
Figure B.15	Relationship between sugar purity and reflected light , using green and brown filters	B-8
Figure B.16	Relationship between sugar purity and reflected light , using orange and brown filters	B-8

Figure B.17	Relationship between sugar purity and reflected light , using orange and yellow filter	B-9
Figure B.18	Relationship between sugar purity and reflected light , using yellow and brown filters	B-9
Figure C.1	Relationship between sugar purity and reflected light at a 18 cm sample distance	C-1
Figure C.2	Relationship between sugar purity and reflected light at a 12 cm sample distance	C-1
Figure C.3	Relationship between sugar purity and reflected light at a 7 cm sample distance	C-2
Figure C.4	Relationship between sugar purity and reflected light , using a blue filter	C-2
Figure C.5	Relationship between sugar purity and reflected light , using a brown filter	C-3
Figure C.6	Relationship between sugar purity and reflected light , using a green filter	C-3
Figure C.7	Relationship between sugar purity and reflected light , using an orange filter	C-4
Figure C.8	Relationship between sugar purity and reflected light , using a yellow filter	C-4
Figure C.9	Relationship between sugar purity and reflected light, using a blue and brown filter	C-5
Figure C.10	Relationship between sugar purity and reflected light , using a blue and yellow filter	C-5
Figure C.11	Relationship between sugar purity and reflected light , using blue and green filters	C-6
Figure C.12	Relationship between sugar purity and reflected light , using a green and yellow filters	C-6
Figure C.13	Relationship between sugar purity and reflected light , using green and orange filters	C-7
Figure C.14	Relationship between sugar purity and reflected light , using green and brown filters	C-7
Figure C.15	Relationship between sugar purity and reflected light , using an orange brown filter	C-8

Figure C.16	Relationship between sugar purity and reflected light , using orange and brown filters	C-8
Figure C.17	Relationship between sugar purity and reflected light , using orange and yellow filter	C-9
Figure C.18	Relationship between sugar purity and reflected light , using yellow and brown filters	C-9
Figure D.1	Relationship between sugar purity and reflected light , using incandescent light of 35 W, Trial 2	D-1
Figure E.1	Relationship between sugar purity and reflected light , using a Red LED at 12 candela	E-1
Figure E.2	Relationship between sugar purity and reflected light , using a Red LED and LDR	E-1

Glossary

WORD	DESCRIPTION
Bagasse	The shredded cane fibre residue following juice extraction.
Boiling	The process of sugar crystallization in vacuum pans.
Brix up	To increase concentration of a sugar solution by sugar addition or evaporation.
Brix	Brix is the sum of the dissolved solid matter in a sugar solution expressed as a percentage by mass or as an actual mass.
Brixing	Changing the concentration of total dissolved solids in a sugar solution by evaporation, addition of water or addition of sugar.
Clear Juice	The liquor following sugar mill clarification.
Colour precursors	Those molecules which are not actually coloured, but react during the refining process to produce colour.
Crystallisation Pan	A vessel in which sugar crystallisation takes place (usually under vacuum).
Grade	Grade is a measure of the quality of a sugar solution and is defined as the ratio of brix to ICUMSA colour.

Grain	The term describing the introduction of crystal nuclei to initiate crystal growth in a saturated liquor.
Magma	A mixture of saturated sugar liquor and sugar crystals.
Massecuite	A molasses/sugar mixture.
Melter	The equipment in which sugar crystals are dissolved in hot water.
Milk of lime	Calcium hydroxide slurry.
Milling	The unit operation used to extract juice from sugar cane by applied pressure.
Molasses	Molasses in the sugar industry is the highly coloured, diluted (with water/steam) mother liquor. The mother liquor is the undiluted and unchanged liquid of the massecuite. It is known as Nutsch molasses. Molasses/diluted mother liquor is used to boil a massecuite.
Mud	Thickened tri-calcium phosphate or calcium hydroxide precipitate recovered from the mill and refinery clarification processes.
Pol	Pol is the apparent sucrose in a substance, given as a percentage by mass or as an actual mass. Pol is determined by a polarimeter. Actual sucrose is determined by gas chromatography.
Purity	Purity is defined as the ratio of sucrose (pol) to total dissolved solids (brix) expressed as a percentage.
Reducing Sugar	

	These are the chemically reducing sugars found in sugar solutions, the main ones being glucose and fructose.
Refractometer	An optical instrument used to determine brix concentration. The instrument measures the amount that a ray of light, passing from air, is refracted (bent) at the surface of a particular solution. This is then related to total dissolved solids in the solution.
Seeding	Seeding is the term describing the addition of crystal nuclei to saturated syrup to induce crystal growth.
Strike	The process of recovering a massecuite from a crystallisation pan.
Sugar colour	Sugar colour is a complex collection of molecules, which increases the light absorbance of a sugar solution at a particular wavelength.
Syrup	Concentrated clear juice following evaporation in the mill.

Chapter 1

INTRODUCTION

Huletts Sugar is produced at the Tongaat-Hulett Sugar mills on the north coast of Natal. Here, the sugar, which is essentially sucrose, is produced from sugarcane. This chapter provides a background to the production of sugar at the Tongaat Hulett Sugar mills. The objectives and approach into the development and evaluation of a meter, measuring sugar purity in a continuous centrifugal, are also stated.

The sugar industry has its own particular characteristic terminology. These terms are defined in the glossary.

1.1 Background to sugar production

Sugar cane

Sugarcane is a giant grass of the genus *Saccharum.* The sugar mills, producers of unrefined (brown) sugar, receive cane stalks from the growers. The roots, tops and leaves of the sugarcane are removed since they have little or no sugar value. The cane stalk consists typically of 15% dissolved matter, 15% fibre (insoluble) and 70% water. Included in the 15% dissolved matter (referred to as brix) is 13% sucrose. The remaining 2% are other sugars, being mainly glucose and fructose. The growers are paid according to the sucrose content of the cane they produce. The stalks are prepared for sucrose extraction by being cut and shredded.

The recovery of sugar from the sugarcane plant involves a series of mechanical and physical processes, which involve the crushing of the sugarcane, extraction of juice, concentration of juice and crystallisation of the sugar. These processes are further discussed.

Juice extraction

Sugar is extracted from the sugarcane by using either the diffusion process or by the more traditional milling process. Since sugarcane fibre retains its own weight in water, both juice extraction processes require copious amounts of water or dilute sugar solution to displace the juice. With diffusion, the cane stalks are finely shredded before passing through counter current washing. This consists of an enclosed carrier through which a bed of shredded cane is conveyed, while large volumes of water are sprayed over the cane to efficiently flush out the sucrose-bearing juice from the fibre. Milling involves a process of sequential squeezing and washing of shredded cane stalks. The cane fibres are crushed/squeezed between a series of rollers while they are co-currently sprayed with jets of water and dilute juice. The fibrous residue (bagasse) remaining after the extraction of the juice is used mainly as fuel for the boilers to produce steam.

Juice purification

Once the juice is extracted (mixed juice) it is purified (the term clarification is more generally used in the sugar industry). The purpose of clarification is to produce a clear juice that is of neutral pH, light in colour and free of suspended matter. The juice is firstly screened (usually for factories which extract the juice through milling) to remove any large fibrous material. The juice is further clarified in large clarification reactors. The process involves the addition of milk of lime (calcium hydroxide slurry), which reacts with the naturally occurring phosphates in the juice to produce a calcium phosphate precipitate. Flocculants are added to assist the separation of impurities and suspended particles from the juice. The settled precipitate (mud) is filtered to recover the sucrose containing juice retained by the mud mixture. The filtrate is returned to the clarifier for further clarification and the filter cake is discarded (used as fertiliser by farmers).

Juice concentration and sugar crystallisation

The clarified product is called clear juice. The clear juice is then concentrated (brixed up) from approximately 11% to 65% brix in multiple effect evaporator vessels. These vessels boil off water under vacuum. The concentrated juice (syrup) is then sent to the vacuum pans for crystallisation (boiling). Vacuum pans are evaporative crystallisers. The syrup is concentrated in the vacuum pans to a level of supersaturation just below that at which spontaneous nucleation of crystals would take place. Seed crystals are added at this point. The purpose of the pan is to grow the seed sugar crystals by controlled evaporation of water and crystallisation of sucrose, in as many steps as may be required to maximise the amount of sucrose recovered. This is typically achieved in three successive boiling steps (three boiling system); each step produces sugar-crystals and molasses in a mixture called massecuite. The three boiling system produces three massecuites of successfully lower purities. Purity is defined as the ratio of sucrose (pol) to total dissolved solids (brix) expressed as a percentage. (The terms pol and brix have been properly defined in the glossary. More detailed information on the determination of pol and brix are presented in chapter 2.)

Figure 1.1 overleaf presents a simplified flow diagram of the sugar production process from sugar cane to raw sugar. The three boiling system employed by the Tongaat Hulett Sugar Mills is presented in Figure 1.2.

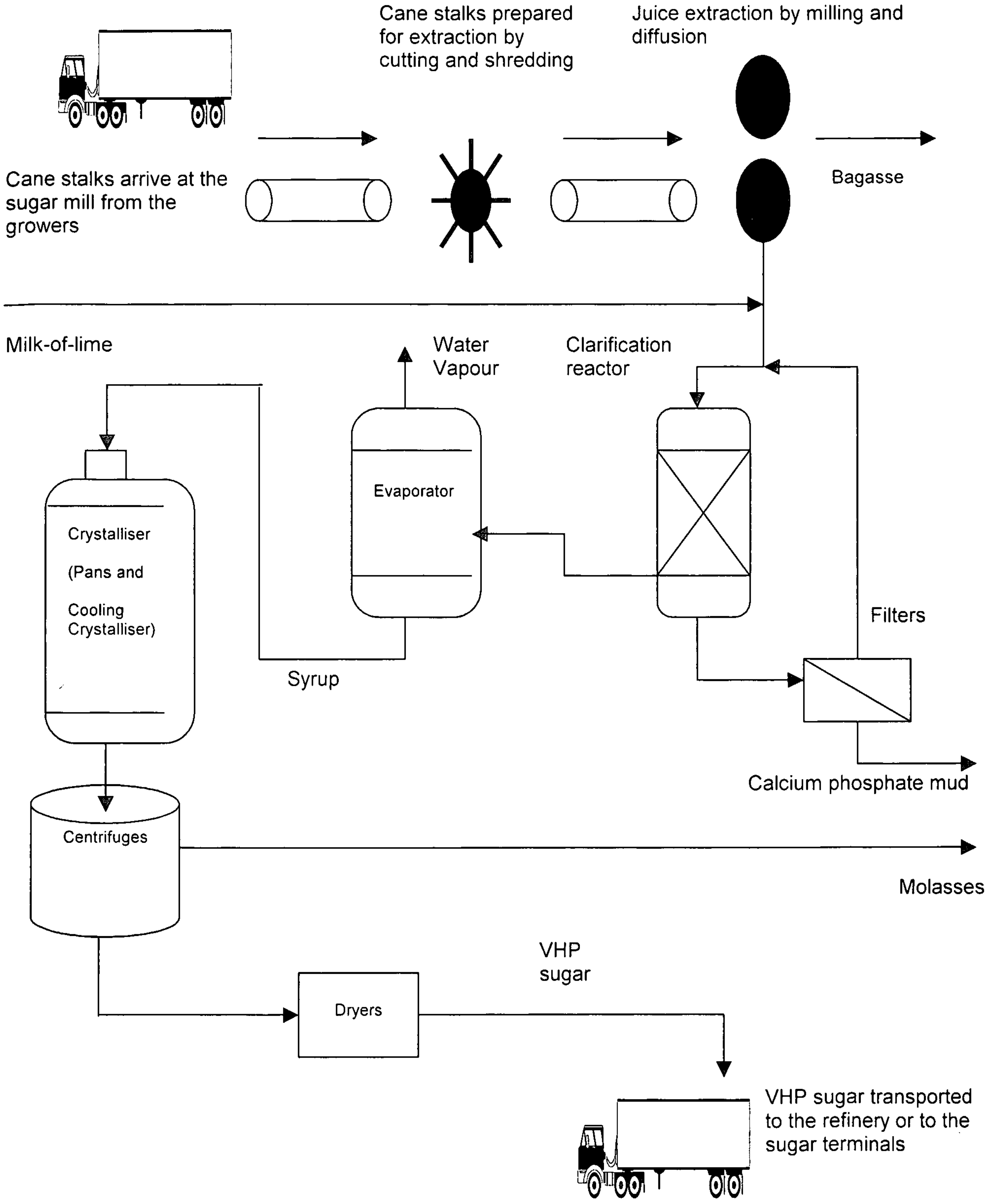


Figure 1.1: Simplified flow diagram of the sugar production process from sugar cane to raw sugar.

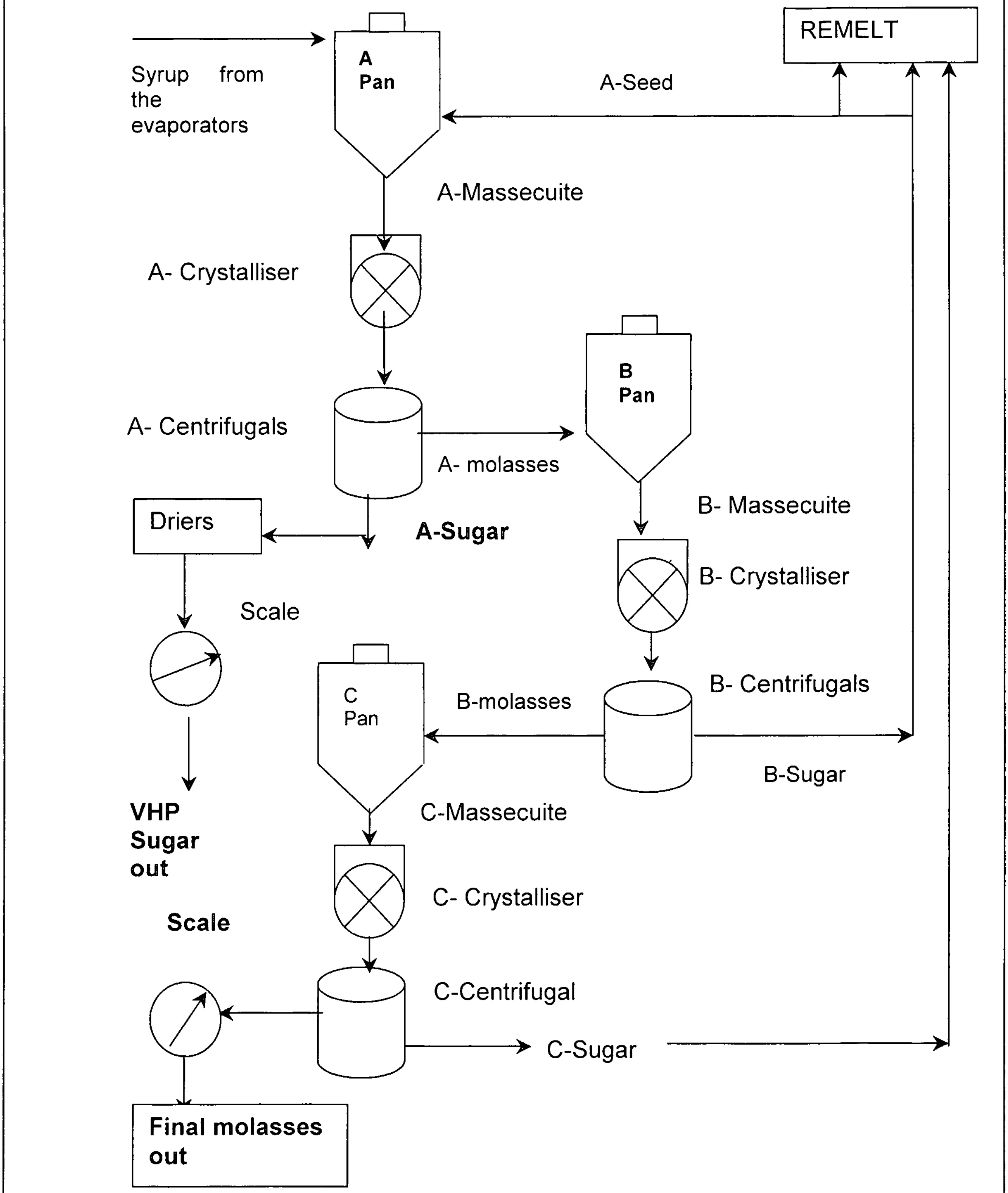


Figure 1.2: The three boiling system.

The three boiling system

As mentioned previously the three boiling system produces three massecuites of successfully lower purities (A, B and C massecuites). Syrup received from the evaporators is used to produce the A-massecuite. This massecuite is of the highest purity and produces the A-sugar product. As seen in Figure 1.2, the sugar crystal and molasses mixture (massecuite) is discharged from the pans into crystallisers (for further crystal growth) and then centrifuged to separate the sugar crystals from the molasses. The sugar crystals are then dried in driers. The dried product constitutes VHP (very high pol) sugar. This sugar has an average apparent sucrose content (pol) of 99.3% by mass and moisture content of 0.1%.

VHP sugar (brown sugar) is sent directly to the sugar refinery where white sugar is produced. VHP sugar is also sent to the South African Sugar Association (SASA) sugar terminal on Maydon Wharf, Durban Harbour, for export purposes.

The molasses separated from the A-massecuite is used to boil a second massecuite (B-massecuite). A slurry made up of finely ground A-sugar crystals is used for seeding the B and C pans. The B-massecuite is discharged into the B-crystallisers for further crystal growth. The B-massecuite is then centrifuged and the sugar crystals are separated from the molasses. This molasses, that is B-molasses, is used to boil the third massecuite, C-massecuite. The B-sugar crystals are used in the A-pans as seed crystals. Any excess crystals will be melted and returned to the syrup tank (after the evaporators) that is used to boil the A-massecuite. Melting here refers to the dissolution of sugar crystals in hot water.

C-massecuite is discharged into the C-crystallisers and then centrifuged. The sugar crystals are melted and returned to the syrup tank. The C-molasses, also called final molasses is weighed and sold by weight to outside companies. Sugar produced from the first boiling (A sugar) and molasses from the third boiling (final molasses) are the final products.

There are two process operations in the sugar factory that directly affect the recovery of sugar from evaporated syrup. These are the processes of crystallisation (boiling) and centrifugal operation. Successful automation of the vacuum pans (boiling) has been implemented using brix control. To date however on-line control of continuous centrifugals has not been successfully implemented.

Process efficiency

At various stages of the 3 boiling system, purity analyses are performed. As mentioned previously purity is defined as the percentage ratio of sucrose (pol) to the total soluble solids (brix) in a sugar product. Purity analysis can be performed for all the process streams i.e. juice, massecuite (combination of sugar-crystals and molasses) and separated sugar-crystals and molasses. These analyses are an integral part of the efficient running of any sugar factory. It provides an indication of the efficiency of the processes involved in the recovery of sucrose. Losses of sucrose can be immediately located where purity analyses are performed. Decisions to improve factory performance are based on these analyses.

Table 1.1 presents typical massecuite, sugar and molasses purities observed in the three boiling system employed by Tongaat-Hulett Sugar Mills. The massecuite is sampled before the centrifugals and analysed as sugar crystals and molasses combination for purity, while the sugar crystals and molasses purities are of samples obtained after centrifugal where the massecuite has been separated into its components.

molasses, also called final molasses is weighed and sold by weight to outside companies. Sugar produced from the first boiling (A sugar) and molasses from the third boiling (final molasses) are the final products.

There are two process operations in the sugar factory that directly affect the recovery of sugar from evaporated syrup. These are the processes of crystallisation (boiling) and centrifugal operation. Successful automation of the vacuum pans (boiling) has been implemented using brix control. To date however on-line control of continuous centrifugals has not been successfully implemented.

Process efficiency

At various stages of the 3 boiling system, purity analyses are performed. As mentioned previously purity is defined as the percentage ratio of sucrose (pol) to the total soluble solids (brix) in a sugar product. Purity analysis can be performed for all the process streams i.e. juice, massecuite (combination of sugar-crystals and molasses) and separated sugar-crystals and molasses. These analyses are an integral part of the efficient running of any sugar factory. It provides an indication of the efficiency of the processes involved in the recovery of sucrose. Losses of sucrose can be immediately located where purity analyses are performed. Decisions to improve factory performance are based on these analyses.

Table 1.1 presents typical massecuite, sugar and molasses purities observed in the three boiling system employed by Tongaat-Hulett Sugar Mills. The massecuite is sampled before the centrifugals and analysed as sugar crystals and molasses combination for purity, while the sugar crystals and molasses purities are of samples obtained after centrifugal where the massecuite has been separated into its components.

Table 1.1: Typical massecuite, sugar and molasses purities.

Purity	Massecuite [pol/brix x 100]	Sugar [pol/brix x 100]	Molasses [pol/brix x 100]
First Boiling (A)	87 %	99.3 %	67 %
Second Boiling (B)	67 %	89 %	43 %
Third Boiling (C)	55 %	83 %	35 %

Centrifugal operation

The sugar crystals are separated from the massecuite in a continuous or batch centrifuge. The separation process involves the addition of water to remove the film of molasses adhering to the sugar crystal. Wash water quantity has a direct impact on the colour and purity of the crystals produced. Too little water added to the massecuite will result in insufficient molasses being washed off the crystals, hence resulting in lower purities and higher colour of the sugar. This incurs a cost penalty when A-sugar is sent to the refinery. Alternatively too much water added will result in the total dissolution of smaller crystals and larger crystals will be reduced in size. This results in a molasses of higher purity, and in the case of final molasses where no further processing is performed; sucrose is lost which indicates monetary losses. The addition of wash water thus has a major effect on the efficiency of the centrifuging process.

Wash water to the continuous centrifugal is presently controlled by manually adjusting wash water addition in delayed response to sugar purity analysis received from the laboratory. This form of control is highly subjective, and varies from one individual to another. Colour bodies that are included in the crystal (a function of poor cane quality and or poor process control) cannot be removed in the centrifugal, however excessive molasses adhering to the surface of the sugar crystal is due to poor centrifugal operation. The manual control of wash water addition is therefore not a highly reliable method of controlling sugar purity in the centrifugal. A more sophisticated method of sugar purity control is required to minimise sucrose losses.

Sugar purity analysis/detection

The current method of laboratory sugar analysis used at all Tongaat Hulett Sugar Mills follows a procedure set by the South African Sugar Association (SASA). This method involves dissolving a sugar sample (50g) in 500ml of water. Two analyses are performed with this solution. Pol (apparent sucrose) is determined using the polarimeter and the brix is determined using the refractometer. Sugar purity is then calculated as the percentage ratio of the pol and brix analyses. The exact method is presented in appendix A.

The sugar purity analysis takes approximately one hour to perform. This method of sugar analysis is therefore not suitable for on-line factory control of centrifugal performance. High sucrose losses can be incurred due to the lag time between sampling and the receipt of the purity analysis. This procedure is covered in more detail in Chapter 2.

A meter for sugar purity detection

Dr P W Rein (Technical Director - Tongaat-Hulett Sugar Ltd) initiated in the early 1980's the development of an on-line sugar purity meter, for continuous centrifugal operation. The objective was to provide the centrifugal operator with a reliable on-line measurement of sugar purity and thereby facilitate the automation of the centrifugal. A meter measuring reflected light intensity off sugar samples was developed and this meter proved capable of predicting C-sugar purities. The results obtained from the development of a purity meter [Proome 1982], supported earlier findings of Miller and Wright [1978]. A definite relationship existed between sugar purity and measured reflected light intensity. Successful operation of the continuous centrifugal using the purity meter was not achieved. Investigations by Tongaat-Hulett Sugar [Proome 1982] were abandoned and have only been recently revisited.

Although the use of optical measurement techniques to predict sugar purity on-line can be traced as far as 1943, [Hovert and Gillett (1943)], an inexpensive commercial instrument for sugar purity detection in a continuous centrifugal is not locally available. This provided the motivation to develop a local meter for sugar purity detection. It was proposed that the research started by Tongaat Huletts Sugar using the measurement of reflected light intensity off sugar samples to predict sugar purity, be re-initiated.

1.2 Objectives of the investigation

This investigation is a continuation from the preliminary work performed by Tongaat Hulett Sugar. The objectives were:

- To develop and evaluate an inexpensive instrument for sugar purity measurement using the measurement of reflected light intensity.

- To provide the centrifugal operator with a reliable on-line measurement of sugar purity.

1.3 Approach to the investigation.

The approach to this investigation is:

- Survey literature on all present technologies for sugar purity analysis.
- Survey the principles of light reflectance and instruments that are used to measure reflected light intensity.

- **Laboratory scale trials**

    - Build a prototype to measure reflected light intensity.
    - Determine the light source and light detector for the purity meter prototype that ideally yields a reliable and repeatable relationship between sugar purity and measured reflected light intensity.
    - Determine the relationship between sugar purity and the measured reflected light intensity.

- **Factory scale trials**

    - Build a field/ factory sugar purity meter and conduct factory trials.
    - Compare the laboratory sugar purity meter with the factory purity meter.

This investigation has been divided into the following chapters:

- Chapter 2 presents the literature survey of all present technologies of sugar purity analysis.
- Chapter 3 provides a brief history and operation of continuous centrifugals.
- Chapter 4 describes the laboratory scale trials. The results leading to the selection of the ideal light source and detector are presented in this chapter. Chapter 4 also describes the simulation of factory conditions in the laboratory in order to anticipate any shortcomings of the laboratory scale apparatus.
- Chapter 5 describes the factory trials and compares the factory trial results with those of the laboratory scale trials.
- Chapter 6 presents the conclusions drawn from this investigation, together with some recommendations for further avenues of research and development.

Chapter 2

LITERATURE REVIEW

This chapter provides a review of the literature relating to the various aspects of sugar chemistry, sugar colourants and equipment using light measurement to measure the purity of sugar crystals. The literature review has been divided into three parts. The first part investigates the chemistry of raw sugar (brown sugar) and its associated colour. This includes the various types of colourants found in sugar and their influence on sugar purity. The second and third parts of the review highlight the current and alternative methods used to measure sugar purity.

2.1 The structure and colour characteristics of raw sugar.

In South Africa sucrose is obtained from sugar cane. Some countries obtain sugar from sugar beet. Sugar cane is defined as a tall grass of the genus *Saccharum* and is produced from sugar cane hybrids, which are the progeny of a number of *Saccharum* species. This section provides an introduction to the structure of the sugar crystal and the causes of colour in and around the sugar crystal.

2.1.1 The structure of raw sugar.

Sucrose is a disaccharide falling under the broader definition of carbohydrates. The chemical formula for sucrose is $C_{12}H_{22}0_{11}$. The pure disaccharide X-D-glucopyranosyl-β-D-fructofuramoside is commonly known as "sugar".

Sucrose is formed from its two building blocks: glucose and fructose by photosynthesis. If sucrose is exposed to high temperatures and low pH it readily breaks down into a 50/50 glucose and fructose mixture. Glucose and fructose are defined as invert sugars and the breakdown process of sucrose is therefore known as inversion [Pillay (1994)].

Figures 2.1 presents the structure of sucrose.

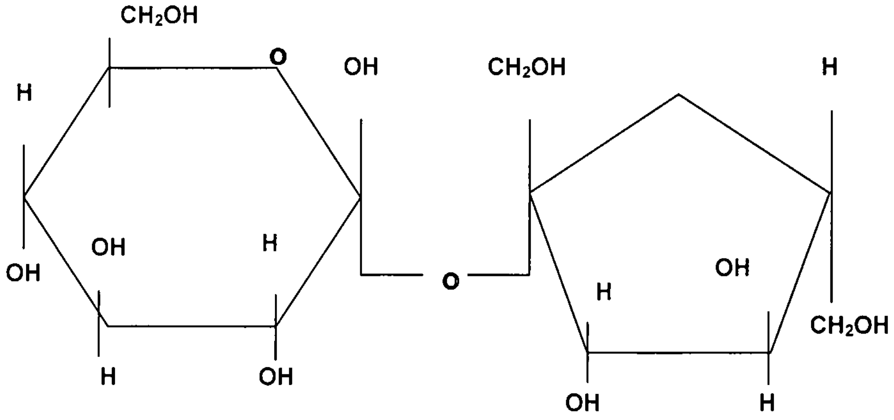


Figure 2.1: The molecular structure of sucrose. [(Moeller *et al* (1984)]

Sucrose is a disaccharide consisting of the two monosaccharides D-glucose and D-fructose held together by a glycosidic link in the α and β configurations respectively.

Figures 2.2 and 2.3 present the structures of glucose and fructose respectively.

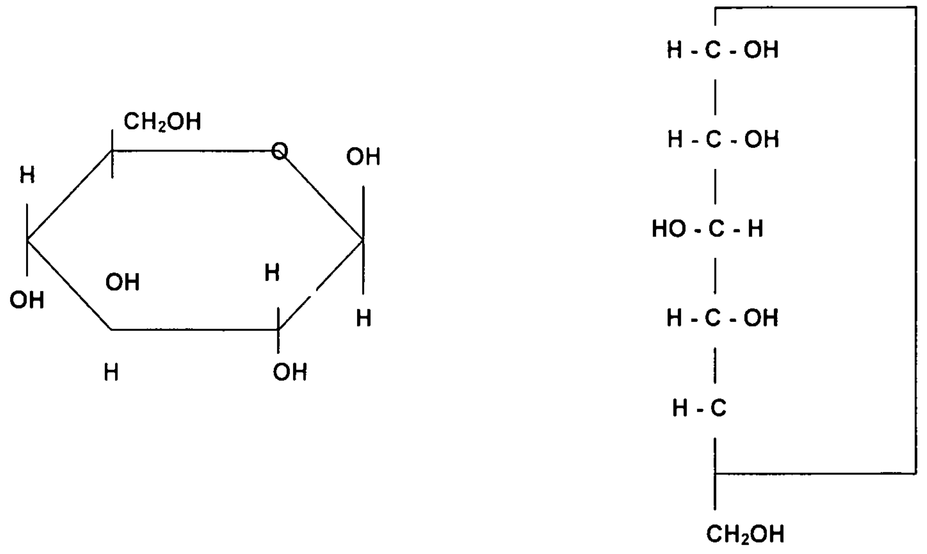


Figure 2.2: The molecular structure of glucose. [Moeller *et al* (1984)]

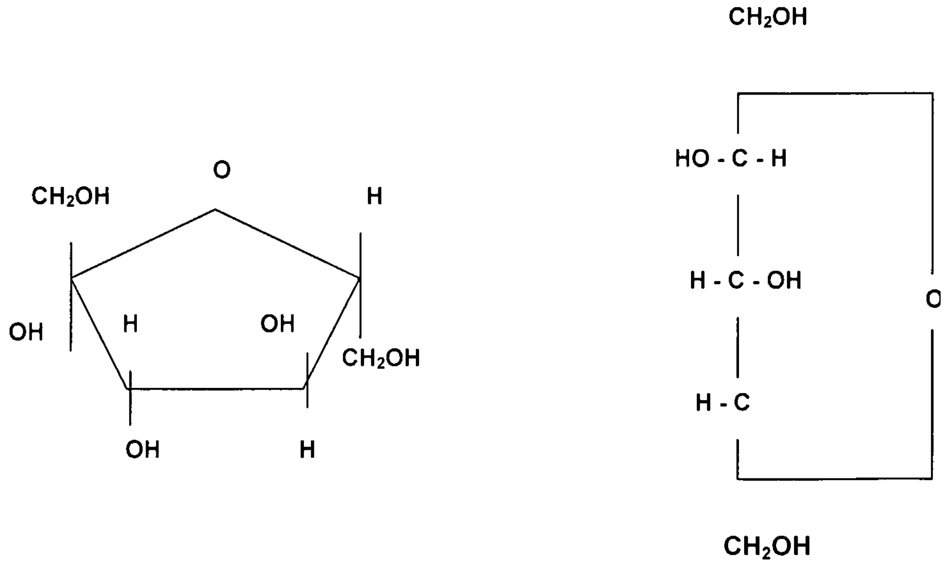


Figure 2.3: The molecular structure of fructose. [Moeller *et al* (1984)]

The investigation into the chemistry of raw sugar also revealed that there are colour bodies that affect the appearance and purity of the sugar-crystal. The next section investigates the colour characteristics of raw sugar.

2.1.2 Colour characteristics of raw sugar

Sugar colour is defined as that complex collection of molecules, which contribute to the increased light absorbance of sugar solutions at a particular wavelength. Although the word “colour” would refer to visual appearance, it is interpreted by the ‘sugar world’ as a measure of impurities due to most of the non-sugars being coloured. The word “colourant” refers to the material causing the colour.

Researchers who have studied sugar colourants have identified colourants as coming from two basic sources: the sugar cane plant and the factory process. Kennedy and Smith [1976] describe this classification as follows: “ Sugar colourants can be classed into two groups – generally monomeric, pH sensitive cane pigments, and generally larger molecular weight, pH insensitive colourants of factory origin”. The classification of the colourants into these two groups may give rise to some confusion, since the presence of colour in any sugar product must arise from compounds originally present in the sugarcane plant [Getaz (1988)]. Some compounds enter the sugar factory in the cane already coloured and contribute to a product colour in a more or less unchanged state, while other compounds entering the factory will not be coloured but form coloured compounds by means of reactions taking place during processing.

An additional way in which colourants are often distinguished is by the characteristics of molecular weight and pH sensitivity [Kennedy *et al.* (1976)].

a) Molecular weight

Generally polymeric colourants have the highest molecular weight (> 25000 daltons), followed by intermediate substances such as degradation products (molecular weight from 10000 to 25000 daltons) and flavanoids (molecular weight <10 000 daltons). A further class of sugar colorant is high molecular weight (HMW) colorant with a molecular weight greater than 100 000 daltons. HMW colourants are generally associated with polysaccharide material. [Hubbard (1993)].

b) pH sensitivity

At pH 4 most sugarcane colourants are not ionised and are relatively lightly coloured. At pH 9, ionisation, is almost complete and the colourants are in an ionic form and are more highly coloured.

Plant derived pigments have the greatest sensitivity to changes in pH due to the molecular rearrangements that occur under alkaline conditions, to give a series of conjugated double bonds. Conjugated double bonds are the structural requirement for visible colour. These rearrangements also occur in non-coloured phenolics as they react with ferric or ferrous ions to form coloured complexes.

Phenolic acid and flavonoids compounds are mainly responsible for the change in sugar colour. It is virtually impossible to measure the sugar colour reproducibly without maintaining a constant pH. The pH sensitivity of a colorant is expressed as an indicator value (IV). This is the ratio of the 420nm colour (wavelength at which the light absorption is measured) at pH 9 to that at pH 4. Therefore the relative quantity of phenolics and flavonoids is determined by comparing the IV of the different sugars and sugar solutions. Factory colourants generally have a relatively low IV of 1 to 3, while plant pigments can range from 3 to 40 for different monomers as flavanoids [Getaz (1988)].

The origin and effects of the various sugar colorant types are discussed in detail below.

2.1.2.1 Sugar cane plant derived colour

Plant derived pigments are phenolic or polymeric in nature and exist as glycosides attached to sugar residues in the cane plant. Some of the plant pigments such as chlorophylls and carotenes are insoluble and are therefore eliminated early in the factory process. Others, such as flavonoids are pH sensitive and these low molecular mass substances are oxidised by enzymes to form enzyme-browning colourants of high molecular mass that are pH insensitive.

Anthocyanins are water-soluble and are highly coloured. They react during the clarification process to form colourless phenols, which react with iron as a precursor, to form highly coloured compounds.

Caffeic, phenolic and other organic acids are colourless or pale yellow while in the cane, but on contact with alkali form yellow to orange colourants, which persist throughout the refining process.

Other alkaline degradation products are formed by the isomerisation of reducing sugars such as glucose and fructose and the decomposition reactions of hexoses [SMRI Sugar Engineering Course, (1996)].

2.1.2.2 Factory produced colour

The following are colourants produced in the factory.

Melanoidins

Melanoidins in sugars are dark polymers. They are produced when the Maillard reaction products of reducing sugars with amines, amino acids and proteins rearrange to form a complex mixture of dark polymers. Browning takes place in this reaction. Melanoidins form only if the mixture is heated for example low heat over long periods (storage conditions) can cause this type of colour formation. This reaction is influenced, by the nature and concentration of the sugars and the amino acid groups as well as temperature, pH, time and the presence of iron and phosphate.

Melanin colour

These are black enzymatic oxidation products of phenolics such as tyrosine (a monophenol) and dihydroxphenylalanine (a polyphenol). Colour formation depends on enzyme, polyphenoloxidase and oxygen. Melanins can be removed during processing but are otherwise preferentially included in the crystal during crystallisation.

Caramels

These colourants are produced when sugars are subjected to heat and/or low pH. They are degradation products of polyhydroxy-carbonyl compounds. Caramels are polymers and both acids and bases can catalyse their formation. Organic acids formed by the degradation of reducing sugars can also catalyse caramelisation.

The measurement of these colourants is needed to determine the quantity of impurities that are inherent to the respective product stream i.e. the sugar, molasses or juice. The present method used to determine colour is defined overleaf.

2.1.2.3 Measurement of colour

The ICUMSA (International Commission for Uniform Methods of Sugar Analysis) method of colour measurement is generally used in the sugar industry [SASTA (1985)]. The measurement is based on five main criteria [SMRI Sugar Engineering Course (1986)]:

a) The wavelength at which the light absorption is measured.

There is little absorption in the red and yellow part of the spectrum but the absorption increases rapidly in the violet and blue region. It was found that the optical centre of gravity of the luminosity curve for the colourants in sugar solutions was 560 nm and this lead to ICUMSA recommending that this wavelength be used. Inspection of the spectrum of a typical raw sugar, however, reveals that readings in the blue to violet range would provide greater values with accompanying better sensitivity for instrument measurements. Instruments such as colorimeters and spectrophotometers are widely used nowadays and ICUMSA now specifies measurement at **420 nm**. It is essential that the spectrophotometer gives correct wavelength and transmission readings and that consideration be given to the wavelength band width and the quality of the reference solution. There can be differences of up to 20% between different makes of instrument and up to 15% between instruments from the same manufacturer.

b) pH of the solution.

Sugar colourants are sensitive to pH with absorption increasing as pH increases. The pH sensitivity varies significantly with the nature of the colourants but there is a rapid increase in absorption in the neutral region and a levelling off above pH = 9. ICUMSA recommends that the solution be adjusted to pH = 7. Care should be taken in adjusting the pH as the reaction is not reversible, i.e., if too much acid or alkali is added and over shooting occurs, the colour will not be the same on readjustment as when the pH is brought to the target gradually. It has been shown that an error of 0.1 pH unit results in an error of 5% or more and it is recommended that the pH be adjusted to 7 exactly or at most, 7,00 ± 0,05.

c) Clarity of the solution.

The presence of solid and colloidal material affects the path of the light through the sugar solution. The solution, therefore, must be as clear as possible and ICUMSA recommends filtration through a 0.45 μm membrane.

d) The concentration of the solution.

This is straightforward. For example consider two cups of tea, one strong and the other weak. The tea is the same but the colours appear to be different. The concentration of the solution, therefore, must be known.

e) *The length of the sample cell (for the spectrophotometer).*

As well as concentration, absorption also varies directly with the length of the sample cell. Beer-Lambert's law adequately represents these variations. The distance the light travels through the sample must therefore be specified.

The colour calculation formula is as follows:

$$\text{ICUMSA Colour} = \frac{\text{Absorbance@ 420nm x 10000}}{\text{Cell Length (mm) x Concentration of Total Solids in solution } \left(\text{g/cm}^3\right)}$$

The colour measurement provides an indication of the impurities or the level of non-sugars of a sugar solution due to the fact that most non-sugars are coloured. The method of analysis for purity is presented in the following section.

2.2 Present Method of Determining Purity

Purity is defined as the percentage ratio of sucrose (pol) to the total soluble solids (brix) in a sugar product. Purity analysis can be performed for all the process streams i.e. juice, massecuite (combination of sugar crystal and molasses) and separated sugar and molasses. The following formula are used:

1. Apparent Purity $\frac{\text{pol}}{\text{brix}} \text{x} \frac{100}{1}$

2. Gravity Purity $= \frac{\text{sucrose}}{\text{brix}} \text{x} \frac{100}{1}$

3. True Purity = sucrose /total dry solids

Pol, brix, sucrose and total dry solids can be expressed as a percentage by mass or as an actual mass. Total dry solids refers to the determination of the solids concentration of an aqueous solution determined by drying.

These formulas are used according to the accuracy of the analysis required. Apparent purity is most commonly used. In order to clearly understand the definition of purity, it is necessary to define the terminology presented. A view of the methods of analysis is also presented to provide a better understanding of the above methods of measuring sugar purity.

2.2.1 Pol

The polarimeter provides a quantitative estimation of sucrose by measuring the rotation of the plane of polarised light. Ordinary light travels in waves that vibrate in an infinite number of planes. These waves when passed through a special optical device (polariser) can be made to vibrate in one place only. When this phenomenon occurs the light is said to be polarised.

When polarised light is passed through a solution containing sucrose, the sucrose is able to rotate the plane of polarisation by an amount proportional to the concentration of the sucrose. Sucrose is therefore said to be optically active. It is this principle that is used in a polarimeter and the reading obtained is converted to a pol concentration, generally

°Z pol (International Sugar Degrees). Pol as can be seen is determined from the word "polarisation".

Pol is not the exact sucrose content. It is identical to sucrose if the solution contains pure sucrose only. Exact sucrose content can be measured accurately using gas chromatography (GC). In a sugar solution, sucrose is not the only optically active substance. The two simple sugars glucose and fructose are also optically active. Sucrose rotates the plane of polarisation to the right, glucose also to the right, and fructose very strongly to the left. Hence the pol of a sugar solution is known as an "apparent" sucrose content, as the concentration of fructose and glucose will affect the pol either positively or negatively. Furthermore the degree of rotation can change with time. Pol is therefore an approximate measure of sucrose.

Due to the expertise required for operating the GC equipment and the high expense of the equipment itself, polarimeters (also called saccharimeters) are used to determine the apparent sucrose content of a solution. A 100-point scale is defined for the measurement of pol. The scale is divided linearly between 0°Z (pure water) and 100°Z (normal sugar solution). Normal sugar solution is defined as 26 g of pure sucrose (weighed in air, with brass weights under normal atmospheric conditions) dissolved into a volume of 100 cm^3 at 20°C. Polarised light of wavelength 546 nm is used and a tube length of 200mm [(Brown and Zerban (1941)].

2.2.2 Brix

Brix is defined as total dissolved solids, including the pol (apparent sucrose). A refractometer is used to determine the total solids of a sugar solution by measuring the refractive index of an aqueous solution. The refractive index of the solution is proportional to the amount of dissolved material and can therefore serve as a measure of solids content. This principle is valid only for pure solutions as non-sugars present in sugar products influence the refractive index in a way similar to sucrose.

The refractive index is defined as follows: When a beam of light from one medium, e.g. air, falling at an inclined angle upon a surface of a second medium, e.g. water, it is found that the beam on entering the second medium is bent or deflected from its original course. This phenomenon is known as the refraction of light. A good example is the bent appearance of an oar of a boat when seen obliquely under water. The ratio of the sine of the angle of incidence to the sine of the angle of refraction is always a constant value for the same temperature. Figure 2.4 presents refraction graphically.

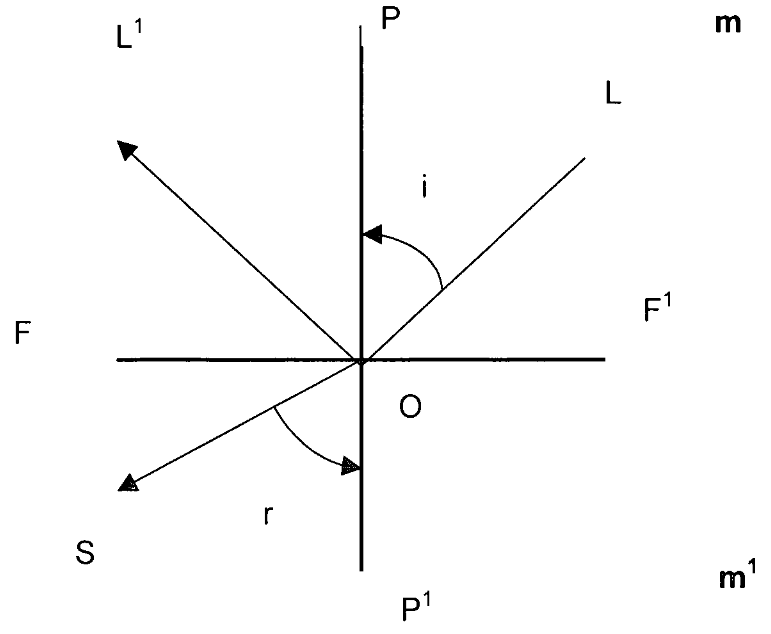


Figure 2.4: Refraction of light

In Figure 2.4:

m and m^1 are the 2 media.

PP^1 is drawn perpendicular to the dividing surface FF^1.

LO is the beam of light passing through medium m. It is refracted in the direction OS. The reflected beam is OL^1.

The ratio of $\frac{\sin i}{\sin r}$ = n is called the index of refraction.

The ratio of $\frac{\sin i}{\sin r}$ is also defined by the velocity of light in the 2 media

$$n = \frac{\sin i}{\sin r} = \frac{V}{V^1}$$

Where V is the light velocity in **m** and V^1 is the velocity in **m^1.**

The ratio of n = $\frac{\sin i}{\sin r}$ is used to determine the brix of the solution.

The measurement of refractometer brix can be simply demonstrated using a refractometer trough [Brown and Zerban (1941)]. Figure 2.5 presents a diagram of a refractometer trough.

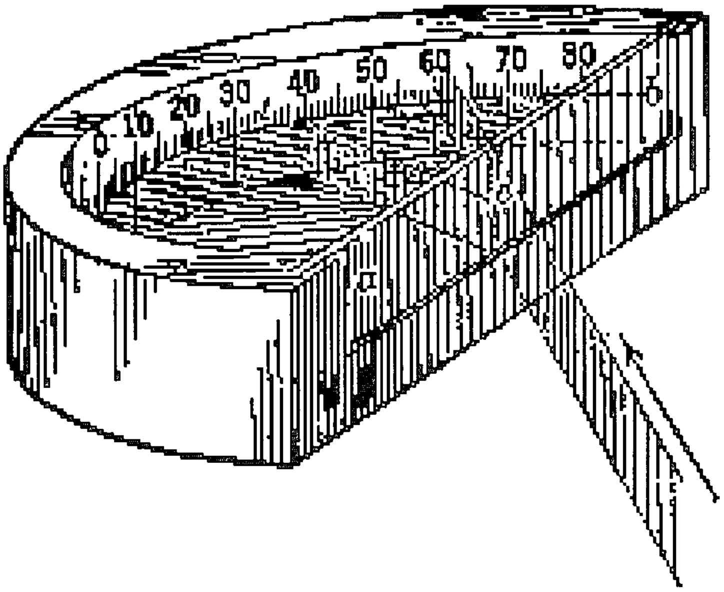


Figure 2.5 Measuring refractive index by refractometer trough.

Light shines through the small glass slit in the trough that has been calibrated (like a protractor). The angle of incidence and refracted angles can be seen from above and below the sugar solution and hence the refractive index can be determined.

Another method used to measure brix is the measurement of the critical angle. This method is considered more accurate. Total internal reflection refers to the critical angle of incidence where the light ray is totally reflected, i.e. no refraction occurs at this angle.

Therefore where previously $\frac{\text{Sin}\,i}{\text{Sin}\,r} = n,$

Here r=90° and Sine 90 = 1, so Sin$i$ =n.

This critical angle is used to determine the solution concentration. Refractometers are fitted with linear scales to be looked up in tables or are calibrated directly in brix.

Refractometers and polarimeters are a common sight in all sugar mill laboratories. The purity of the respective sample is calculated once the pol and the brix readings have been obtained. This procedure (SASTA method) is explained in detail in Appendix A.

2.3 Other methods used to determine sugar purity.

The methods for determining sugar purity and colour discussed above apply to sucrose solutions and not to solid crystalline sugar. Techniques to determine the sugar purity and colour of solid sugar crystals were therefore explored. The principle of colour measurement using wavelength or frequency is fairly common and is presented in most Physics textbooks. An alternative optical technique of measuring reflected light intensity to predict the colour and purity of brown sugar crystals was documented and presented by Miller and Taylor [1974]. In this study the two methods of measuring light (frequency/wavelength and light intensity) to predict the purity of low-grade C-sugar is investigated. The details of the two methods investigated are presented below.

2.3.1 The measurement of light wavelength or frequency

Relevant theory

The physical theory of light regarding the measurement of wavelength provided a greater understanding into the operation of optical instruments used to measure reflected light wavelength. Light is luminous energy that causes the sensation of vision. Examples of light sources are the sun and the stars, which are self-luminous while electric lamps are artificial sources of light. When light falls on an object it is reflected, refracted or transmitted (absorbed). The different colours are produced by light and are electromagnetic vibrations recurring at discrete wavelengths. Light consists of localised packets of electromagnetic energy called photons, which move, through space at a speed (C) of 3 x 10^8 m/s. Photons have wave-like properties (wavelength and frequency) [Nelkon (1981)]. A photon is a localised wave packet of time varying, oscillating self-sustaining electric and magnetic fields - hence the use of the term electromagnetic waves.

According to Huygens principle [Nelkon (1981)], light consists of vibrations or wave motions. Waves of light, contrary to those of sound, vibrate transversally instead of longitudinally. Figure 2.6 presents the wave properties of a light wave.

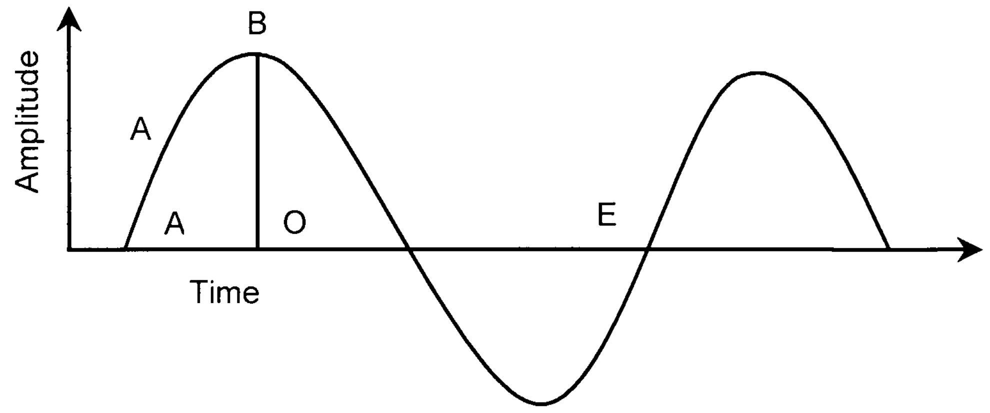


Figure 2.6: Diagram of a light wave

OB	is known the amplitude, that is the distance from the middle to the extremity of the oscillation.
A to E	is know as the wavelength. Wavelength is measured in nano-metres.

Frequency is the number of waves per second. The unit of frequency measurement is Hertz (Hz).

Therefore: $C = \lambda\ f$

Where : C is the speed of light (ms^{-1}).

λ is the wave length (m)

and f the frequency (Hz or s^{-1}).

The colour depends on the length of the wave. The colour of the light may therefore be expressed mathematically in terms of frequency or of its wavelength. The human eye can perceive light of wavelengths between 373 and 820nm. White surfaces reflect light while black surfaces absorb light. Coloured surfaces reflect some frequencies of light and absorb others.

The spectral colours are as follows:

Colour	(nm)
Red	683
Orange	615
Yellow	559
Green	512
Blue	473
Indigo	439
Violet	410

Longest wavelength

↓

Shortest wavelength

If a certain wavelength is absorbed by the medium, the remaining mixture of wavelengths reflected back to the observer is perceived as a colour other than white.

One of the main components in a spectrometer, measuring wavelength is a diffraction grating. A diffraction grating acts like a prism, by spreading light into its spectral components. As mentioned above a white light source is composed of a spectrum of colours i.e. it is a polychromatic light source. Each colour corresponds to a different frequency of light. The diffraction grating sorts light by frequency with violet (highest frequency) at one end and red (the lowest frequency) at the other.

Gratings rely on the interference between wave fronts caused by microscopically ruled diffraction lines on a mirrored surface. Figure 2.7 presents the diagram showing the operation of the diffraction grating. The wavelength of the reflected light varies with angle as defined by the grating equation where m is the order of the spectrum (m = 1,2,3....).

$m \quad = d\,(\sin\alpha \pm \sin\beta)$. As depicted in figure 2.7, d is the distance from the incident wavefront to the defracted wavefront in nm.

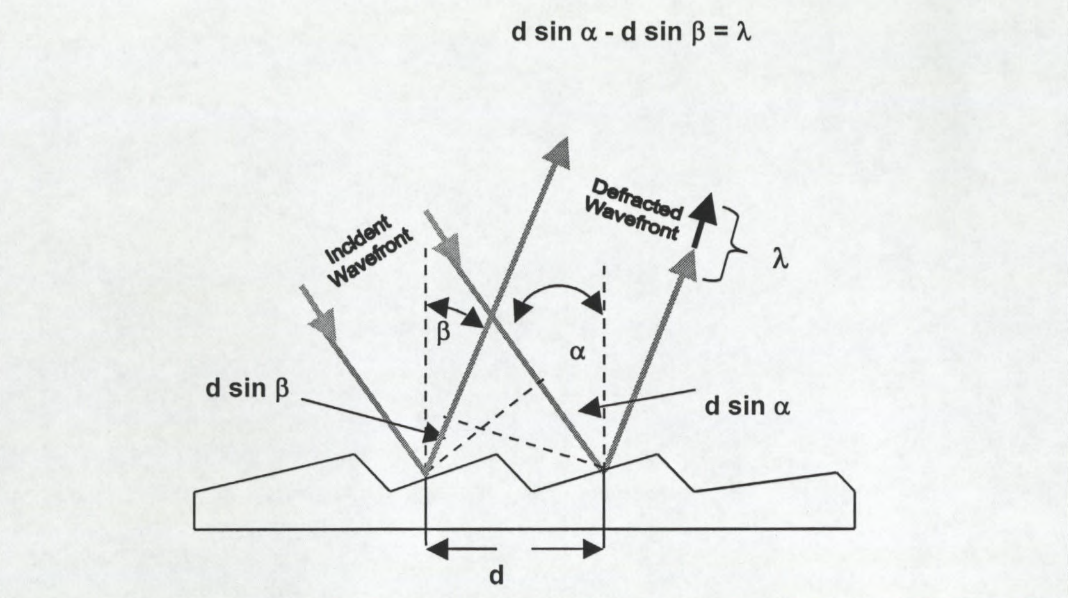


Figure 2.7: Diffraction grating

Hence it can be seen that the measurement of frequency/wavelength can be used to directly predict the colour and purity of sugar crystals.

Instruments for measuring wavelength of reflected light off the surface of sugar crystals

Nielson [1996] developed the Neltec colour Q800 colorimeter to measure sugar colour. This instrument is being used successfully in the American sugar industry [Clarke (1997)]. With the colorimeter, reflected light off a sugar surface is separated into the spectral components and analysed by an on-line computer. The Neltec colour Q800 is able to measure colour rapidly on solid crystalline sugar wet or dry with good correlation to the ICUMSA colour measurement at 420nm. The instrument has only been applied to measure the colour of sugar on a moving sugar belt conveyor.

Hunterlab [1999] also produces colour measurement equipment that employs the principle of measuring the reflected light wavelength. These colour instruments have been applied in the food industry where the colour of breads, bread rolls and cookies have been monitored in an oven. Sugar, cereals and coffee are other products have also been monitored for colour by the Hunter Lab colour meters. These colour meters have been used by the TSB Sugar Mill (Transvaal, South Africa) in the laboratory [Moodley (1999)]. Moodley achieved a favourable correlation between the Hunterlab sugar purity measurements and laboratory analysis of C-sugar, however the instrument was not tested in the factory. Hunterlab colour meters have proven to be robust enough to survive factory conditions.

The Hunterlab colour meters presented above were tested either on a conveyor belt or in the laboratory. The literature review also revealed colour meters that were able to detect sugar colour inside a continuous centrifugal. These particular instruments related reflected light intensity to sugar colour or purity. The findings are presented in the following section.

2.3.2 The measurement of reflected light intensity off the surface of sugar crystals

Relevant theory

The concepts of reflection, refraction and transmission were introduced previously. The laws of reflection state that the incident rays, the reflected rays and the normal lie on the same plane with the angle of incidence being equal to the angle of reflection. Light falling on an object is reflected, refracted or transmitted (absorbed). Light has both wave and particle nature and can there fore be seen to be travelling in straight lines. This is called rectilinear propagation of light.

Reflection of light is that fraction of light falling on a surface, which is reflected. Reflection off smooth surfaces is regular, that is, light is reflected in one direction due the smoothness of the surface. Lightly coloured and/ or smooth surfaces reflect light more readily. Rough surfaces result in light being reflected in many directions (scattered or diffusely reflected). Dark and textured surfaces absorb a lot of light and therefore have low reflectance [Sternheim and Kane (1983)]. The theory on the reflectance of light off coloured bodies revealed that lightly coloured bodies reflect more light and darkly coloured bodies absorb more light. The intensity of the reflected light will therefore vary according to the quantities of light that are absorbed or reflected by the relevant surface. Hence the intensity of reflected light should correlate with the colour of a body.

The equipment used to measure reflected light intensity off solid crystalline surfaces were investigated and are presented below.

Instruments for measuring reflected light intensity off the surface of sugar crystals

a) The SRI reflectance meter

The Sugar Research Institute (SRI) of Australia began investigations into the development of a reflectance meter for the determination of raw sugar purity in 1974 [Miller and Taylor]. Up until this stage a method to continuously monitor the purity of sugar leaving the centrifugals and sugar driers was not available. The method used to monitor sugar purity relied on visual assessment of sugar colour by the operator. As can be expected this form of assessment is not exact and varied from individual to individual. Initial attempts at developing a reflectance meter to measure sugar purity, were performed on raw sugar leaving the centrifugals on a conveyor belt. The reflectance meter consisted of a white light source, which was directed on to the sugar surface. The reflected light was received by a photo-resistor or photoelectric cell (a photo-sensor) i.e. the photo-sensor measured the intensity of the reflected light. No pre-treatment of the sample was required apart from a level sample surface and a constant geometry between light source, sample surface and receiving sensor.

The results achieved were favourable with good correlations between sugar purity and cell resistance being achieved. For the factory trials a Phillips 150W light and an ORP - 12 (cadmium sulphide) light dependant resistor was used. The reflectance meter developed was considered a success. However it was acknowledged that the meter needed to operate in a relatively harsh environment where readings could be affected by sugar dust settling on the lamp and photocell. Vibration was also recognised as a contributing factor to unsettled or varying light detector output.

The reflected light intensity meter was accepted as a reliable indicator of sugar purity by chemists and operators.

A similar method to automatically control raw sugar purity in a centrifugal is described by King [1975]. The attempt to automate low grade C-sugar purity exiting a continuous centrifugal was presented by Wright [1977]. Wright describes the experiment with a commercially developed reflectance meter [Davis (1976)], testing its applicability to C-sugar purity control in a continuous centrifugal. Two arrangements were tested, one measuring the purity of mixed diluted sugar exiting the centrifugal and the second the measurement of the purity of sugar on the top of the spinning conical screen of the centrifugal. The measurement of the reflectance off dilute magma was not successful. However trials measuring the sugar purity on top of the screen of the centrifugal produced favourable results with a linear relationship between reflectance and sugar purity.

Miller and Wright [1978] presented a review of the progress on the development of an automatic method to control C-sugar purity. Working with the linear correlation of sugar purity and reflectance reading, the automation of wash water addition was tried. It should be emphasised that the meter should be robust enough to withstand the harsh conditions in a centrifugal (high temperature and moisture content).

During testing the reflectance meter experienced excessive molasses fouling of the tubes, thus indicating that the distance of the tubes from the basket required optimisation. The meter was calibrated using extremes of high and low sugar purities. Results of work conducted by Miller and Wright [1978] revealed favourable correlations of C-sugar purity by the reflectance meter, with an estimated standard error of 0,75 units of purity.

Testing by Tongaat Hulett Sugar was also conducted in an attempt to develop a reflectance meter to predict C-sugar purity in a continuous centrifugal. Their experiences are presented below.

The Tongaat -Huletts reflectance meter.

Shorn [1982] and Proome [1982] performed the preliminary trials at Darnall Sugar Mill (North Coast, Natal), where the reflectance meter was installed on a K850 BMA "C" - centrifugal. The Huletts team called their reflectance meter a Purity Meter. Proome [1982] presented the principle of operation as simple and based on measured reflected light intensity. A light source was focused onto a centrifugal screen containing the surface of sugar crystals and a cadmium sulphide photoconductive cell was used to detect the variation in intensity of the reflected light beam.

The unit was calibrated for the purity range of 75 to 85 %. The photoconductive cell's output was electronically conditioned to produce a 4 - 20mA output signal. A graduated meter (0 - 100%) connected to the output signal was used to indicate purity and the operator used this reading to adjust water addition to the centrifugal. It was concluded from these trials that there existed a definitive relationship between the Purity Meter (reflectance meter) readings and the sugar purity. This relationship was considered good enough to control C-sugar purity. The relationship between sugar purities and the purity meter readings were linear with regression correlation's of up to $r^2 = 0,99$ being obtained for individual tests. The automation wash water addition however was not successfully implemented. The purity meter required calibration and cleaning frequently i.e. every week.

Although trials provided a strong linear relationship between sugar purity and the purity meter reading and the operator was able to successfully control the sugar purity by manually adjusting the wash water valve, no further investigation was pursued.

2.3.3 Wavelength versus intensity measurement.

The use of measured wavelength is a more scientifically accepted optical technique for colour detection in that the exact colour could be predicted using the measured wavelength. Moodley's [1999] and Nielson' [1996] results confirmed this with regard to predicting sugar purity. The SRI meter and the Huletts meter (measurement of light intensity) have also successfully predicted sugar purities. Hence it can be seen that both the methods can be used to predict sugar colour/purity.

The cost of Hunterlab equipment used by Moodley [1999] is considered too high (at approximately R120000 per unit). When taking into account that that an average sugar mill possesses 6 - 10 C-centrifugals, the installation of these meters is not a practical option. The use of the Neltec [Nielson (1996)] colour meter was successfully tested on a sugar conveyor belt, but no trials were performed inside a continuous centrifugal. The Hulett meter is a low cost apparatus and its operation is fairly simple. It was therefore decided on the basis of low cost and simple operation that the research initiated by Tongaat Hulett in 1982 be continued.

Chapter 3

CONTINUOUS CENTRIFUGALS

In Chapter 2 it was stated that the purity meter to be developed is intended to operate in a continuous centrifugal. In order to develop the purity meter an understanding of the environment in which the purity meter is to operate is needed. Therefore Chapter 3 provides a basic knowledge of continuous centrifugals used for the separation of molasses and sugar-crystals from massecuite (molasses and sugar-crystals mixture) in the sugar industry.

3.1 Continuous centrifugals in the sugar industry.

Continuous centrifugals have been in use in the sugar industry since 1950 [Wiehe (1974)]. These continuous machines are generally used for the separation of B and C massecuites where crystal breakage is not of paramount importance. High crystal breakage in A-sugar is not acceptable as this is the final product and must adhere to the required product specification. Batch centrifugals are therefore used for A-sugar separation. The technology/design of continuous centrifugals have however advanced and high-grade centrifugals are on the market (for A sugar).

The operation of the centrifugal is based on the model consisting of a thin layer of massecuite (approximately 3 mm thick) moving continuously over the basket screen, while the mother liquor is being purged. As the massecuite moves up the basket screen, and molasses is drained under centrifugal force, the sugar becomes drier. The cured sugar goes over the top of the basket into a sugar chamber. Massecuite is fed continuously in the apex of the cone. The cured sugar and molasses are separated in different streams through chambers at the bottom of the centrifugal.

The centrifugal consists of a conical basket and is mounted vertically. The basket is driven at constant speeds by vee belts from an electric motor. Baskets are generally made of stainless steel, which can be perforated or of the solid type with slots for molasses drainage. A backing screen is fitted to the top of the basket to which a sugar screen is fitted. The basket is housed in a monitor casing where provision is made for sugar and molasses chambers.

Figure 3.1 presents the layout of a typical continuous centrifugal.

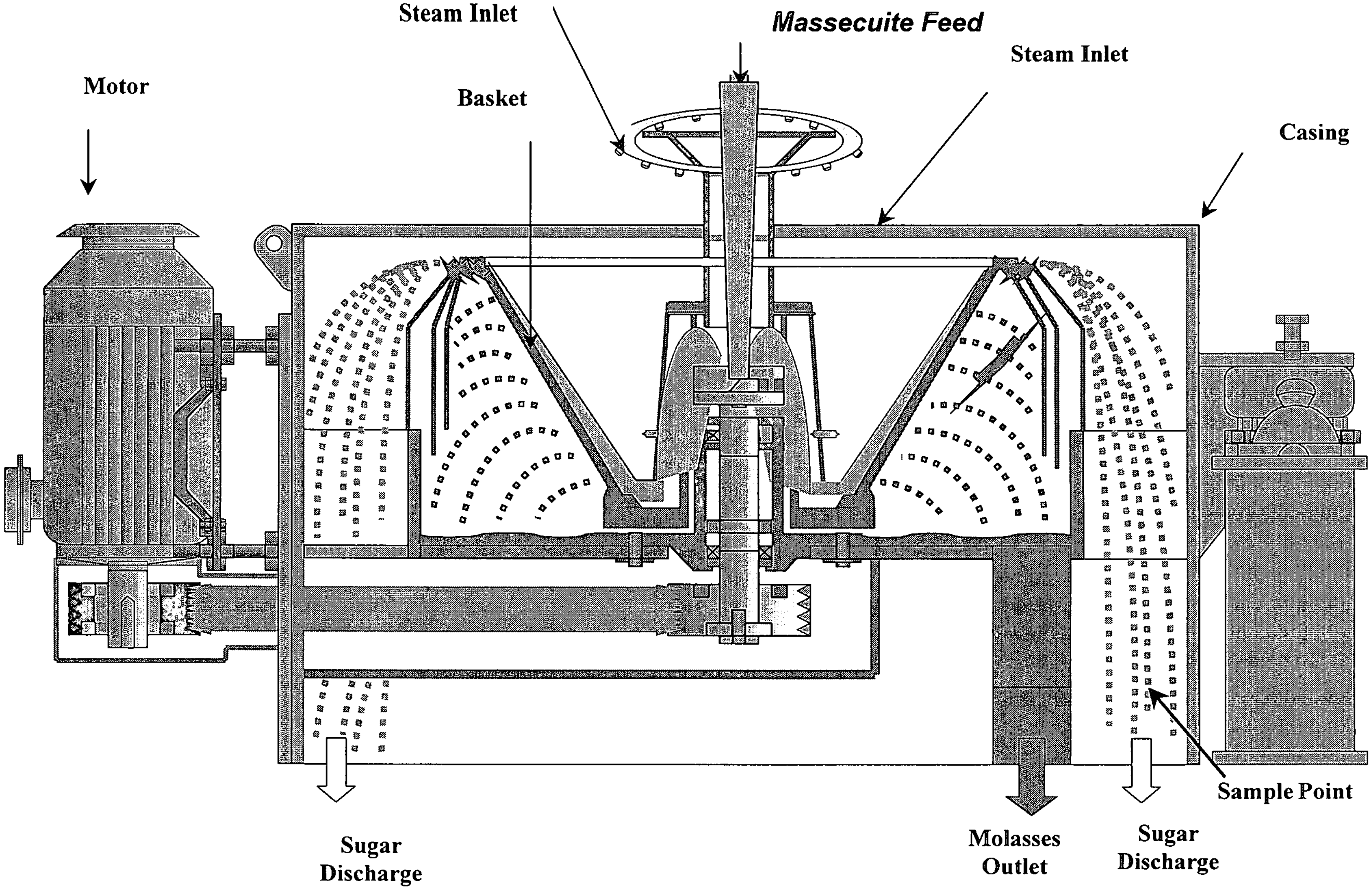


Figure 3.1: Diagram of a typical continuous centrifugal.

The throughput of a centrifugal is expressed in terms of volume of massecuite treated (not in terms of the quantity of sugar produced). The brix of the massecuite is used as an indicator of viscosity. The feed of massecuite to a centrifugal when observed with a strobe scope looks like a series of 'fingers' spreading from the bottom to the top of the basket. This is presented in Figure 3.2. The 'fingers' are caused by erratic surges of massecuite from the accelerating bell cup. The accelerating cup helps with massecuite distribution on to the screens.

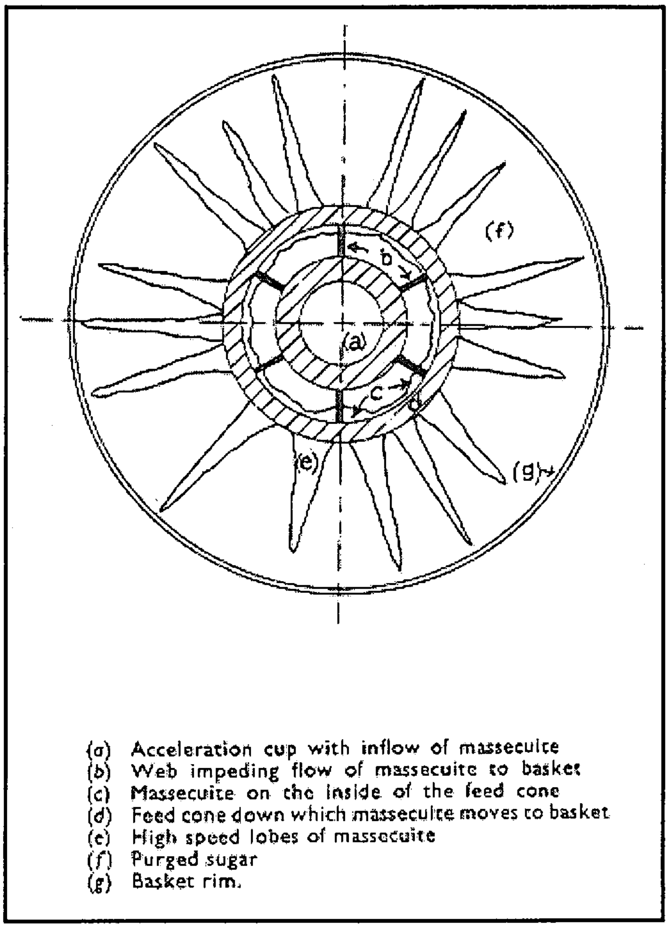


Figure 3.2: Movement of massecuite on the centrifugal screen.

3.2 Present continuous centrifugal control.

The continuous centrifugal can be controlled manually or automatically by controlling the feed and wash water addition. Automatic regulation of feed can be achieved by linking the input current to the drive motor with a feed valve mechanism. There is no form of automatic control on the B- and C-continuous centrifugals at Tongaat Hulett Sugar. The amount of water addition on continuous centrifugals is dependent on the operator's visual inspection of the sugar exiting the centrifugal. The appearance (colour) of the sugar is related to sugar purity analysis received from the laboratory before making water adjustments.

Water and steam are required for the separation of crystals from the mother liquor for the following purposes:

Due to the very strong relationship between temperature and viscosity, and the massecuite feed to the centrifugal being very viscous, the addition of steam is necessary to reduce the

a) Viscosity of the massecuite. Steam allows for an increase in temperature with minimal dilution to the molasses. Steam and water addition are also necessary to have proper distribution of the massecuite over the screen.

and

b) To effectively wash the molasses off the crystals and to ensure that the required sugar purity is maintained

Steam is introduced around the massecuite feed (piping is seen on top of the monitor casing). Water is added to the massecuite feed column by means of a perforated pipe or by circumferential sprays. Figure 3.1 shows the present method of water addition (circumferential sprays). A flow meter on the water line can be used to adjust the water addition while steam addition is relatively small and the flow is therefore not measured.

3.3 C-Sugar purity control.

The C–sugar purity (the sugar that was tested for this investigation) required is in the range of 82 - 85%. As mentioned previously, the sugar purity is controlled by the operator's visual inspection and laboratory analysis. This kind of sugar purity control is subject to an individual's judgement and will naturally vary from one individual to another.

Another important factor in controlling wash water addition is controlling the final molasses purity. A purity rise of 1,5 to 2 units is acceptable from the original mother-liquor to the molasses exiting the centrifugal. Purity rise is determined by comparing the purity of the mother liquor extracted from the massecuite to the molasses purity exiting the centrifugals. Incorrect water addition not only results in unacceptable sugar purity but also affects the molasses purities. Excessive water addition can dissolve sugar crystals, raising the exiting molasses purity.

Sucrose losses resulting from over-washing can be curtailed by massecuite conditioning. Massecuite conditioning involves the addition of hot water or molasses to reduce the massecuite viscosity and thereby provide "easier" separation of the crystals and the molasses. This practice requires high supervision as dissolving of the sugar crystals can easily occur and is therefore generally not recommended (especially the addition of hot water).

3.4 Proposed method of continuous centrifugal control.

It can be seen that the present method of sugar purity control (manual wash water addition) is inadequate. This investigation aims to provide the operator with a reliable on-line measurement of sugar purity by developing a sugar purity meter. The environment in which the purity meter is to operate was acknowledged as a relatively harsh one. The factors that would affect the operation of the purity meter were therefore investigated. These factors were recognised as:

- The effect of temperature. The temperature experienced inside the centrifugal is approximately 65°C. The purity meter components must be able to withstand this temperature.
- Crystal Movement. The sugar crystals move up the centrifugal basket and also tumble over each other as they move up the basket.
- Steam. Steam added to the centrifugal for the reduction of the massecuite viscosity may obscure the 'vision' of the meter.
- Vibration. The meter must be sufficiently robust to withstand the effects of vibration experienced on the centrifugal.

It is believed that the development of such a meter would be of significant benefit to the sugar industry so that proper control of sugar purity is achieved. The benefits of proper control of sugar purity are a more uniform product and lower sucrose losses to molasses.

Chapter 4

DEVELOPMENT OF THE LABORATORY PURITY METER

In the preceding chapters the need for the development of a sugar purity meter was stated. Chapter 4 describes and discusses the preliminary laboratory investigation performed in the development of an industrial meter for the detection of sugar purity in a continuous centrifugal. Included in this chapter is the development of the geometric design of the purity meter, the trials that lead to the selection of the purity meter components, that is, the selection of the light source and light detector, and the trials that evaluated the effects of the centrifugal environmental conditions on the performance of the purity meter.

Chapter 4 consists of the following sections:

4.1 Geometric design.
4.2 Selection of light source.
4.3 Selection of light detector/sensor.
4.4 Testing of the centrifugal environmental conditions.
4.5 Summary.

Each section describes the aim of the experiment, details of experimental equipment used, the experimental procedure, and the results obtained. Results are summarised to complement only the specific aims of the experiment. The full experimental results and raw data are presented in Appendices B, C, D and E.

4.1 Geometric design.

Initial trials were performed in a cardboard box (650 x 430 cm). The box was painted black on the inside to simulate the dark environment found on the inside of a centrifugal. The light source and light detector were housed in two separate tubes. This rig was later improved to the more robust wooden box (28 x 26 x 50cm) presented as Figure 4.1. The purpose of the tubes was firstly to direct the incident light rays onto the sugar surface thereby reducing light scatter and secondly to protect the light source and light detector from physical damage and molasses fouling.

The light source and detector require protection from molasses due to the high centrifugal forces in the centrifugal, where molasses has a natural tendency to be spun off the basket. This molasses may obscure the light source and the light detector resulting in incorrect readings. It was also envisaged that molasses ingress might damage the light source and detector. The tubes in the laboratory rig were adjustable so that the ideal distance from the sugar sample could be measured.

The tubes inserted from the top of the box were held in place by a metal clamp. The laboratory rig was equipped with a door that allowed for the adjustment of the tube and sugar sample distance. During trials the door was shut to prevent ambient light from interfering with the reflectance measurement. Sugar samples were inserted through a specially designed sample holder to minimize interference (seen on the right side on figure 4.1).

Figure 4.1 overleaf presents the physical and the geometric design of the Laboratory Purity Meter Rig.

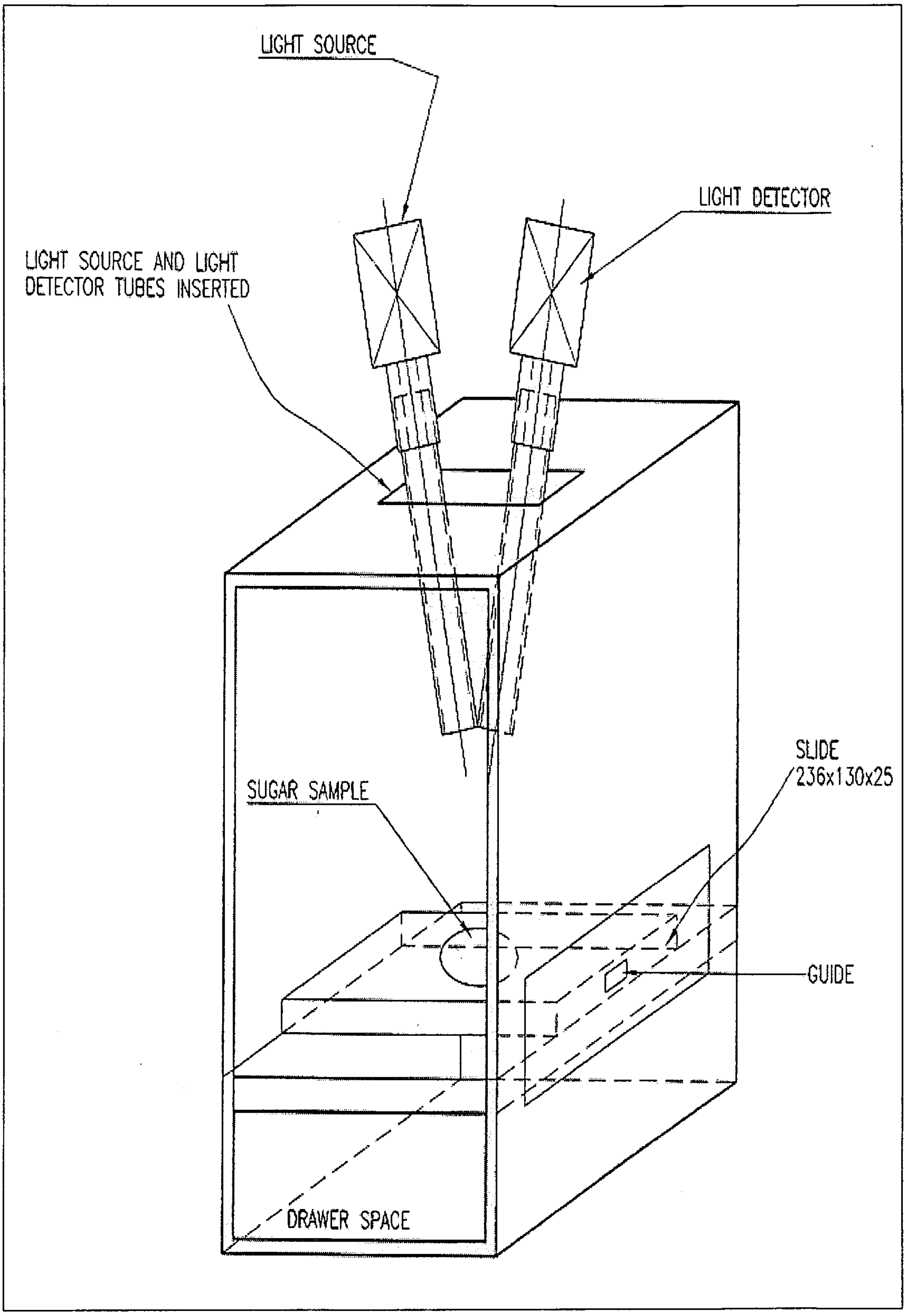


Figure 4.1: Laboratory purity meter rig.

4.2 Selection of light source

The selection criteria for the light source were; the achievement of a reliable and repeatable relationship between sugar purity and measured reflected light intensity, and a physically robust light source that can withstand the environmental conditions of the sugar mill.

4.2.1 Aim of the experiment

To identify light sources suitable for the measurement of reflected light intensity off sugar samples, and to relate this measurement to varying sugar purity.

4.2.2 Experimental method and equipment

4.2.2.1 Light sources

The following light sources were investigated:

a) Incandescent lights (12W and 35 W)

b) Strobe light: 35 W, strobe at 4 Hz

c) Red light emitting diode (12 candela)

Light sources investigated in the preliminary trials were selected for possessing characteristics of physical robustness, long lamp life, low maintenance and cost effectiveness. The characteristics of each light sources are presented below.

a) Incandescent light

Previous literature shows the use of incandescent light by Miller and Taylor (1974) and Proome (1982)]. Incandescent light is a polychromatic light source, that is, it includes the entire colour spectrum. The ability of the sugar surface to absorb a certain fraction of the incident light and reflect the rest formed the parameter tested during these trials.

The advantage of using an incandescent light source is its easy availability. Incandescent light sources were also available in very high outputs (>150W), thus allowing the advantage of greater illumination and hence greater sample to tube distance. As mentioned previously this is required for the prevention of molasses fouling of the light source and detector.

The disadvantage of the incandescent lamp is its shorter life span compared to a light emitting diode (LED). The life expectancy of an incandescent lamp is 10 000 to 20 000 hours. LEDs have life spans of between 5 and 10 times longer [(Lamps vs LEDs (1998)]. Another disadvantage of the incandescent lamp is that it has a large heat output, thus making it difficult to handle. The light output of an incandescent lamp also deteriorates with time and it is sensitive to shock and vibration.

There are ways in which the life span of the light bulb may be extended. The use of direct current (DC) is recommended where possible and in areas of shock and vibration, the lowest possible voltage should be used. Operating at voltages lower than the rated voltage dramatically increases the bulb life [Lamps vs LEDs (1998)].

The general arrangement of the electrical set-up for the testing of incandescent light is presented in Figure 4.2.

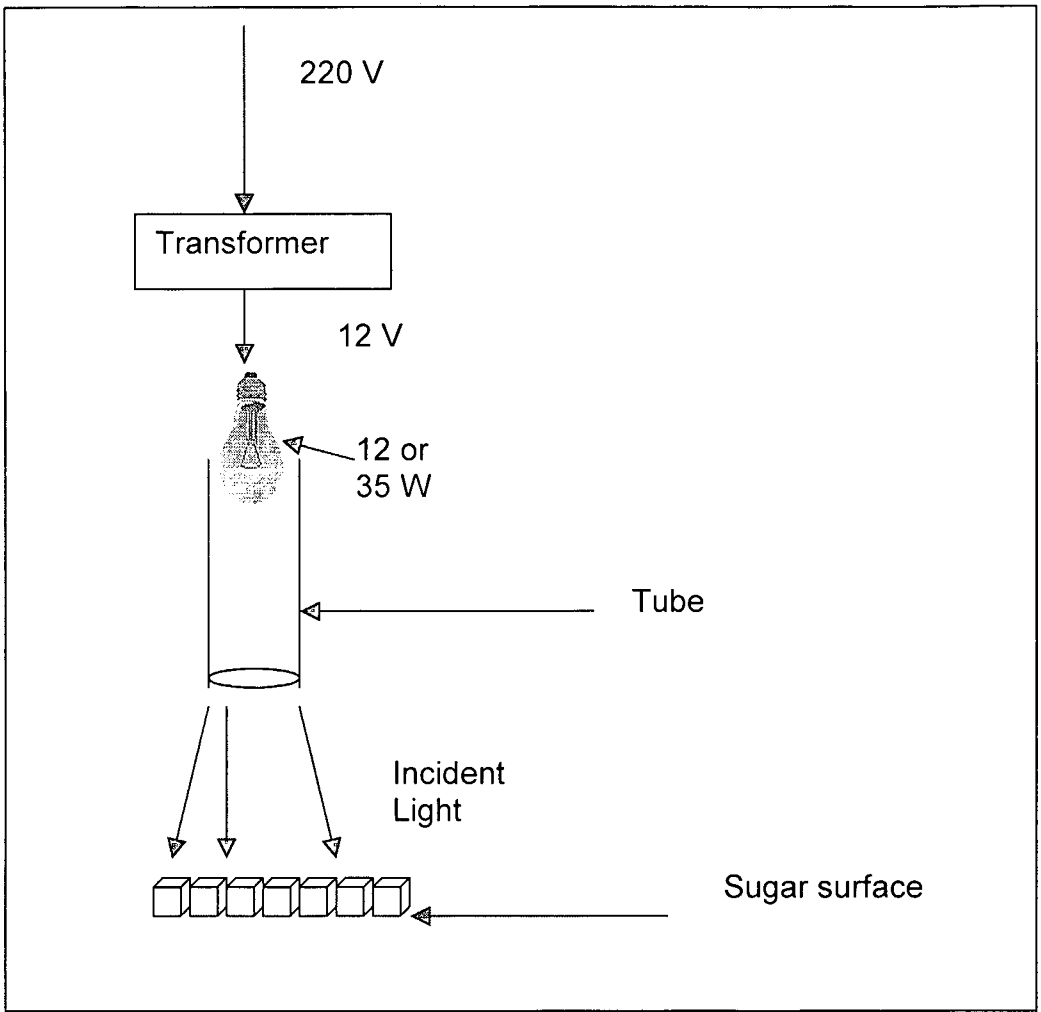


Figure 4.2 Incandescent Light – Electrical set-up

b) Strobe light

The strobe light is basically an incandescent light that is equipped with an electrical circuit allowing for an ON/OFF system thereby allowing for the 'strobe' effect. As explained previously in the literature review, the sugar climbing up the screen occurs in finger like projections. Also it was evident that the sugar was not uniform in colour. It was envisaged that the strobe light would allow for an 'averaging' effect of the light and dark bands of sugar.

It was with these expectations that the strobe was selected for preliminary trials. Note an averaging effect can also be applied electronically to the output of ordinary incandescent. The general arrangement of the electrical set-up for the testing of the strobe light is presented in Figure 4.3. A 4 Hz strobe frequency was used during these trials.

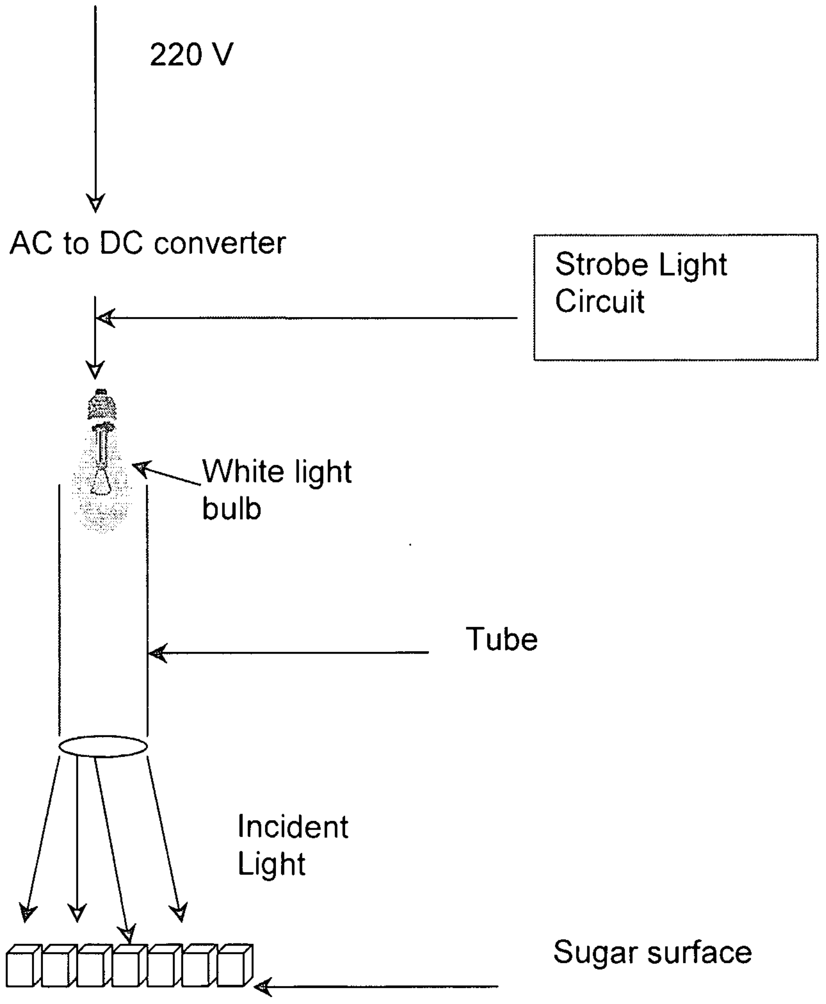


Figure 4.3 Strobe Light – Electrical Set-up

c) Red light emitting diode (LED)

The use of LEDs was investigated as they are claimed to have some advantages over incandescent lamps [Mantech Electronics (1998)]. As mentioned previously LEDs have a longer life span than an incandescent lamp. They are also resistant to shock and vibration due to their solid make-up. They have low heat generation (~7°C), and unlike the incandescent lamp, do not deteriorate over time and therefore do not require frequent replacement. In an industrial environment this is a great advantage.

The greatest disadvantage of the LED was that it is available in much lower outputs. The highest LED output that was obtained was a red LED of 12 candelas. Candela refers to candle power. Candela is the unit used to measure the intensity of light in a particular direction [Language of Light (1998)]. One candela is equivalent to 0.8 W. Another disadvantage was that it is generally more expensive than an incandescent lamp. The above properties were considered when selecting the red LED for preliminary trials.

The general arrangement of the electrical set-up for the testing of red light from a LED (light emitting diode) is presented in Figure 4.4

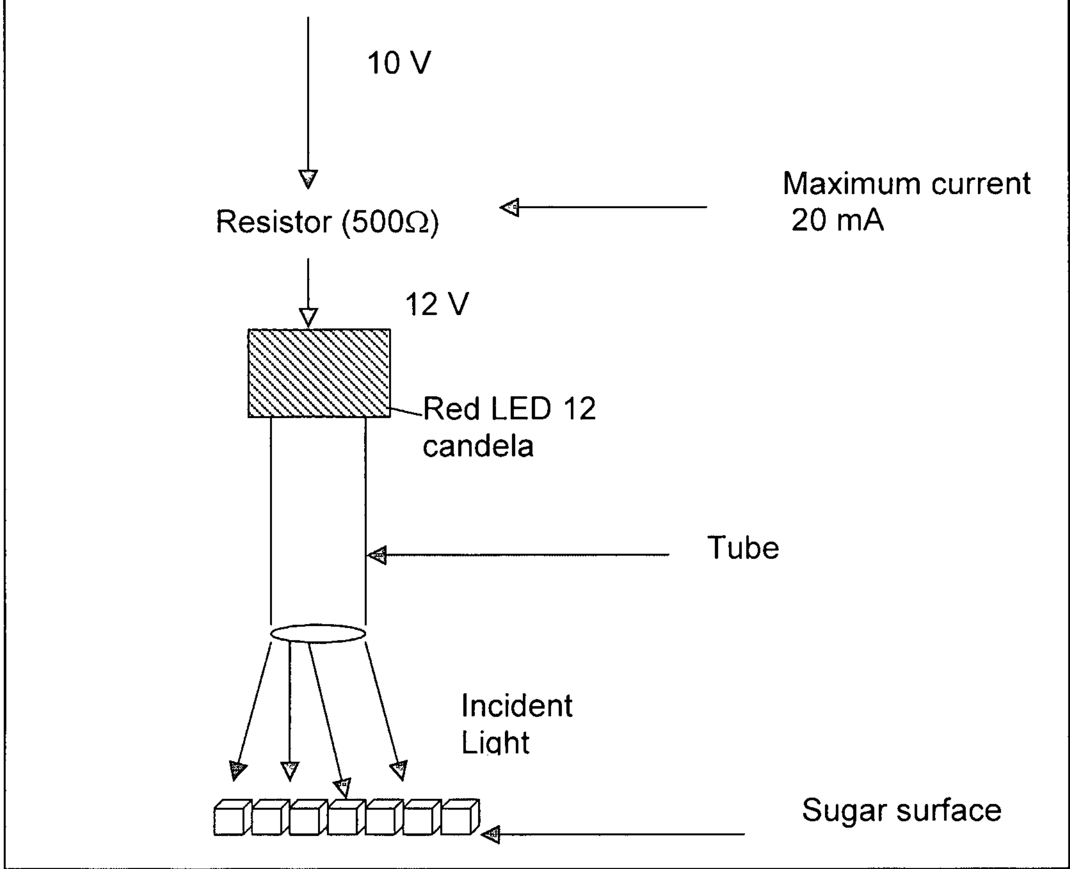


Figure 4.4 Red LED- Electrical Set-up

4.2.2.2 Light detector

The light detectors are equipped with photoconductive cells. Previous literature shows the use of two types of industrial photo-detectors [Miller and Taylor (1974) and Proome (1982)] namely the photodiodes and the light dependent resistors (LDR). The light detectors operate in specific wavelength bands, therefore the choice of the photodiode or LDR must be in accordance with the light source selected. Proome [1982] used the photodiode as the light detector. As these trials were a continuation of Proome's investigation, the light detector used in the light source selection trials was a photodiode.

The photodiodes are made of cadmium sulphide photoconductive (semi-conductive) cells. The light received by the photo-diode increases the conductance of the semi-conductors that is the light falling on the photodiode increases electron movement. The output of the photodiode is simplified using electronics to provide a standard instrumentation output of 4 to 20 mA (milliamps) or a 0 to 10 V (volts). Voltage was recorded for these trials. The photodiode used for these trials was the R5652-995-U335. This photodiode operates in the visible light range.

These voltages were recorded using an oscilloscope or a voltmeter. In the case of the incandescent and red LED light sources the oscilloscope was unable to detect low voltages, and hence a voltmeter was used to accommodate for this shortcoming. Trials also included the placing of colour filters over the light sensor to enhance the light sensors ability to distinguish between the varying sugar purities.

Figure 4.5 presents a block circuit diagram of the operation of the photo-diode.

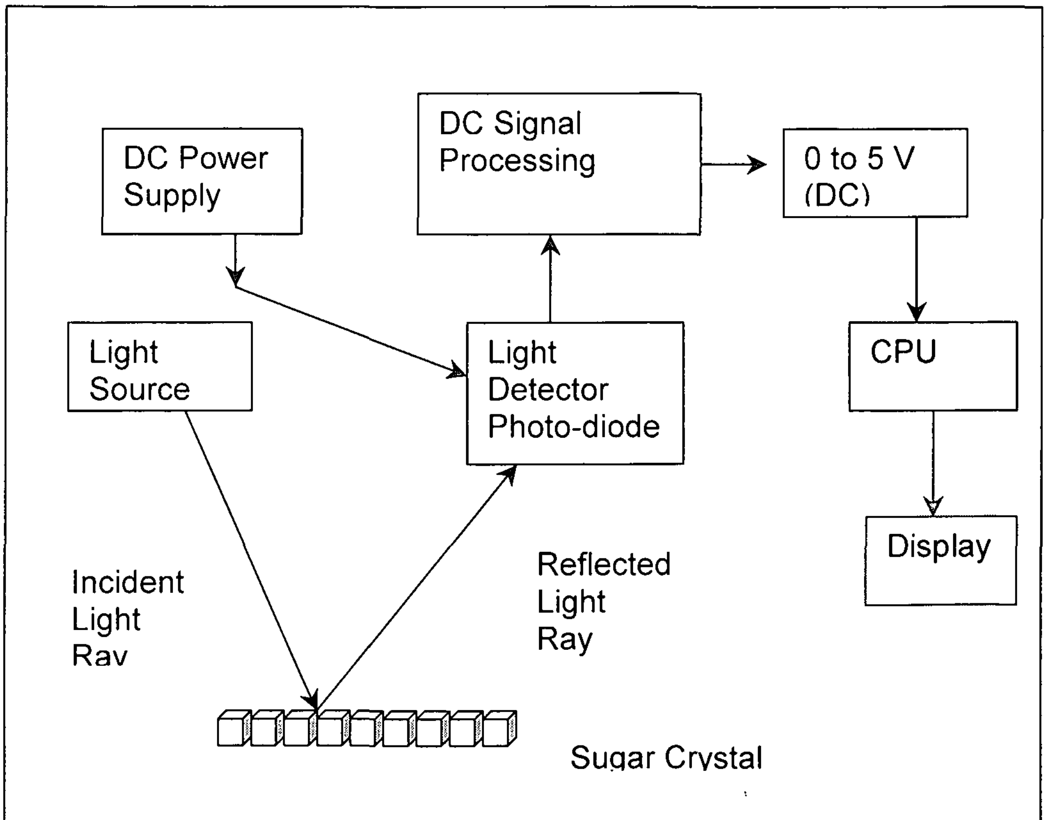


Figure 4.5 Light Detector – Photodiode

Light emitted from the light source is reflected off the sugar surface and the detector measures the intensity of the reflected light. Reflectance is the fraction of light reflected from a surface compared to the amount of light falling on that surface. A direct current (DC) amplifier amplifies the signal received to a 0 to 5 Volt DC output. This signal can be used directly to correlate a relationship with sugar purity or can be conditioned by a central processing unit (CPU) that will electronically produce a 0 to 100% output. The voltage output or the 0 to 100% output is correlated to the sugar purity and a relationship is established using statistics.

4.2.2.3 Sugar sampling and analyses

Low grade (C-sugar) samples used in the laboratory trials were obtained from Maidstone Sugar Mill. These were analysed in the laboratory using the method prescribed by the South African Sugar Technologists Association (SASTA). The method is presented in Appendix A. The analytical equipment used are as follows:

a) Polarimeter/ Saccharimeters

The polarimeter was used to measure the apparent sucrose (pol) of the sugar samples for sugar purity detection. The procedure for ICUMSA pol determination is presented in Appendix A.
Manufacturer: Schmidt and Haensch
Make: Polartronic Universal
Serial: 25054

b) Digital Refractometer

The refractometer was used to measure the brix of the sugar solutions for colour analysis. The procedure for ICUMSA brix analyses is presented in Appendix A.

Manufacturer: Bellingham and Stanley Limited
Make: RFM 500 Digital refractometer
Serial: Y95019

These analyses showed the sugar purity to be in the range of 81 to 92 % purity.

4.2.2.4 Sample preparation

The sample preparation for the laboratory test rig was as follows:
The sugar samples were placed in containers allowing for an approximate thickness of 5 mm. The samples were compacted to provide a flat surface. Care was taken not to damage the sugar crystals during sample preparation. The sugar samples were replaced whenever they dried out.

4.2.2.5 Data collation and analyses

The voltage measurement corresponding to the different sugar purities were recorded and analysed using statistical analysis. As mentioned in Chapter 2, the theory on the reflectance of light off coloured bodies revealed that lightly coloured bodies reflect more light and darkly coloured bodies absorb more light. As C-sugar colour varies from dark brown (low purity) to light yellow (high purity) it was envisaged that there would be a linear relationship between sugar purity and the reflected light intensity. Therefore regression analysis and correlation coefficients were obtained to establish the relationship between reflected light intensity (voltage) and analysed sugar purity (sucrose percentage).

Regression analysis is the use of graphically display trends in data to analyse problems of prediction. Linear regression calculates the least squares fit for a line represented by the equation $y = mx + b$, where m is the slope and b is the intercept.

When a suitable correlation between y and x has been obtained, either by least-squares analysis or graphical curve fitting, it is necessary to know how good the this fit is and the parameter which conveys this information is the correlation coefficient (r). The correlation coefficient r is a dimensionless index that ranges from –1.0 to 1.0 inclusive and reflects the extent of a linear relationship between the two data sets. A trend line is most reliable when the correlation coefficient is at or near –1.0 or 1.0. The negative or positive value of r indicates a negative (y tends to decrease as x increases) or positive (y tends to increase as x increases) correlation respectively.

A student's t-test was used to determine whether values achieved for the various trials were statistically significant or not at a given probability level. A 95% level of confidence was used for the analysis. If the calculated t-(statistical) is less than the t-(critical) then there is no significant difference between the values tested.

The formulas and their derivations for regression analysis, correlation coefficient and the student t-test can be found in any statistical text.

4.2.3 Experimental results and discussion

4.2.3.1 Strobe light

The distance between the sugar samples and the tubes housing the light source and the light sensor were arbitrarily chosen at 18 cm, 12 cm and 7 cm. Correlation coefficient values (r) of 0.61, 0.66 and 0.72

were calculated for the trials performed at these respective distances. Although it was apparent that the relationship improved when the sugar sample to the tubes distance decreased, the relationship was not considered to be highly linear (not sufficiently close to the desired 1.0). The graphical representations of these trials have been presented in Appendix B.

As explained previously light sensors operate in specific wavelength ranges. The selected light sensor (photodiode) operates in the visible light spectrum, (~400 nm to 700nm). In order to determine the optimum wavelength detected by the specific light sensor, that can be used to measure sugar purity, the reflected light was passed through colour filters before reaching the sensor. Five filter colours were used in the following combinations:

1. Green
2. Green and orange
3. Green and blue
4. Green and yellow
5. Green and brown
6. Orange
7. Orange and blue
8. Orange and yellow
9. Orange and brown
10. Blue
11. Blue and yellow
12. Blue and brown
13. Yellow
14. Yellow and brown
15. Brown

Preliminary testing showed the optimum correlation between sugar purity and light reflectance using a separation distance of 7 cm between the sugar samples and the tubes. This distance between the sugar sample and light source and detector tubes was therefore used during colour filter trials. A marked improvement was observed in the relationship between sugar purity and measured light reflectance when using the blue and the combination filters of blue and brown. Correlation coefficients of r = 0.92 were obtained. The results of these trials presented graphically in Figures 4.6 and 4.7.

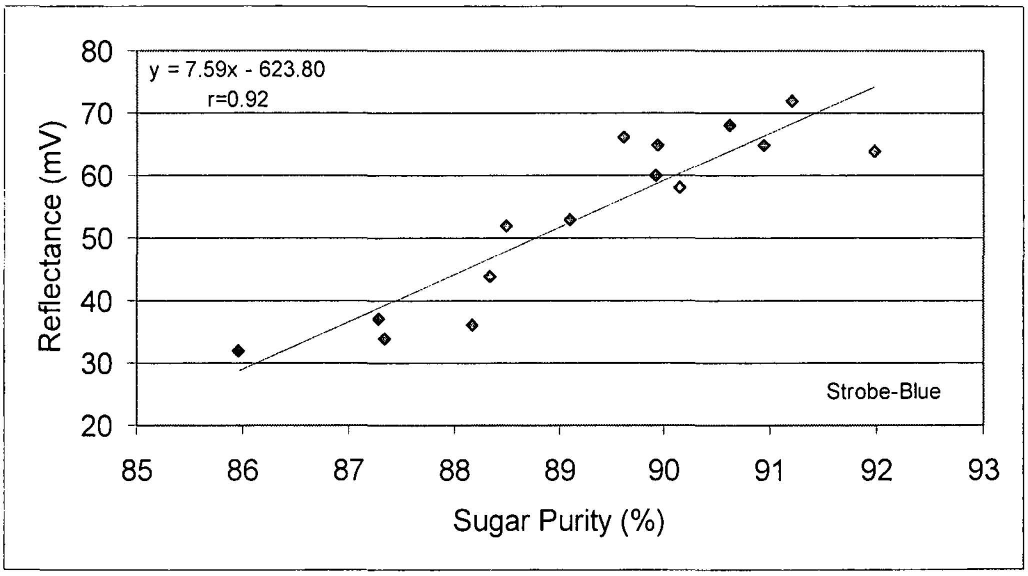


Figure 4.6: Strobe Light: The relationship between sugar purity and reflected light intensity, using a blue filter.

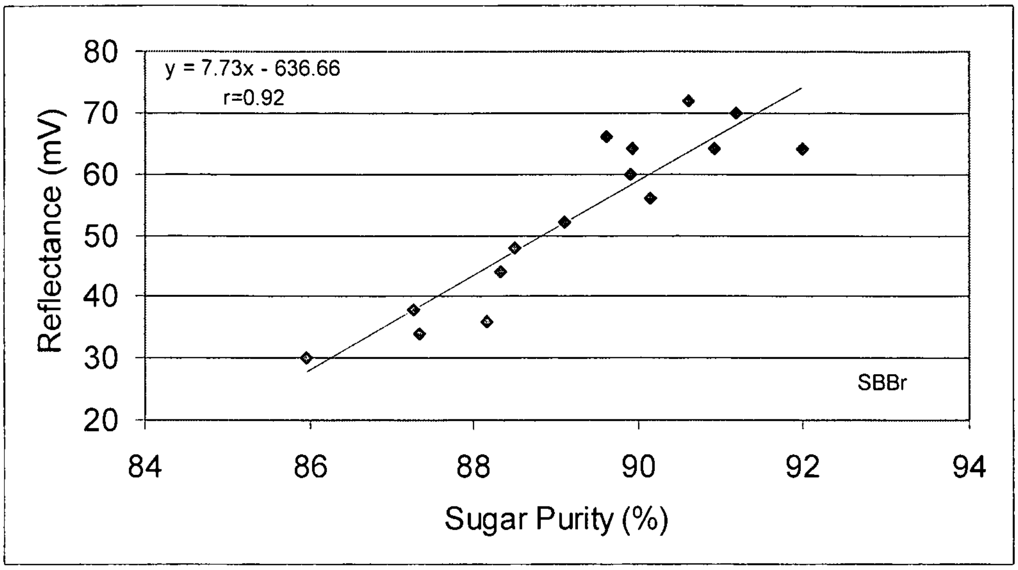


Figure 4.7: Strobe Light: The relationship between sugar purity and reflected light intensity, using a blue and brown filter.

The results of the strobe light trials using colour filters are presented in Table 4.1. The correlation coefficient between sugar purity and reflected light intensity were calculated for the various colour filter combinations.

Table 4.1 Overall Strobe Light Test Results

Distance and Colour Filters	**Corrélation Coefficient (r^2)**
Samples @ 18 cm	0.62
Samples @ 12 cm	0.66
Samples @ 7 cm	0.72
Blue Filter	0.92
Brown Filter	0.88
Green Filter	0.90
Orange Filter	0.86
Yellow Filter	0.86
Blue and Brown Filters	0.92
Blue and Yellow Filters	0.88
Blue and Green Filters	0.89
Green and Yellow Filters	0.88
Green and Orange Filters	0.87
Orange and Brown Filters	0.87
Green and Brown Filters	0.87
Orange and Brown Filters	0.88
Orange and Yellow Filters	0.90
Yellow and Brown Filters	0.91

As indicated in Table 4.1, there was poor correlation between sugar purity and light reflectance without the use of colour filters. This indicates that a light sensor works optimally at selected wavelengths. The strobe light results show that the combination of yellow and brown filters also yielded a high correlation coefficient for this specific light sensor. The colours blue and yellow lie in the wavelength range of 473nm to 559nm. The more suitable light sensor would need to be in this wavelength range. The results therefore indicate that the light detector was inadequately selected.

Further experimentation using the strobe light source was not pursued as other light sources yielded better results.

4.2.3.2 Incandescent light (12 W)

The experimental method of the strobe light also applies to the incandescent light. Trials without colour filters produced a correlation coefficient of r= 0.88 for the distances of 18 and 7 cm from the sugar samples to light source and light sensor tubes. Additional trials using coloured filters yielded better correlation results. Similar colour filter combinations were used for the strobe light trials, with a separation distance of 7 cm between the sugar sample and tubes.

Table 4.2 presents the colour filters and their combinations together with the calculated correlation coefficients. All raw data for the incandescent light trials are presented in Appendix C.

Table 4.2 Overall Incandescent Light (12W) Test Results

Distance and Colour Filters	**Correlation Coefficient (r^2)**
Samples @ 18 cm	0.88
Sample @ 7 cm	0.88
Blue Filter	0.87
Brown Filter	0.53
Green Filter	0.90
Orange Filter	0.91
Yellow Filter	0.85
Blue and Brown Filters	0.89
Blue and Yellow Filters	0.88
Blue and Green Filters	0.88
Green and Yellow Filters	0.90
Green and Orange Filters	0.89
Orange and Brown Filters	0.89
Green and Brown Filters	0.90
Orange and Blue Filters	0.89
Orange and Yellow Filters	0.90
Yellow and Brown Filters	0.91

Generally a fairly linear relationship was observed, with correlation coefficients ranging from 0.85 to 0.91. The use of a brown colour filter yielded a rather poor correlation coefficient of 0.53. This was contrary to other trials which produced correlation coefficients higher than $r^2 = 0.85$. The reason for this anomaly was unclear, however due to the success of other trials this matter was not pursued.

The most linear relationship achieved was $r^2 = 0.91$, using an orange filter. The colour orange corresponds to a wavelength of 615nm. The result of this trial has been graphically presented in Figure 4.8.

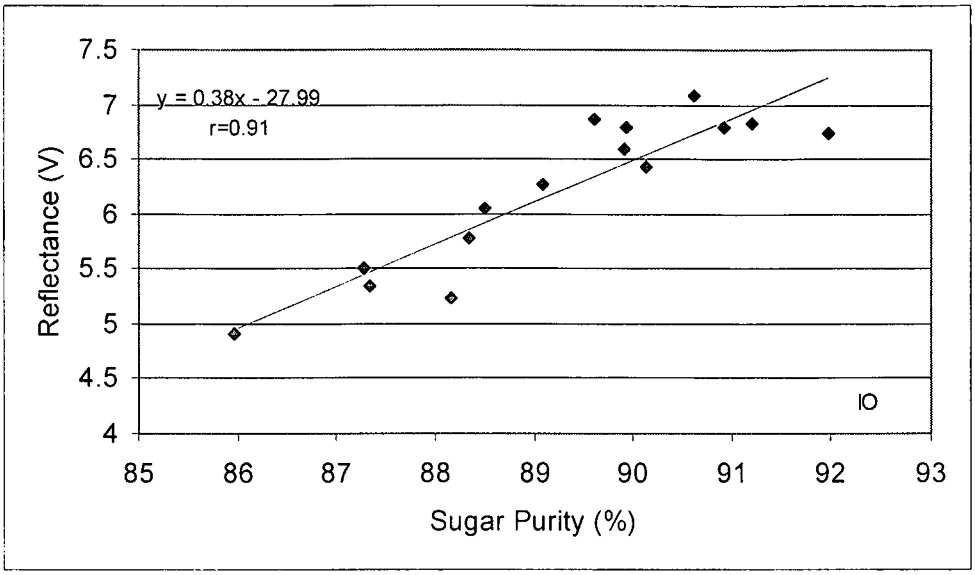


Figure 4.8: Incandescent Light (12 W): The relationship between sugar purity and reflected light intensity, using an orange filter

The use of colour filters together with the incandescent light source of 12W clearly produced more definite relationships between sugar purity and measured reflectance than using the 12 W light source on its own. As noted with the strobe light trials, previously, there was a limitation in the selected light detector, thus indicating that the light detector selected was inadequate.

4.2.3.3 Incandescent Light (35 W)

Although the results achieved from the strobe light and incandescent light (12 W) trials were encouraging, it was envisaged that a lamp emitting a higher light intensity would improve results. A 35 W incandescent lamp was therefore tried. These lamps are easily available and the cost was not considered to be significantly high. The results produced a correlation coefficient of r = 0.98. This was considered to be an excellent breakthrough in terms of improving the relationship between sugar purities and measured reflected light intensity. Due to the highly linear correlation coefficient obtained no colour filter trials were conducted. The consideration was that the simpler the mechanics of the purity meter the higher its chances were of surviving the harsh environment of the sugar factory.

Figure 4.9 presents the results of the 35 W lamp incandescent trials.

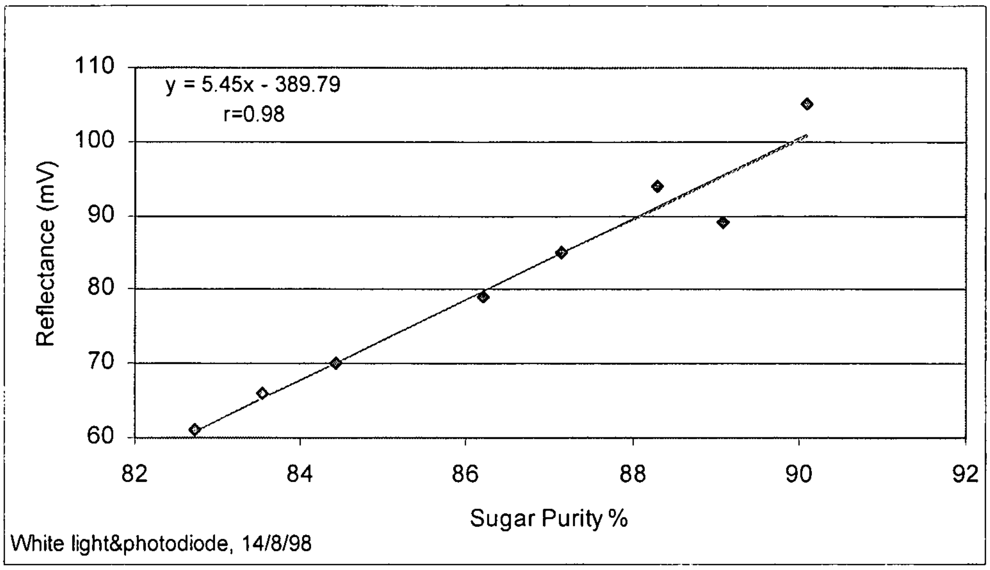


Figure 4.9: Relationship between sugar purity and reflected light, using incandescent lamp of 35 W.

Two trials were performed to check for repeatability. The second trial produced a correlation coefficient of 0.97. The repeatability of the trial results was considered to be very satisfactory. A graphical representation of the second trial has been presented in Appendix D (Figure D1.1).

4.2.3.4 Red Light Emitting Diode (LED)

Trials were performed using a 12 candela red LED. The 12 candela red LED was of the highest output available during these trials. These trials produced encouraging results with a correlation coefficient of 0.97. A sugar sample to tube distance of 7 cm was used for the red LED trials. No colour filters were required as the red light is a monochrome light source. Figure 4.10 shows a graphical presentation of the results obtained for the red LED.

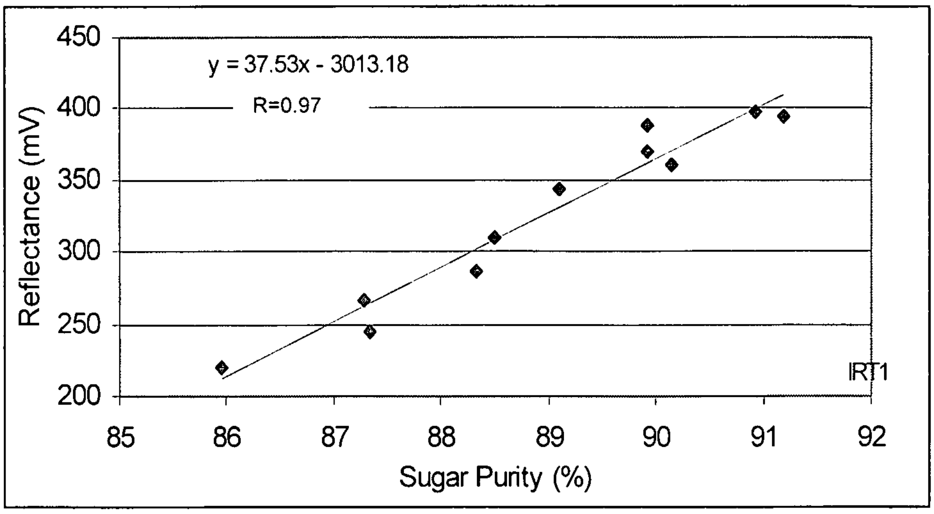


Figure 4.10: Relationship between sugar purity and reflected light, using a Red LED at 12 Candela.

Two trials were performed to check for repeatability. The second trial produced a correlation coefficient of 0.96. The repeatability of the trial results was considered satisfactory. A graphical representation of the second trial has been presented in Appendix E (figure E1.1).

4.2.4 Conclusions

The selection criteria for the light source were; the achievement of a reliable and repeatable relationship between sugar purity and measured reflected light intensity, and a robust light source that can withstand the environmental conditions of the sugar mill. These criteria were adequately met by all four light sources. However of the four light sources tested (the incandescent lamp 12W and 35W; the 12 candela red LED, and the strobe light) the results obtained for the 12 candela red LED and the 35 W white incandescent light sources were the most favourable.

The use of colour filters for the strobe and incandescent light (12W) enhanced the light sensors' ability to detect varying sugar purities, suggesting that the selection of the light sensor for these light sources were inadequate. The light sensors used for the red LED and the incandescent (35W) were adequate.

4.3 Selection of the light detector/sensor.

As mentioned in section 4.2.2.2 there are two types of industrial photodetectors that are generally used, they are the photodiodes and the light dependent resistors (LDR). The photodiode was selected for the light source selection, as part of the continuation of the earlier investigation by Proome [1982]. It was decided to test the LDR on the selected light sources i.e. 12 candela red LED and the 35 W white incandescent light sources, to check if the LDR would produce better results than the photodiode.

The selection criteria for the light detector were; the achievement of a reliable and repeatable relationship between sugar purity and measured reflected light intensity, and a robust light detector that can withstand the environmental conditions of the sugar mill.

4.3.1 Aim of the experiment.

To test the light dependent resistor (LDR) as a suitable light detector for the measurement of reflected light intensity off sugar samples, and to relate this measurement to varying sugar purity.
To compare results achieved from the LDR trials to those from the photodiode trials.

4.3.2 Experimental method and equipment.

The properties of the photodiode have been discussed in section 4.2.2.2.

The light dependent resistor (LDR) measures photo emission by a principle of varying electrical resistance. The resistance decreases with increasing light levels (intensity). The LDR used for these trials was the NORP12. This LDR is physically robust for use in an industrial environment.

Figure 4.11 presents a block circuit diagram of the operation of the LDR.

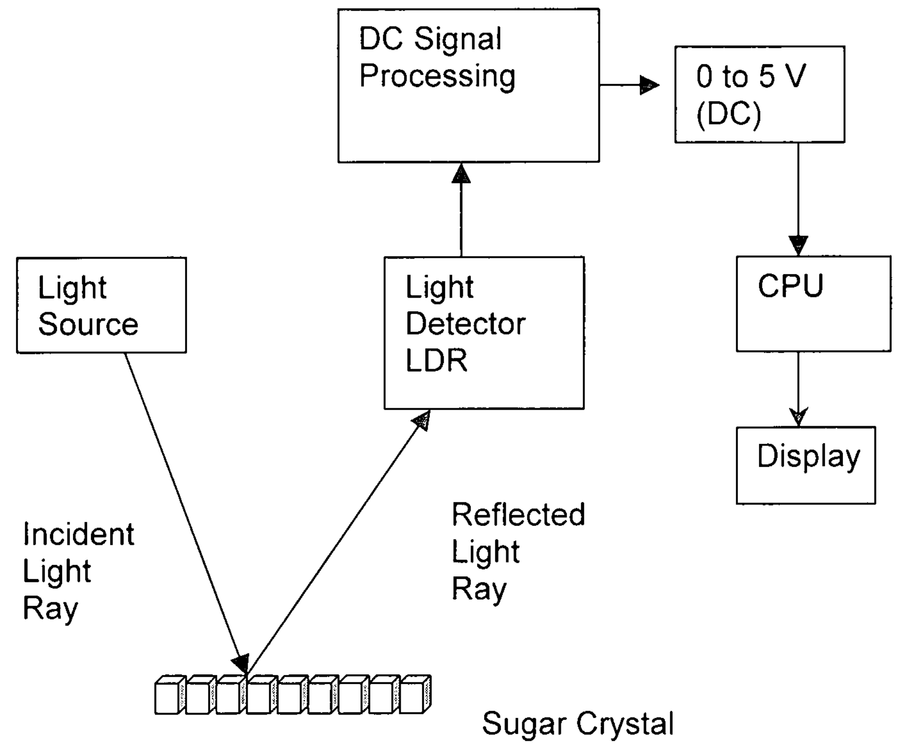


Figure 4.11: Light Detector – LDR.

The processing of the signal from the LDR was the same as that of the photodiode. The LDR unlike the photodiode does not require a power supply. The following trials were performed to ascertain the optimum light sensor for measuring sugar purity:

The red LED and the 35 W incandescent light sources were tested to determine if a reliable and repeatable relationship between sugar purity and measured reflectance could be obtained when using the LDR. A separation of 7 cm was used between light source and sensor tubes and the sugar. Reflectance readings were recorded in ohms for the LDR.

4.3.3 Experimental results and discussion.

It was established in the light selection trials (for the 35 W incandescent and 12 candela red LED lamps) that there was a linear relationship between measured reflected light intensity and sugar purity when using the photodiode as the light detector. To summarize the results were as follows:

a) Incandescent Light

A correlation coefficient value of r=0.98 was obtained with a regression analysis curve of y = 4.45x – 389.79.

b) Red LED

A correlation coefficient value of r=0.97 was obtained with a regression analysis curve of y = 37.53x – 3013.18.

Trials performed using the LDR on the incandescent (35W) and red LED lamps yielded the following results:

For the 35 W incandescent lamp a correlation coefficient value of r=-0.99 was calculated. A repeat of this trial produced a correlation coefficient of r = -0.99. Note the negative correlation coefficient. As mentioned previously the negative correlation coefficient merely indicates y tends to decrease as x increases. All other trials thus far have yielded positive correlation coefficients. Figure 4.12 presents the results of trials using the white light (35W) source and a LDR sensor. The raw data for these trials are presented in Appendix D (Table D.1). The regression analysis curve generated was y=-1.05x+101.41.

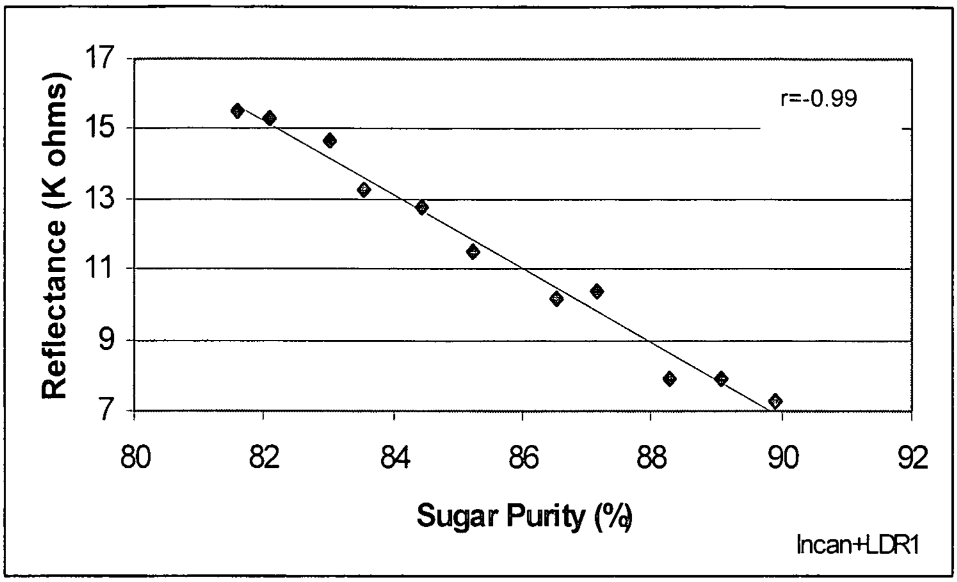


Figure 4.12: Relationship between sugar purity and reflected light, Using Incandescent Lamp and a LDR

Figure 4.13 presents the red LED trials using a LDR. A correlation coefficient of r=-0.96 was obtained. A repeat of this trial produced a correlation coefficient of r = -0.95. The graphical presentation of this is shown in Appendix E (Figure E.2). The regression analysis curve generated was y=-0.21x+11.49.

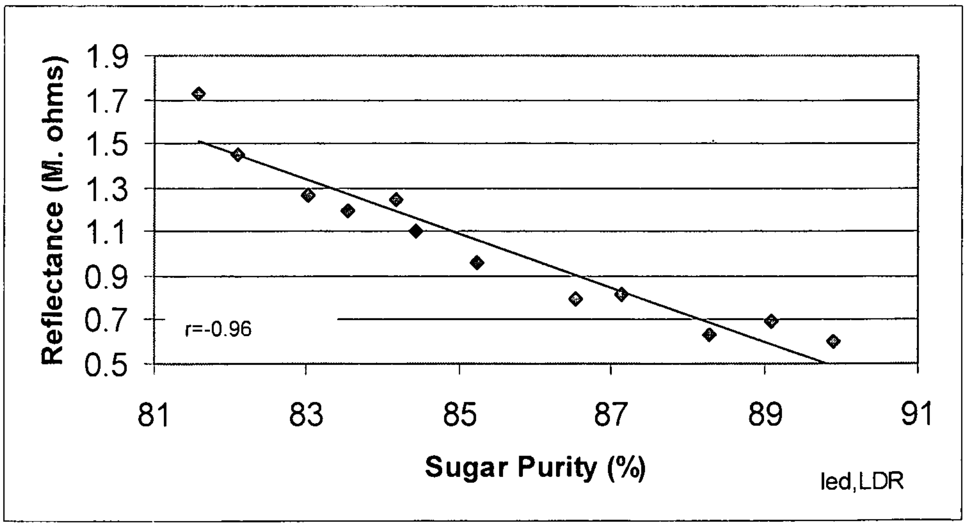


Figure 4.13: Relationship between sugar purity and reflected light, Using a red LED and a LDR

The results show that for both the light sources tested with the LDR light detector, a linear relationship existed between sugar purity and measured reflected light intensity.

4.3.4 Conclusions

The results achieved for the incandescent lamp 35 W using the photodiode and the LDR were fairly similar. Correlation coefficient values of r=0.98 and r=-0.99 were achieved for the photodiode and LDR respectively. The results achieved for the red LED lamp using the photodiode and LDR were also fairly similar, where the correlation coefficients obtained were r=0.97 and r=-0.96 for the photodiode and LDR respectively. The negative slopes were not of great concern as these values can be electronically modified. The aim was to establish a reliable relationship between sugar purity and measured reflected light intensity.

It can therefore be concluded that both light detectors (the photodiode and the LDR) can be used for the successful detection of reflected light intensity for the prediction of sugar purity.

4.4 Testing of centrifugal environmental conditions.

The centrifugal environmental conditions/variables were identified as temperatures ranging from 60 to 70°C, the spinning motion of the sugar samples, steam addition and vibration experienced on the centrifugal. Attempts were therefore made to replicate these environmental conditions in the laboratory purity meter and test their effect on the light reflectance intensity measurement.

4.4.1 Temperature tolerance testing of the light sensor/detectors.

4.4.1.1 Aim of the experiment.

The aim of these trials was to assess the ability of the light detectors (the photodiode and the LDR) to provide stable light reflectance intensity measurements under high temperature (60 to 70°C) conditions.

4.4.1.2 Experimental method and equipment.

The operating temperature of the centrifugal in the factory (specific to Maidstone No. 2 centrifugal) was approximately 65 °C. It was therefore necessary to ensure that the sensors are capable of producing a steady output in the range 60 to 70 °C. The following experiment was therefore performed to determine the effect of temperature variations on the performance of the photodiode and the LDR sensors. The photodiode and the LDR were heated by using a hair drier. The experiment was performed in a closed box to obtain better temperature control. A digital thermometer was placed close to the sensor. The relationship between temperature and light intensity viz. voltage (photodiode) and resistance (LDR) was determined under ambient light conditions.

4.4.1.3 Experimental results and discussion.

The temperature tolerance testing of the two light detectors/sensors yielded the following results:

Figure 4.14 presents the reaction of the photodiode to increasing temperatures under ambient light conditions.

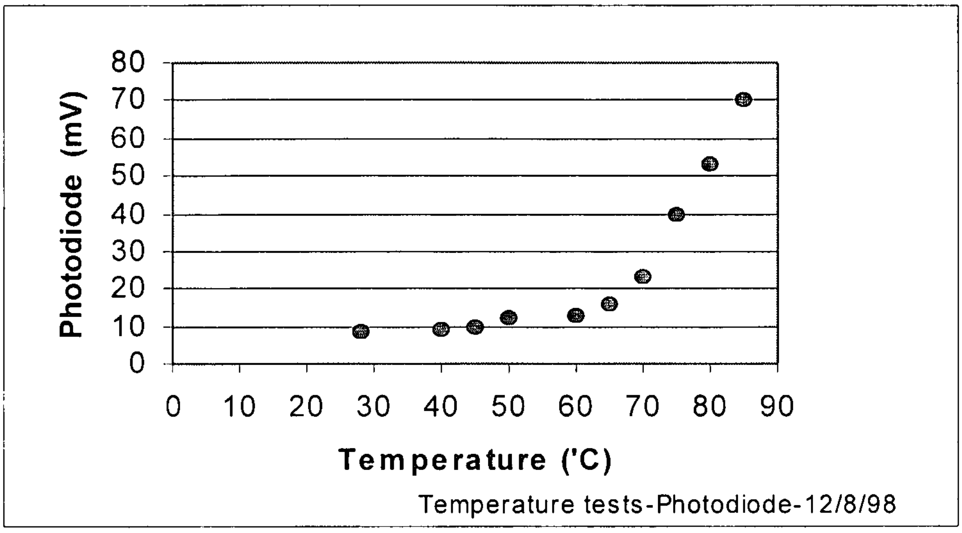


Figure 4.14: Relationship between the photodiode output and increasing temperature.

It was clear that the photodiode output changed rather drastically with increasing temperature. This shows that the photodiode is obviously unsuitable for use in a factory centrifugal in the operating temperature range of 60 to 70 °C.

Figure 4.15 presents the effect of increasing temperature on the performance of the LDR.

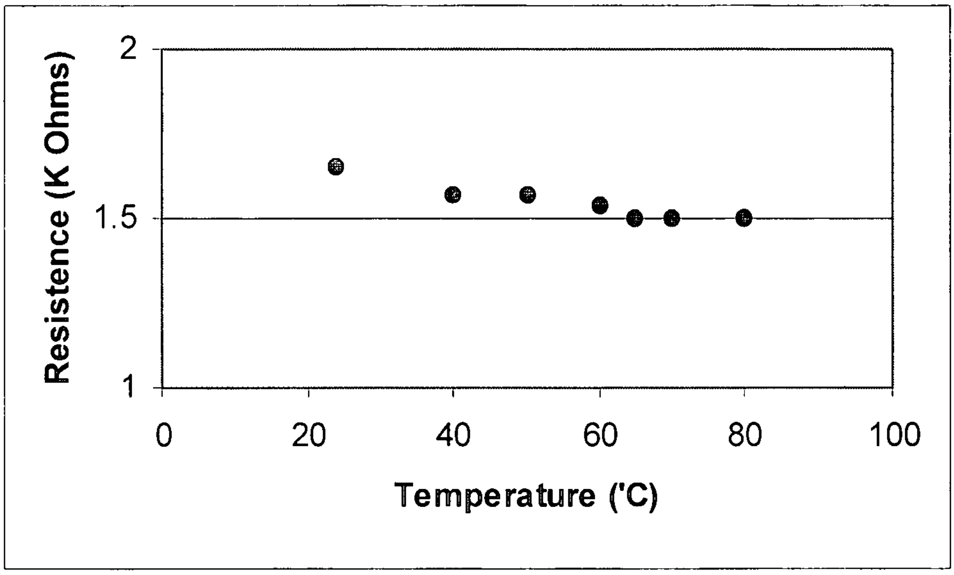


Figure 4.15: Relationship between the LDR output and increasing temperature.

The results obtained from the LDR trials were very encouraging. The LDR output fluctuated slightly in the temperature range 20 °C to approximately 50 °C. The output was however steady in the temperature range of 60 to 70 °C (as desired).

4.4.1.4 Conclusions

The LDR met both the requirements of producing a reliable and repeatable relationship between sugar purity and the reflectance measurement, and being able to produce a steady output at the centrifugal operating temperature range of 60 to 70 °C. The LDR was therefore chosen for subsequent trials.

4.4.2 Effect of sugar crystal movement on the light reflectance intensity measurement .

4.4.2.1 Aim Of experiment.

Sugar crystals in a centrifugal, apart from spinning with the basket at approximately 2000 rpm, tend to tumble over each other as they move up the basket. The aim of these experiments was to examine the effect of sugar crystal movement on measurement of light reflectance.

It was acknowledged that the actual motion of sugar crystals would be difficult to simulate in the laboratory rig. However it was necessary to ascertain if crystal movement of any kind affected the reflectance reading.

For simplification these trials from hereon are referred to as the motion trials.

4.4.2.2 Experimental method and equipment.

A laboratory variable speed stirrer (normally used to mix liquids) was used to spin the sugar samples. The stirrer was turned upside down to accommodate the sugar sample holder. A speed of 120 rpm was selected. Higher speeds could not be attained, as the sugar sample would spin off the sample holder. It was acknowledged that this speed is low compared to the 2000rpm experienced in the factory centrifugal. However as mentioned above it was necessary to ascertain if crystal movement of any kind affected the reflectance reading.

Sugar samples were placed on the holder on top of the stirrer and light reflectance measurements were taken before and during spinning of the sugar samples. These trials were performed using the red LED and the incandescent lamps.

Figure 4.16 below presents a simplified schematic of the laboratory set-up for these motion trials.

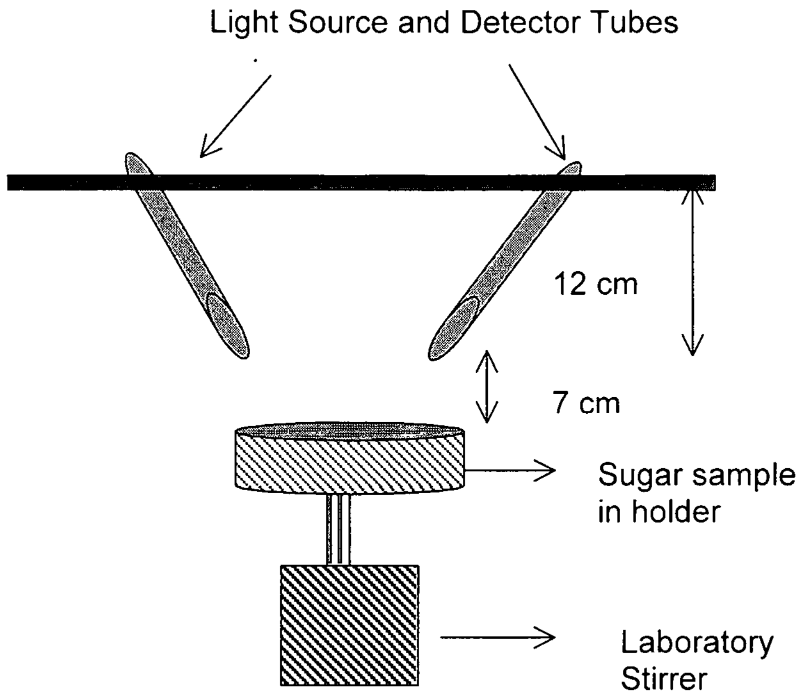


Figure 4.16. Laboratory set-up for the motion trials.

4.4.2.3 Experimental results and discussion.

When sugar samples are taken out of the centrifugal they are analysed in the laboratory for sugar purity as a solution. However when this solid sample is placed on the sample holder the sample may have areas that vary slightly in appearance (colour). This effect can be visually observed. It was therefore envisaged that the spinning motion was likely to have an 'averaging effect'.

The results obtained for the motion trials using incandescent (35W) and red LED light sources are presented below.

a) Incandescent motion trials.

The motion trials for the incandescent light source showed that there was little difference between the light reflectance measurement on stationary and spinning sugar samples. The relationship between sugar purity and measured reflectance remained linear, irrespective of whether the sample was stationary or being spun.

Figure 4.17 presents the average results of the spinning trials. The raw data from the motion trials are presented in Appendix D as Table D.2. A correlation coefficient of r = 0.99 was obtained for both the stationary and motion trials. A students t-test, produced no significant difference between the stationary trial values and the spinning trial values (t-(stat) =-2.1 < t-(critical) =2.2 at a 95% level of confidence.).

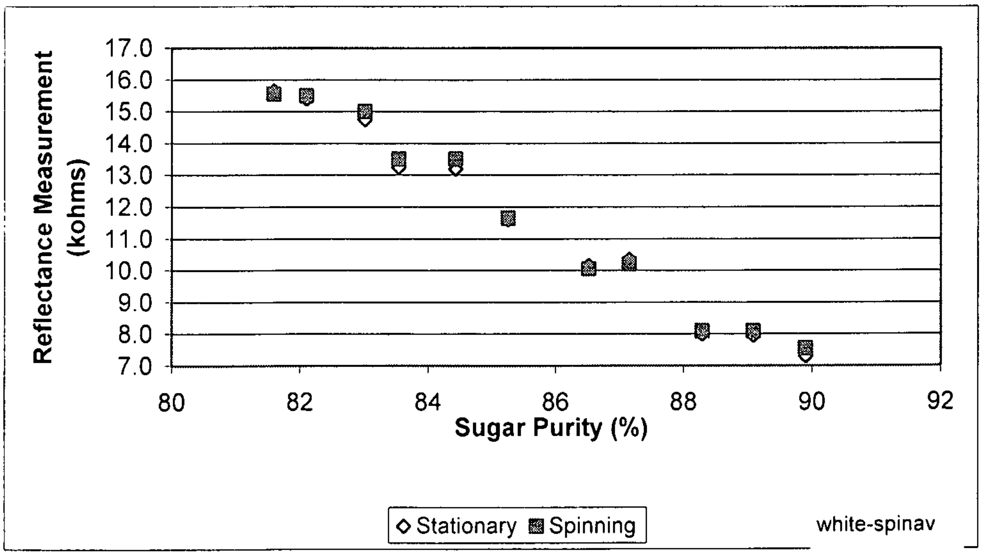


Figure 4.17: Motion Trials: Incandescent Light Source and the LDR

b) Red LED motion trials.

The motion trials showed that there was very little difference in the reflectance measurement between the stationary and spinning sugar samples. The results were similar to that generated with the 35 W incandescent lamp. Here too it was found that even with the slight difference in the reflectance measurements, the reflectance measurement taken for the stationary and spinning sugar samples displayed the same trend. Figure 4.18 presents the results of the spinning trials. The raw data for the motion trials are presented in Appendix E (Table E.1).

The relationship between sugar purity and measured reflectance remained linear, irrespective of whether the sample was stationary or being spun. A correlation coefficient of r = 0.96 and r = 0.95 was obtained for the stationary and motion trials respectively. A students t-test, produced no significant difference between the stationary trial values and the spinning trial values (t- (stat) =--8.0 E-15 < t- (critical) =2.2 at a 95% level of confidence).

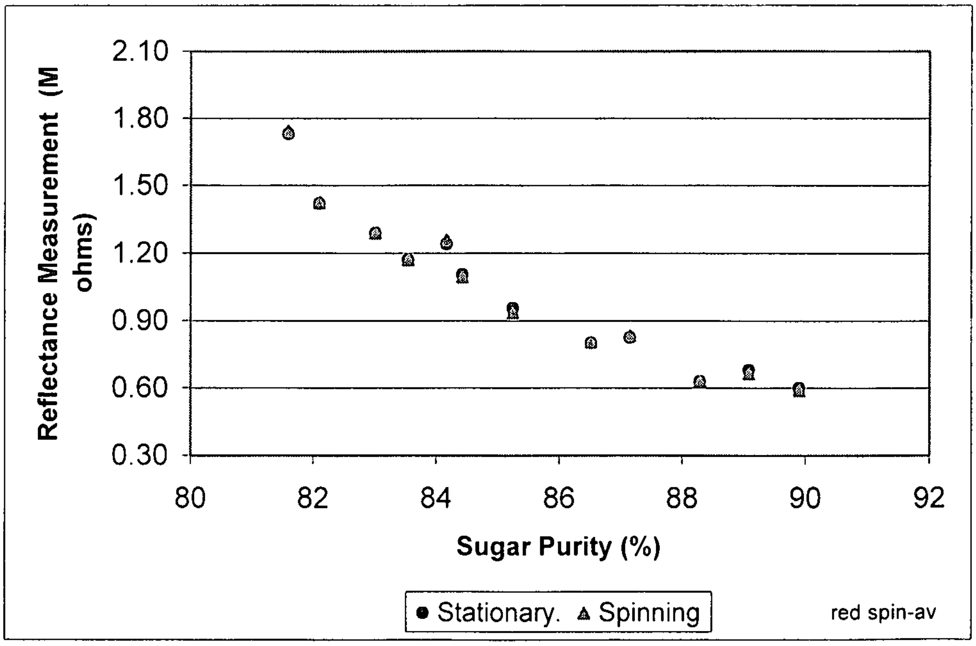


Figure 4.18: Motion Trials: Red LED and a LDR

4.4.2.4 Conclusions

The motion trials show that for both the incandescent and red LED lamps that the spinning of the sugar samples had no significant effect on the light reflectance measurement.

As mentioned previously these trials did not take into account the tumbling effect of the sugar crystals. The possibility that this effect (in the centrifugal) could have an effect on the measured light reflectance reading can therefore not be totally ignored.

4.4.3 The effect of steam addition on the measurement of reflected light.

4.4.3.1 Aim of the experiment.

In the continuous centrifugal steam is introduced around the massecuite feed to reduce massecuite viscosity. The aim of these experiments was to examine the effect of steam on the light reflectance measurement.

4.4.3.2 Experimental method and equipment.

Initially steam was applied to the laboratory rig, however the steam condensed inside the rig and proceeded to moisten the sugar samples, to the extent that some of the sugar crystals dissolved. This adversely affected the appearance of the solid sugar samples. A decision was made to simulate a 'steam effect'. Dry ice was added to water to create a 'steamy' environment. This dry ice-water container was placed adjacent to the sugar samples for maximum interference.

Sugar samples of varying purities were tested. Reflectance measurements were taken before and after the introduction of the 'steam'. The quantity of dry ice added was sufficient to allow for vigorous bubbling (approximately 10 g of dry ice in 50ml of water).

These trials were performed for the incandescent and the red LED lamps. Trials were performed at a sugar sample to light source and sensor tube distance of 7 cm.

The raw data of these trials are presented in appendices D and E.

4.4.3.3 Experimental results and discussion.

a) Incandescent (35W) trials.

The steam simulation trials using the incandescent lamp show a slight difference in the reflectance measurement after placing the dry ice in the vicinity of the sugar samples. The difference was however not considered to be significant. These results were contrary to interference effects expected from the steam. Figure 4.19 presents the average results obtained from the steam simulation trials using the 35 W incandescent lamp.

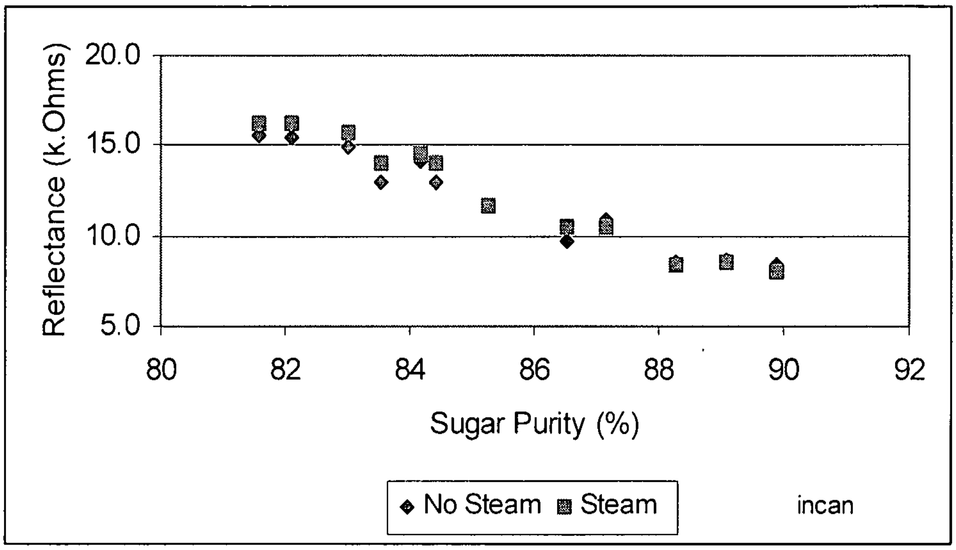


Figure 4.19: Steam Trials: Simulation of the Steam Effect on the Reflectance Measurement, Using a 35W Incandescent lamp and a LDR

A correlation coefficient of r = 0.98 and r = 0.97 was obtained for the steam and no steam trials respectively, indicating highly linear relationship between sugar purity and measured reflectance. A students t-test, produced no significant difference between the steam and no steam addition values (t- (stat) =-2.4 < t- (critical) =2.2 at a 95% level of confidence).

b) Red LED Trials

The steam simulation trials using the red LED light source show that there were no significant changes in the reflectance measurement after placing dry ice and water in the vicinity of the sugar sample. Here the difference between the readings with and without the addition of dry ice seems less noticeable than the measurements with the incandescent lamp. These results were contrary to interference effects expected with the steam. The average results achieved from the steam simulation trials for the red LED are presented in Figure 4.20. The raw data for these trials are presented in Appendix E (Table E.2).

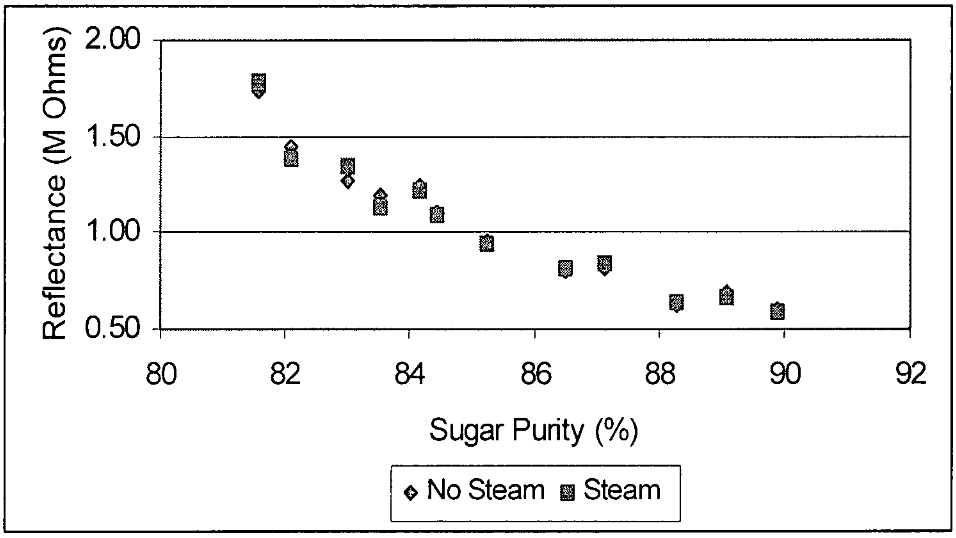


Figure: 4.20 Steam Trials: Simulation of the Steam Effect on the Reflectance Measurement, Using A Red LED And A LDR

A correlation coefficient of r = 0.96 and r = 0.95 was obtained for the steam and no steam trials respectively, indicating highly linear relationship between sugar purity and measured reflectance. A students t-test, produced no significant difference between the steam and no steam addition values (t- (stat) =0.4 < t- (critical) =2.2 at a 95% level of confidence.).

4.4.3.4 Conclusions

The 'steam' addition, trials showed that there was no significant effect on the measurement of reflected light intensity. The reflectance readings follow the same trend with and without the steamy effect. The relationship between sugar purity and measured reflectance was linear and repeatable. It was acknowledged that the steam simulation trials did not exactly replicate the environment on the insides of a continuous centrifugal.

4.4.4 Efforts to accommodate the effect of vibration.

The continuous centrifugals are mounted on steel frameworks. When the centrifugals are in operation, vibration of the centrifugal casings can always be observed. A major contributor to the vibration levels experienced in continuous centrifugals is the improper installation of centrifugal screens, which results in an imbalance. However it was apparent that no matter how perfectly the screens were installed there is always some vibration. Based on past experience on the centrifugal station, where due to the vibration levels, screws, nuts and bolts have slowly come undone; it was necessary to take these factors into account when building the purity meter prototype.

Since the purity meter prototype would be installed on top of the monitor casing it was necessary to assess the effect this vibration would have on the purity meter. Trying to subject the laboratory rig to the vibration levels experienced on the monitor casing would not have had any effect on the reflectance reading as the entire rig would move/vibrate. Therefore the sugar samples and light sensor and detector are moving relative to the monitor casing, but are stationary to each other. A relationship between the stationary sugar samples of varying purities and measured reflectance has already been established.

It was therefore decided that the tubes would be welded on to a tube plate and that the tube plate needed to be welded on to the monitor casing. The opening in the monitor casing would be sufficient to allow for tube distance to the centrifugal screens to be adjusted. This could be achieved by sliding the tube plate forward and backward. The light source and the light sensor were fitted securely to avoid damage by vibration.

It was with the knowledge of the preliminary trials in the laboratory that the second purity meter prototype was built and was ready for trials in the factory.

4.5 Conclusions of the Laboratory Trials

The following is a summary of the conclusions drawn from the laboratory purity meter trials.

I. It was established that there was a reliable and repeatable, linear relationship between sugar purity and measured reflected light intensity.

II. The light sources selected for the factory purity meter prototype was the red LED and the 35 W incandescent lamps. These lamps would be tested separately.

III. The light detector/sensor chosen for the factory purity meter prototype was the LDR due to is ability to provide stable readings in the required temperature range of 60 to 70 °C.

IV. The testing of the environmental variables (crystal motion and steam addition) in the laboratory showed that these factors had no effect on the light reflectance measurement.

V. The need to build a robust factory purity meter to accommodate for the effects of vibration was highlighted.

VI. The correlation coefficient value for the red LED was approximately $r=0.96$. The regression analysis curve generated was $y=-0.21x+11.49$.

VII. The correlation coefficient value for the incandescent lamp (35W) was $r=0.99$. The regression analysis curve generated was $y=-1.05x+101.41$.

Chapter 5

DEVELOPMENT OF THE FACTORY PURITY METER.

The experiences from the laboratory purity meter trials were used to construct the factory purity meter. Chapter 5 describes and discusses the factory experimental work performed in the development of an industrial meter for the detection of sugar purity in a continuous centrifugal. Both light sources were tested (the red LED and the 35 W incandescent lamps) with the aim of selecting the best light source. Trials were performed on the number 2 C-centrifugal at Maidstone Mill. Chapter 5 is divided into the following sections:

5.1 Red LED factory trials.
5.2 Incandescent lamp (35W) factory trials.

5.1 Red LED factory trials.

5.1.1 Aim of the experiment.

The aim of these factory trials was to test the purity meter prototype using the red LED (light emitting diode) as a light source and the LDR (light dependent resistor) as the light sensor. Trials were performed on low-grade C-sugar in a continuous centrifugal.

5.1.2 Experimental method and equipment.

a) Factory purity meter rig.

The purity meter factory prototype was built of stainless steel tubes. A clamping plate held the two tubes on to the top surface of the centrifugal. The tubes housed the light source (12 candela red LED) and the light dependent resistor (LDR- NORP 12). Figure 5.1 presents the factory prototype. The tubes were mounted on a base plate that slides on the monitor casing, allowing for the adjustment of the distance from the tubes to the centrifugal basket surface. This was necessary for focusing purposes and to prevent fouling of the tubes. Figure 5.2 illustrates the purity meter installation on the centrifugal monitor casing. The tubes are angled at 90 ° to the basket.

Purity meter prototype I was constructed such that the electronic unit was mounted on top of the tubes. The electronics in prototype II were remotely panel mounted, adjacent to the centrifugal operating panel. The reasons for this are explained in the experimental results and discussion section.

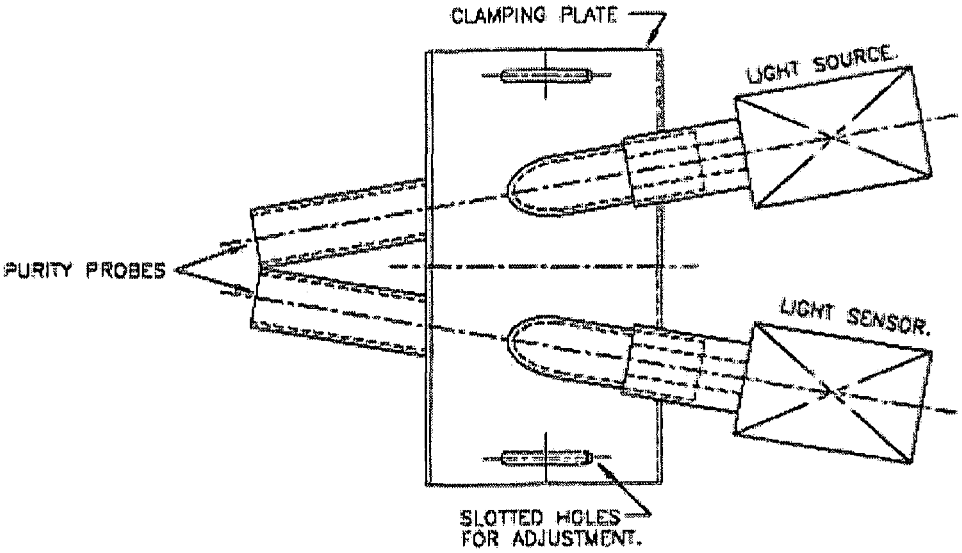
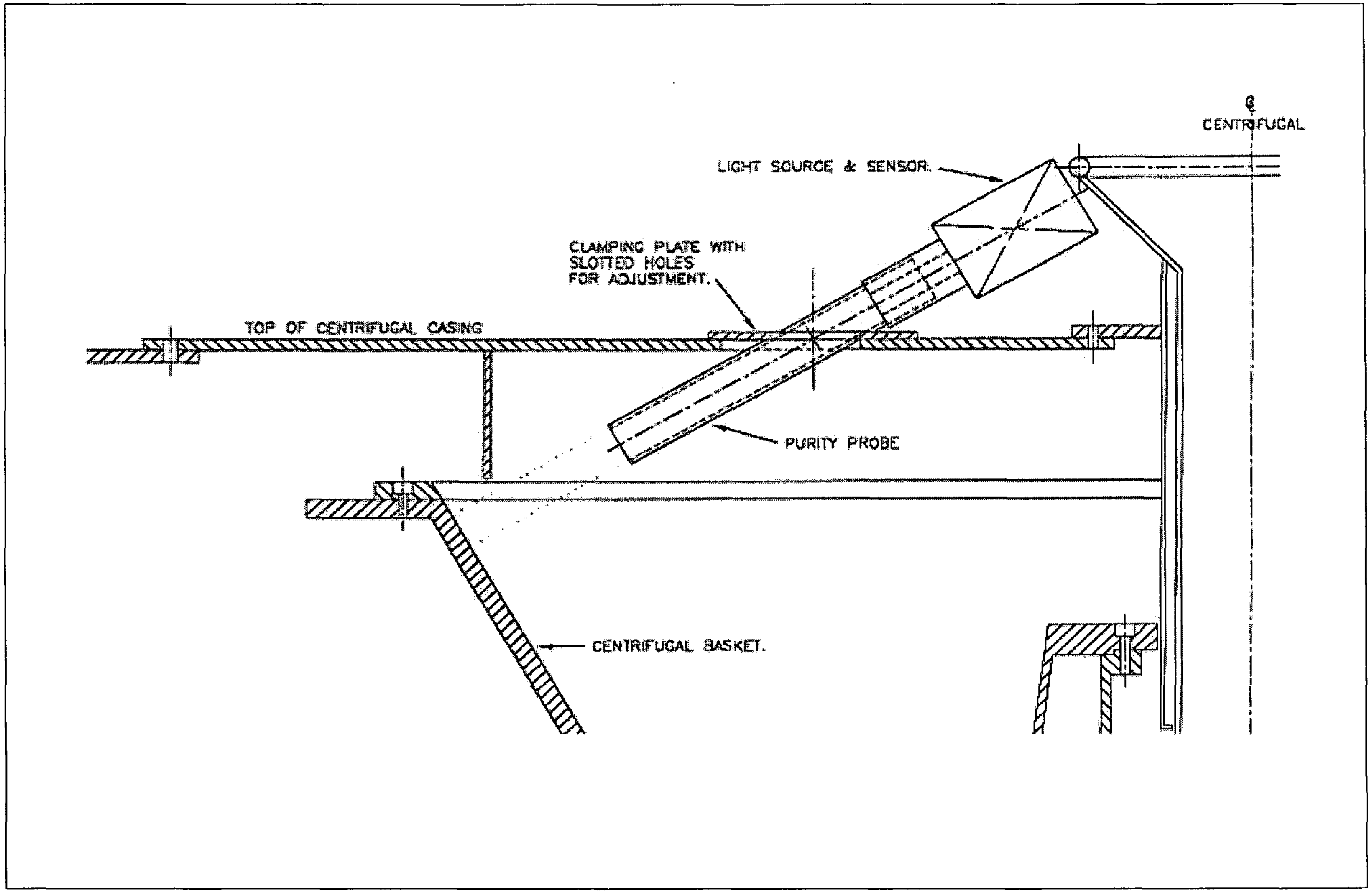


Figure 5.1: Purity meter prototype

Figure 5.2 Purity meter set-up on the centrifugal



b) Light and light detector signal processing.

Figure 5.3 presents the general layout of the light source and the light detector.

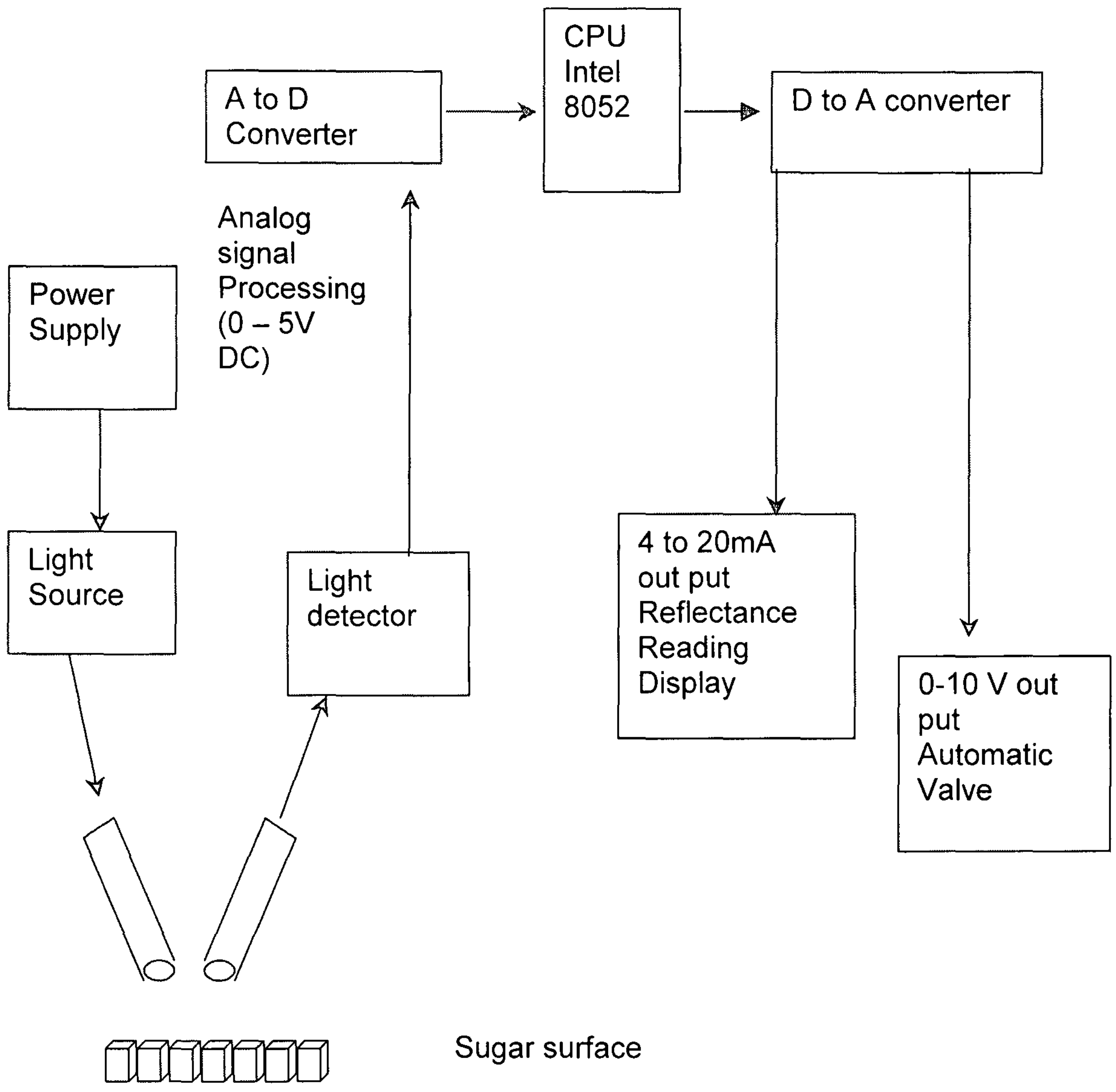


Figure 5.3: Light and light detector processing.

Power is supplied to the light source. It is important that the light source emits light of a repeatable and constant level since the failure to provide a constant light source will result in a light source of varying light emitting intensities. To achieve a constant light intensity, a constant AC voltage supply is needed.

Light reflected off the sugar surface is received by the photo-detector. The analogue signal (A) from the photo-detector is converted to a digital signal (D). This signal is processed by the central processing unit (CPU). The CPU is the PID (proportional, integral and derivative) control and the signal-processing unit. The digital output from the CPU is converted to a 4 to 20 mA output for the display and is read as a 0 to 100 % output. Preliminary laboratory trials did not include the processor and thus those trials recorded volts (for the photodiode) and resistance (for the light dependent resistor). The signal processing with the 0 to 100% output display was used in later trials.

A 0 to 10 volt DC output was required to operate the water valve. The use of the automatic valve to automatically control wash water was not within the scope of this research report.

c) Calibration of the purity meter.

Sugar samples of purity ranging from 85% to 94% were obtained from the continuous centrifugal. These were analysed as per the SASTA manual, in the laboratory (Appendix A). Calibration was required to establish an operating range. The purity meter was calibrated in the laboratory before being installed in the factory.

d) Sugar Samples

Sugar samples were periodically taken from the centrifugal and corresponding light reflectance measurements were recorded. The massecuite feed and water addition to the centrifugal were changed in order to achieve different sugar purities. Sugar samples were analysed as per the prescribed SASTA method (Appendix A). Laboratory analyses were necessary to compare the purity meter measurement to the actual sugar purity.

5.1.3 Experimental results and discussion.

5.1.3.1 Purity meter operations.

The following sub-sections describe initial shortcomings and development of the purity meter prototype.

a) Water ingress into the electronics.

Purity meter prototype I was constructed such that the electronics were mounted on top of the tubes. Due to water ingress into the electronics, (by the washing of the centrifugal surface as a housekeeping function) there was the resultant short-circuiting of the instrument. This obstacle was overcome by having the electronics in prototype II remotely panel mounted, adjacent to the centrifugal operating panel.

b) Fouling of the purity meter tubes.

During trials it was found that molasses blocked the meter's tube openings thus preventing accurate reflectance measurements. The red LED purity meter prototype was constructed with tubes of 13mm diameter. A deflector metal plate was installed immediately 'upstream' of the meter tubes so that it could shelter and protect the tubes from direct contact with the molasses.

This plate initially seemed to reduce the problem of fouling of the tubes but the problem reappeared with time. The molasses collected on the plate and dripped onto the tubes. Once again the tube openings became obscured rendering the purity meter useless. The plate was therefore removed.

In an effort to reduce molasses fouling the purity meter tubes were shortened such that the distance from the tubes to the centrifugal basket was 22 cm. Air supply was added to the light and light detector tubes to provide a positive pressure down the tubes to minimize fouling of the tubes. Figure 5.4 represents graphically the final position of the purity meter tubes relative to the centrifugal basket for the red LED trials.

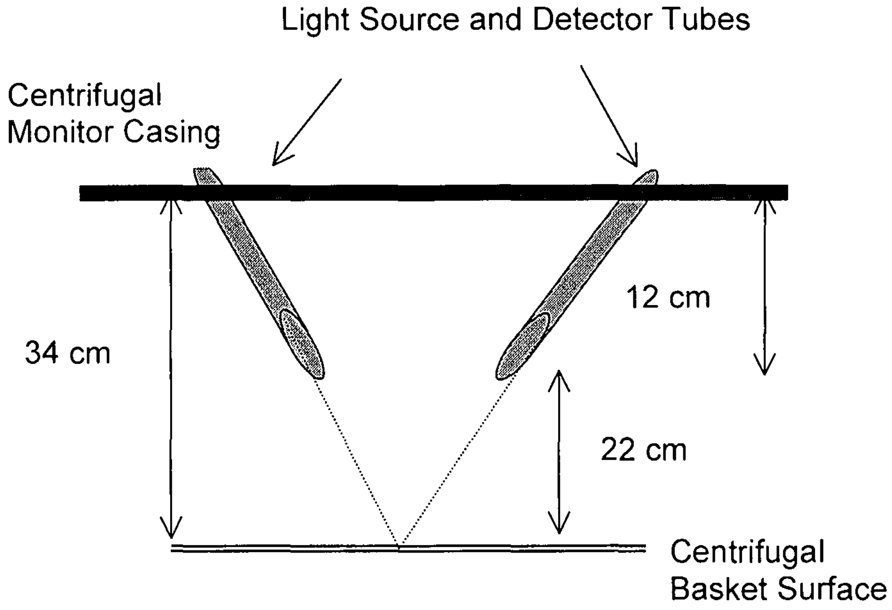


Figure 5.4 Red LED light source and detector tube distance to continuous centrifugal basket.

On reducing the length of the purity meter tubes it was noted that after one week of operation, the tubes remained relatively free of blockage by the molasses. It was therefore agreed that the cleaning of tubes once per week was a reasonable maintenance period. A standard procedure was prepared for the cleaning of the reflectance meter tubes and involved washing off all molasses from the tubes with hot water. The light source and detector are also removed and wiped clean to prevent unreliable readings.

5.1.3.2 A comparison between laboratory and factory trials.

The reduction of initial fouling problems allowed for further testing of the purity meter. As explained in previously the purity meter electronics were adjusted to provide a percentage output. The laboratory purity meter was re-calibrated using new samples and a correlation coefficient of r=0.98 was achieved. The regression analysis curve generated was y=-2.05x-127.75. The purity meter was then installed in the continuous centrifugal.

It was found that the reflectance measurements obtained from the laboratory trials and those obtained from the factory trials were significantly different. This variation can be seen in figure 5.5 where sugar samples were taken from the centrifugal in the factory and compared to the calibration curve obtained from the laboratory rig.

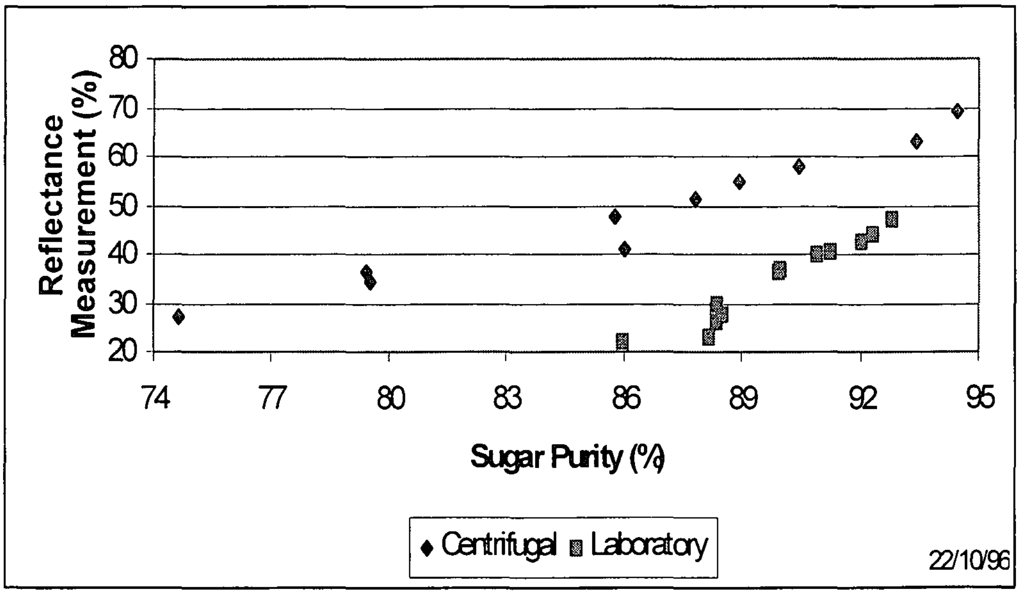


Figure 5.5: Relationship between the Laboratory Calibration and the Centrifugal Reflectance Measurements.

A correlation coefficient of r = 0.97 was obtained and the regression analysis curve generated was $y=-2.05x-127.75$ (for the centrifugal). Although the linear relationship between sugar purity and measured reflected light continues to exist the regression curves have changed significantly. It was apparent that the purity meter was operating in different ranges in the centrifugal and in the laboratory rig. This indicated that the purity meter was capable of measuring sugar purity in the continuous centrifugal, but that the initial laboratory calibration cannot be used to predict sugar purity in the continuous centrifugal. There was therefore the need for independent calibration of the purity meter electronics in the factory.

A reason suggested for the significant offset between the factory and laboratory reflectance measurements was that in the centrifugal the meter sees the top surface of the sugar only. Any liquid, that is, water and molasses drain away rapidly under the high centrifugal forces. The withdrawn sample on the other hand may be a blend of the sugar and the molasses when it leaves the top of the basket. Hence the range in which the purity meter detects the purity of sugar under ambient conditions in the laboratory and the range in which purity is detected in the continuous centrifugal are not the same. For this reason it should be expected that reflectance readings in the centrifugal, of specific sugar purities might be slightly different to those of extracted sugar samples.

The surface of the sugar may provide another reason for the variation of the light detection range. The laboratory samples are placed in a container and the surface is levelled (compacted) to the height of the container. In the centrifugal the sugar surface is essentially compressed to the centrifugal basket due to the centrifugal forces. Hence a possible reason for the different light detection ranges.

The sheer difference of environment of the laboratory rig and the continuous centrifugal was also a likely reason for the shift in the detection range. Although the preliminary laboratory trials attempted to simulate conditions found in the centrifugal, it was acknowledged that the exact conditions were very difficult to simulate without actually acquiring a pilot plant scale continuous centrifugal.

It is clear from the above trials that the sensor detects the varying sugar purity, but the calibration of laboratory sugar samples does not apply to the centrifugal.

5.1.3.3 The Relationship between the measured light reflectance and sugar purity in the continuous centrifugal.

Having concluded that the laboratory rig could not be used for calibrating the purity meter, further calibrations were performed on the continuous centrifugal. Sugar samples were collected at varying massecuite feed and wash water additions and the purity analysis were performed in the laboratory. Corresponding reflectance measurements were recorded and together with laboratory analysis a purity curve was generated. Figure 5.6 presents a typical purity curve generated from these trials. The relationship between measured light reflectance and sugar purity was linear.

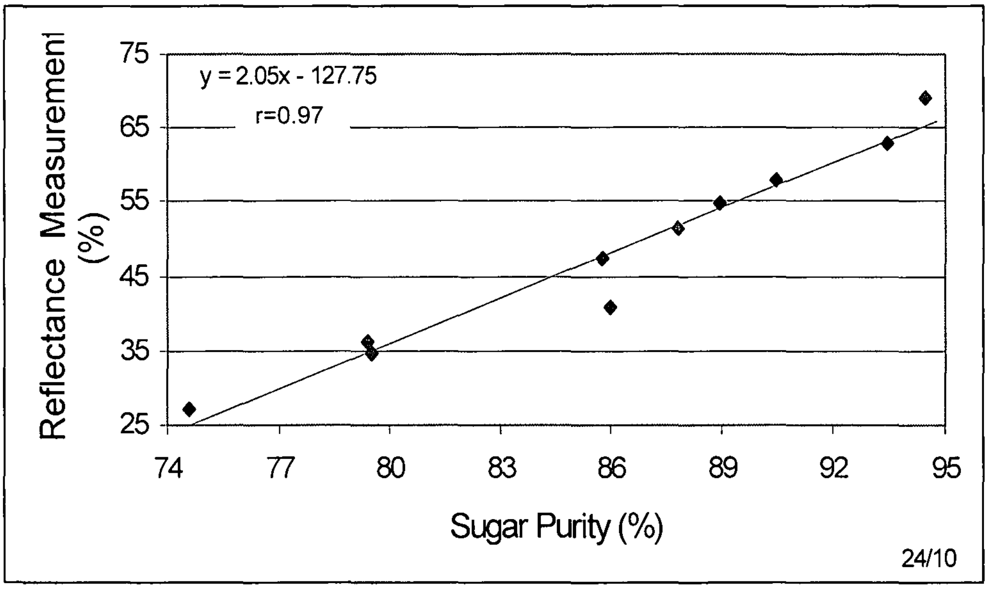


Figure 5.6 Typical calibration curve for the continuous centrifugal.

Massecuite quality in terms of crystal content, crystal size, shape and colour can change with changing sugar cane quality and process operations (boiling and crystallisation parameters). In order to check the effect that the quality of massecuite had on the reflectance measurement, calibration curves were generated on different days (during one week). Figure 5.7 presents data obtained on three separate days.

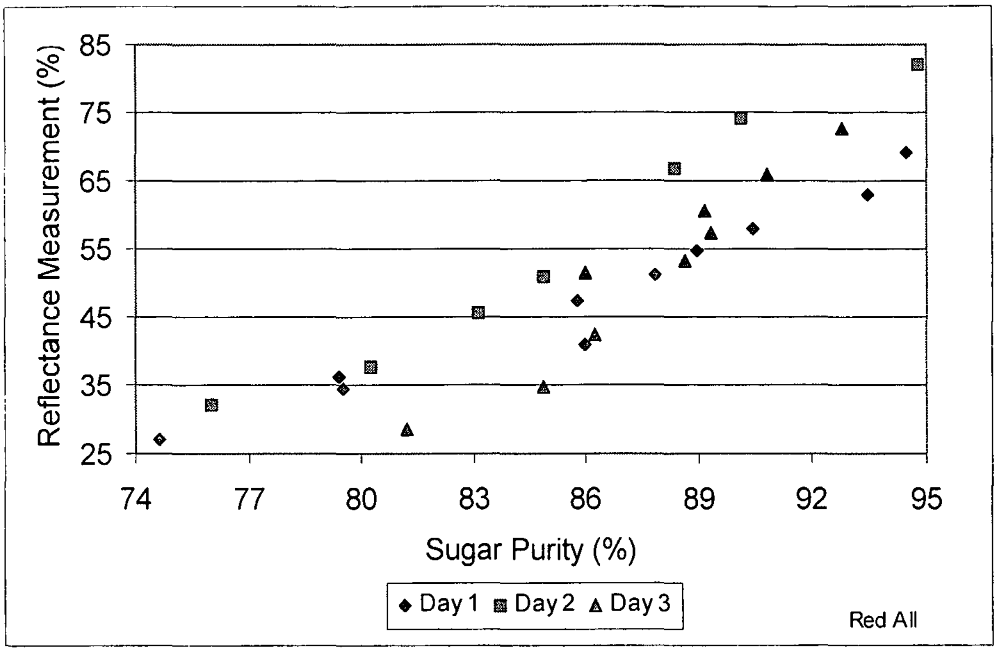


Figure 5.7:Calibration curves generated on separate days (red LED Trials).

Under conditions of varying massecuite quality the relationship between sugar and light reflectance measurements remained linear. There was however a change in the curve gradients. Table 5.1 presents the regression analysis and correlation coefficients calculated for the sugar purity measurement trials.

Table 5.1: **Regression analyses and correlation coefficients generated on separate days (Red LED).**

Day	Regression Analysis	Correlation Coefficient
1	$Y=2.05x-127.75$	r=0.97
2	$Y=2.95x-195.77$	r=0.98
3	$Y=4.01x-299.87$	r=0.96
Combined	Y=2.51-165.77	r=0.90

Correlation coefficients generated for the 3 days are not significantly different from each other. When the data for these three days were combined, the general curve generates was; $y = 2.51x - 165.77$ and the correlation coefficient was r=0.90. The relationship between sugar purity and measured reflected light intensity is fairly linear, however the linearity has decreased. These results indicate that there exists a possibility to calibrate once per week, however in order to acquire finer control of sugar purity, calibration is required on a daily basis. Daily calibration was considered to be a reasonable period.

5.1.4 Conclusions

The red LED (12 candela) and the LDR (NORP 12) produced a reliable and repeatable linear relationship between sugar purity and measured reflected light. Calibration of the factory purity meter is required to be performed while the purity meter is operational in the centrifugal. The laboratory calibration of the purity meter does not apply to operation in the centrifugal. Although there were various reasons suggested for the difference in the laboratory and factory measurements the exact reason for the fundamental difference between the laboratory and the factory purity meter is a fact that the laboratory purity meter failed to identify.

The factory purity meter is however capable of providing the centrifugal operator with a reliable measure of sugar purity.

Calibration of the purity meter on a daily basis is suggested due to the changing quality of massecuite and for purposes of greater accuracy in sugar purity control. Calibration of the purity meter once per week seems possible. No lamp deterioration was noted during operation (6 months).

5.2 Incandescent light - Factory trials.

5.2.1 Aim of the experiment.

The aim of these trials were to test the purity meter prototype using the 35 W incandescent lamp as a light source and the LDR (light dependent resistor) as the light sensor in a low grade C-sugar continuous centrifugal.

5.2.2 Experimental method and equipment.

The experimental equipment and method are the same as that used for the red LED trials. The light source was the incandescent lamp (35W) and the light dependent resistor (LDR- NSL 19).

5.2.3 Experimental results and discussion.

5.2.3.1 Purity meter operations.

Experiences from the red LED trials allowed for a more informed approach to the incandescent light trials. The new purity meter was installed on the number 2 C-centrifugal at Maidstone Sugar Mill on the North Coast. The following sub-sections describe the setbacks and developments of the purity meter prototype using an incandescent lamp.

a) Modification to the light source and light detector tubes.

The major advantage of the incandescent lamp (35 W) was that the lamp radiated a high light intensity. This property offset the negative effect of the shortened tubes (so that molasses fouling can be minimized). The high intensity light source indicated that more light would be reflected off the sugar surface and would provide the light detector with a stronger signal. The purity meter tubes were shortened such that the distance from the tubes to the centrifugal basket was 25 cm (previous distance was 22 cm). Another modification to the purity meter tubes was that the tube diameter was increased from 13mm to 30mm. These modifications significantly reduced the molasses fouling. The weekly maintenance period remained unchanged.

Figure 5.8 represents graphically the positions of the purity meter tubes relative to the centrifugal basket.

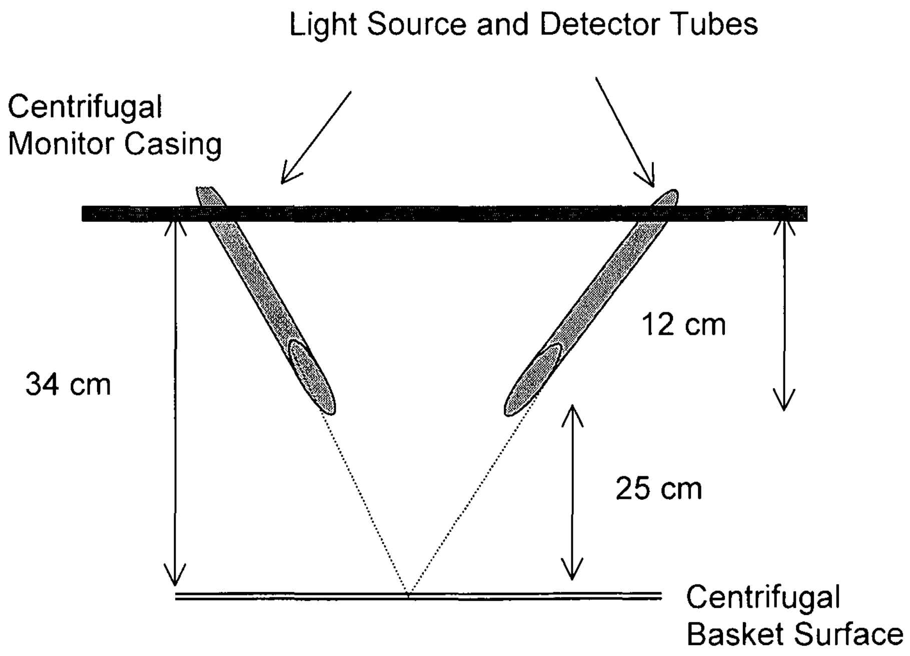


Figure 5.8: Incandescent lamp and detector tube distance to the continuous centrifugal basket.

It was noted that the 35W incandescent lamp operated at such high temperatures that the plastic insulation the electrical wiring (inside the tube) melted. In order to prevent further damage, high temperature resistant plastic fittings were used to prevent electrical contact with the stainless steel tube housing.

An air purge was added to the light source tube to assist in cooling of the lamp and to provide a positive pressure down the tube so that molasses fouling could be reduced.

c) Purity meter electronics.

The collaborating Instrument Engineer, Mr. Simon Proome performed all the electronic equipment design and their calibration. Due to confidentiality the actual makeup and circuitry of the reflectance meter electronics have been omitted from this report.

d) Purity meter reflectance measurement.

During the red LED trials a concern was raised, that the meter was unable to provide operators with a direct readout of sugar purity. Reflectance measurements and sugar purity are not necessarily of the same magnitude and hence actual sugar purity would have to be read off calibration curves. For the incandescent lamp reflectance measurements (resistance in kilo ohms) were therefore electronically modified to provide a sugar purity reading in the range of 70 to 99%. The operation range for the C-sugar purity was 80 to 84%. Therefore the purity measurement that the operator reads off the purity meter is a direct indication of the purity of sugar exiting the centrifugal basket.

e) Calibrating the purity meter.

It was established from the red LED trials that the calibration of the purity meter had to be performed in the centrifugal. Calibration at high sugar purity (high wash water rate) and at low sugar purity (low wash water rate) was necessary to establish an operating range. A constant massecuite feed and water addition, were maintained during each calibration. This was necessary to prevent the conditions to the machine from changing. Calibration was such that the purity meter measurements and the laboratory analysis were compatible.

The procedure for calibration was as follows: A sugar sample was obtained at low wash water rate, analysed in the laboratory and the required adjustment was made to the purity meter. A sugar sample was then obtained at high wash water rate, analysed in the laboratory and the required adjustment was made to the purity meter. Sugar samples were analysed as per the prescribed SASTA method (Appendix A).

5.2.3.2 The relationship between measured light reflectance and sugar purity in the continuous centrifugal.

As mentioned previously it was necessary that the calibration of the purity meter be performed while the purity meter was installed in the continuous centrifugal. The calibration method has been discussed previously. Figure 5.9 presents a typical curve generated from these trials.

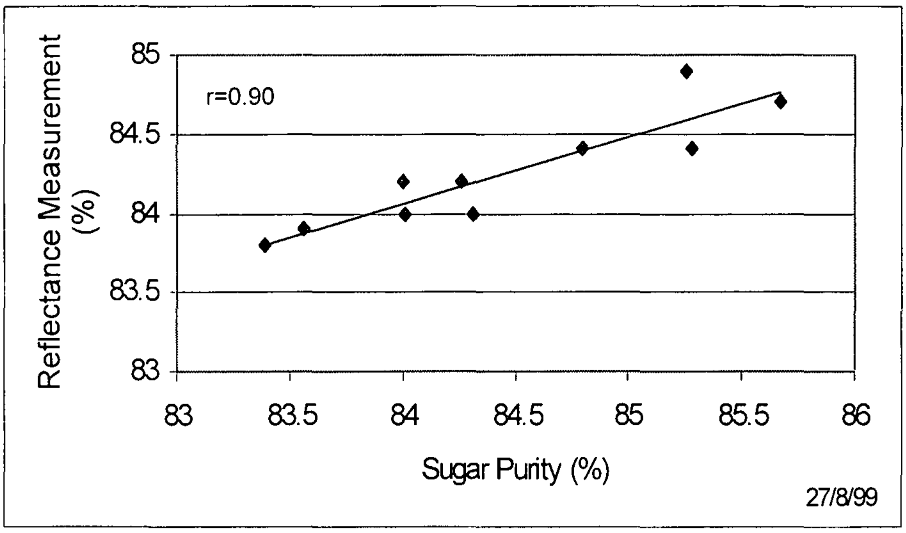


Figure 5.9: Relationship between purity meter measurements and laboratory purity analysis.

The relationship between measured light reflectance and sugar purity was linear.

As with the red LED trials, the effect of changing massecuite was tested. Figure 5.10 presents data obtained on three separate days of the same week. The relationship between sugar purity and the light reflectance measurement remained linear for the three sets of data. As experienced with the red LED trials, the gradients of the lines varied. This implied that the range, in which the purity meter operated, changed daily. This phenomenon is more clearly expressed in Table 5.2 where the regression analysis and correlation coefficients calculated for the sugar purity measurement trials are presented.

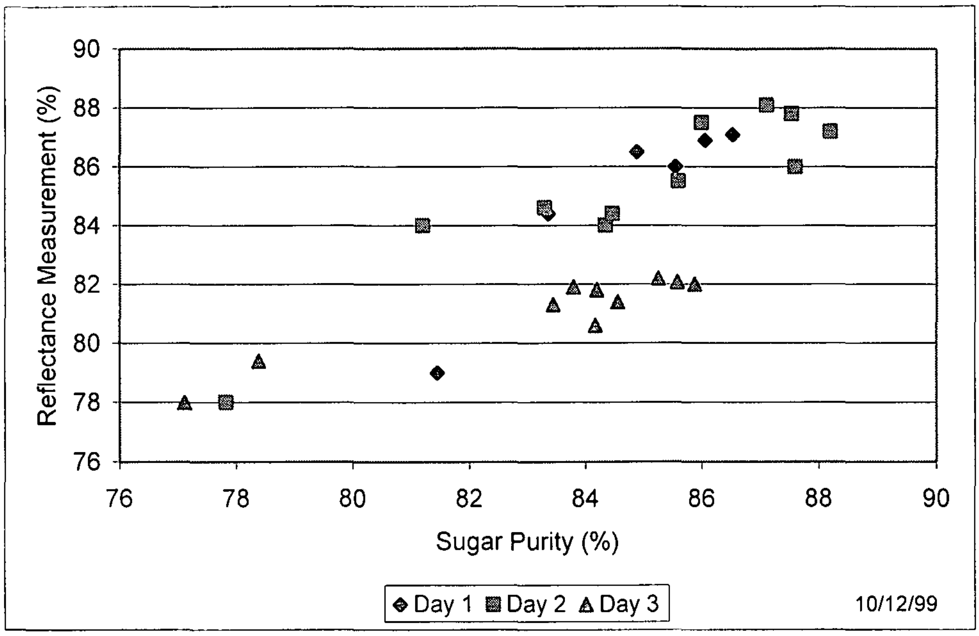


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Figure 5.10: The effect of changing massecuite quality on the Purity Meter measurement.

Table 5.2: Regression analysis and correlation coefficients generated on separate days (incandescent lamp).

Day	Regression Analysis	Correlation Coefficient
1	$Y=1.52x-44.16$	r=0.94
2	$Y=0.83x+14.43$	r=0.92
3	$Y=0.43x+0.45$	r=0.95
Combined	$Y=0.87x+10.47$	r=0.80

The changing quality of massecuite (crystal size, shape and colour) has a definite impact on the calibration curve. When data the three days was combined, the regression produced was $y= 0.87x + 10.47$ and the correlation coefficient was r=0.80. The correlation coefficient has decreased substantially. Therefore a general equation cannot be produced once per week. Calibration is required daily. This is considered to be a reasonable period for a factory.

The correlation coefficients of factory trials decreased from the r=~0.98 recorded in laboratory trials. This may be due to the deterioration of the incandescent lamp. The deterioration of the lamp was visually observed and the lamp had to be changed twice during the three- month trial. The deterioration of the lamp may also account for the poor combined regression curve generated. The daily measurements however were a reasonable measure of the sugar purity in the continuous centrifugal.

5.2.4 Conclusions

The 35W incandescent lamp produced a reliable and repeatable linear relationship between sugar purity and measured reflected light intensity. As experienced with the red LED, calibration was required daily due to the changing quality of the massecuite. Lamp deterioration was noted during the 3- month trial period.

5.3 CONCLUSIONS FOR THE FACTORY TRIALS

The factory purity meter (using both red LED and the 35W incandescent) lamps is capable of producing a reliable and repeatable relationship between measured reflected light intensity and sugar purity in a continuous centrifugal. Calibration of the factory purity meter is required to be performed while the purity meter is operational in the centrifugal. The laboratory calibration of the purity meter does not apply to operation in the centrifugal. The reason for the fundamental difference between the laboratory and the factory purity meter is a fact that the laboratory purity meter has failed to identify. The factory purity meter is however capable of providing the centrifugal operator with a reliable measure of sugar purity.

No lamp deterioration was noted for the red LED trials. Lamp deterioration was observed for the 35W incandescent lamp. The correlation coefficients generated for the red LED in the laboratory (r=0.96) was fairly consistent with the factory trials of r=0.97 to 0.98. The correlation coefficients generated for the 35W incandescent lamp in the laboratory (r=0.99) was not consistent with the factory trials of r=0.92 to 0.95. Weekly calibration seems to be a possibility with the red LED but not with the 35W incandescent lamp. This may be attributed to lamp deterioration.

The red LED seems to be the more reliable light source for the purity meter.

Chapter 6

Conclusions and Recommendations

The main objective of this investigation was to develop a purity meter that would provide the centrifugal operator with a reliable on-line measurement of sugar purity, thereby facilitating the automation of the continuous centrifugal. The conclusions and recommendations for this investigation are stated below.

Preliminary laboratory investigations involved the construction of a laboratory rig for the housing of the light sensor and the light detector, followed by the selection of the light source and light detector for the purity meter prototype. The selection criteria for the light source and sensor were:

a) the achievement of a reliable and repeatable relationship between sugar purity and measured reflected light intensity, and
b) a light source and sensor that can withstand the environmental conditions of the sugar mill.

Four light sources were tested viz. incandescent lamp (12W and 35 W), red LED (12 candela), and a strobe light (35W strobe at 4 Hz). As part of the continuation of earlier trials by Tongaat Hulett Sugar, the light detector used for the light selection trials was the photodiode. Two lamps were selected. The 12- candela red LED and the 35W incandescent lamps both provided a repeatable, highly linear relationship between laboratory analysed sugar purity and measured reflected light intensity.

The light detector selection trials involved the testing of the light dependent resistor (LDR) and the photodiode sensors to check if better results could be produced for the selected light sources. Results showed both the LDR and the photodiode sensors were able to successfully predict sugar purity. The relationship between sugar purity and measured reflected light intensity was linear and repeatable. The light sensor selection trials were performed at ambient temperatures.

Attempts were made to replicate the environmental conditions of the continuous centrifugal. As a result high temperatures (60 to 70°C), the spinning motion of the sugar samples, steam and vibration effects on the light reflectance measurement were tested. The following results apply to both the red LED and the 35W incandescent lamps.

- For the temperature tolerance testing the two light detectors were tested viz. the photodiode and the LDR (light dependent resistor). The LDR was selected for its ability to provide a steady output at the specified temperature range of 60 to 70°C. The photodiode output was unstable in this temperature range.

- The investigation to determine the effect of sugar crystal movement on light reflectance measurements showed that the movement (spinning) of sugar crystals had no significant effect on the measurement of light reflectance for the red LED and the incandescent lamps. The samples were spun at 120 rpm. Higher speeds could not be attained as the sugar samples tended to be spun off the sample holder. It was acknowledged that although the laboratory rig simulated some movement of the sugar crystals it was unable to accommodate the tumbling action of sugar crystals as they move up the centrifugal basket on a continuous centrifugal.

- The addition of steam to laboratory rig resulted in the condensation of steam onto the sugar samples and eventually, also in the dissolving of the sugar. The effect of steam was therefore simulated with the use of dry ice in water. There was no significant effect on the measured light reflectance readings in the steam simulation trials for both the red LED and the incandescent lamps. The relationship between sugar purity and measured light reflectance remained linear and repeatable for both light sources.

- The effect of vibration could not be simulated for the laboratory meter, however efforts were made accommodate for this when building the factory meter prototype. It was decided that purity meter tubes would be welded on to a tube plate and the plate would be welded on to the centrifugal monitor casing. The light source and detector would be held securely with appropriate electrical securing equipment.

The success of the laboratory trials led to the construction of the factory purity meter prototype. Both the red LED and the 35W incandescent lamps were tried in the factory. The following results were obtained for the factory trials:

For the red LED trials the relationship between sugar purity and measured light reflectance remained linear and repeatable in the continuous centrifugal. However calibration of the purity meter had to be performed with the purity meter installed in the continuous centrifugal as the laboratory calibration did not apply. It was discovered that the range in which the purity meter operated in the centrifugal and the laboratory rig varied. Although there were reasons suggested for this occurrence the exact reason for the fundamental difference between the laboratory and the factory purity meter is a fact that the laboratory purity meter has failed to identify. The factory purity meter is however capable of providing the centrifugal operator with a reliable measure of sugar purity. Correlation coefficients in the region of 0.97 were achieved for the red LED factory trials.

The effect of varying massecuite quality was tested and it was found that although the relationship between sugar purity and measured light reflectance remained linear and repeatable, the gradient of the lines changed with changing massecuite quality. When the results of 3 days (trials performed in the same week) were combined to verify if calibration could be performed once per week, it was discovered that the linear relationship between sugar purity and measured reflected light deteriorated from r = 0.97 to 0.90. Due to the narrow range in which the sugar purity has to be controlled (82 to 85%), it was decided that the calibration of the purity meter had to be conducted daily.

The following modifications were made to improve the purity meter prototype. The light source and detector tubes were shortened so that they were a distance of 22 cm from the centrifugal basket. This was performed to reduce molasses fouling of the tubes. A cleaning period of once per week was achieved and considered a reasonable maintenance period. The electronics were remotely panel mounted after short-circuiting occurred due to water ingress when the electronics were initially mounted on top of the centrifugal monitor casing.

The following results were obtained from the incandescent lamp trials:
The experiences from the red LED trials led to a more informed approach to the incandescent light trials. The purity meter was subjected to a few modifications before the initiation of the factory trials. The tubes were increased from 13 mm to 30 mm. It was noted that the small diameter tubes from the red LED trials would sometimes become totally obscured by molasses. Larger diameter tubes reduced this phenomenon and the

large diameter tubes also allowed for the further shortening of the tubes. The incandescent lamp had the advantage of high light intensity thereby offsetting the negative effect of the shortened tubes. The tubes were shortened such that there was a distance of 25cm to the centrifugal basket.

The molasses fouling was significantly reduced and a weekly maintenance period was maintained. Disadvantages noted with the 35W incandescent lamp were high heat emission and deterioration of the lamp light intensity with time. Electrical insulation was added to the electrical wiring for the incandescent lamp as the high temperatures resulted in burning of the wires. An air purge was added to assist in cooling of the lamp and also for applying a positive pressure down the tubes so that molasses fouling could be minimised.

The purity meter electronics were modified to operate in a range of 70 to 99%. This allowed operators to have a direct correlation of sugar purity in the continuous centrifugal. Correlation coefficients in the region of 0.94 were achieved for the incandescent lamp factory trials. The purity meter was calibrated daily while the centrifugal was operational. This was necessary as the calibration gradient changed with changing massecuite quality. Attempts to use the combination of 3 days data (of the same week) resulted in a correlation coefficient of r =0.80. This relationship was considered unacceptable. This was the same result as experienced with the red LED trials.

The objective of this investigation, to provide the centrifugal operator with a reliable measure of sugar purity was ***adequately achieved*** with both light sources. The results from the red LED trials are however better than those achieved from the incandescent lamp trials. The correlation coefficients achieved with the incandescent lamp in the laboratory (r=0.99) deteriorated when tested in the factory (r=0.94). Lamp deterioration was the reason for this phenomenon. The red LED maintained the good linear relationship of correlation coefficient values of approximately r= 0.97 in both the laboratory and the factory trials.

The LEDs as mentioned previously have the advantage of a long life span. They are also resistant to shock and vibration due to their solid makes up and they have low heat generation (~7°C). LEDs unlike incandescent light do not deteriorate over time and therefore do not require frequent replacement. In light of these advantages it is believed that the *red LED would be the better choice* for the light source for use in the detection of sugar purity in the continuous centrifugal.

The purity meter although capable of providing a reliable measure of sugar purity cannot totally replace daily laboratory analyses. This is proven by the fact that the meter requires daily calibration. The meter will however assist in significantly reducing the number of laboratory analyses performed and assist in reducing the loss of sucrose to molasses.

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Appendix A

Experimental Procedure

Appendix A

EXPERIMENTAL PROCEDURES

A 1.1 PROCEDURE FOR PURITY DETERMINATION OF MAGMA

Purity of magma (C-sugar) is the ratio percentage of pol to brix. It is determined according to the procedure specified by the SASA (South African Sugar Association). The procedure is as follows:

a) **Preparation of a stock solution**

i) 50 g of well mixed sugar sample is weighed in a 500ml Erlenmeyer flask.

ii) Distilled water is added to the flask to give a final mass of 250,0g. The flask is then stopper-ed.

iii) The sample is shaken until completely dissolved (ca 1 hour).

b) **Brix Determination**

i) 100ml from (a) is transferred into an Erlenmeyer flask. 2g of kieselguhr is added. This is well mixed.

ii) The mixed solution is filtered through a filter paper. The funnel must be covered with a watch glass to prevent evaporation losses and contamination.

iii) The first 10ml is rejected.

iv) When sufficient sample is collected, the brix is determined at 20°C using the refractometer described in section 3.3.2.

v) If the brix is not obtained at 25°C, Table 2 (P380) [SASTA (1985)] allows for brix adjustment at 20°C.

The final brix value is multiplied by 5.

c) Pol Determination

i) 150ml of the stock solution prepared in (a) is poured into an Erlenmeyer flask.

Add 4g of lead sub-acetate.

ii) The flask is stopped and shaken thoroughly to dissolve the lead sub-acetate.

iii) The solution is allowed to stand for 5 minutes.

iv) The solution is then filtered. The funnel must be covered with a watch glass to prevent contamination and evaporation losses.

v) The first 25ml is rejected.

vi) The clear filtrate is collected in a clear, dry beaker.

vii) Rinse the Pol tube three times with portions of the filtrate and determine the Pol using the polarimeter described in section 3.3.1. Pol is read in degrees Pol (°Z).

viii) The saccharimeter and refractometer readings must both be taken at 20°C. If the saccharimeter reading is not taken at 20°C, the brix reading from (b), before multiplying by 5, must be adjusted using table 4 (P386) [SASA (1985)]. The Pol is then calculated using the saccharimeter and refractometer reading from (b). The Schmitz's table [table 3, P381), [SASA (1985)].

The final Pol is multiplied by 5.

d) Purity Determination

Purity is the ratio percentage of Pol and brix

$$\text{Purity} = {}^{\text{Pol}}/_{\text{brix}} \times \frac{100}{1}$$

An example is provided below:-

Brix

Refractometer reading @ 26,4°C = 18,21°
Temperature correction @ 26,4°C= + 0,49°
Corrected brix at 20°C = 18,70°
Final brix = 5 x 18,70 = 93,50°

Pol

Saccharimeter reading @ 26,2°C = 67,80°
Brix @ 20°C = 18,70°
Adjustment for 26,2°C = - 0,40°
Adjusted brix = 18,30°

From the Schmitz's table Pol is calculated using the saccharimeter reading of 76,80 and the brix reading of 18,30°.

The result is 16,42°C.

Final Pol = 16,42°s x 5
= 82,10°s

$$\therefore \text{Purity} = \frac{82{,}10}{93{,}50} \times 100$$

= 87,81%

e) Computer Calculation

Mill laboratories are now equipped with computers that automatically calculate the purity after the samples have been added to the saccharimeter and refractometer.

Appendix B

Strobe Light Trials

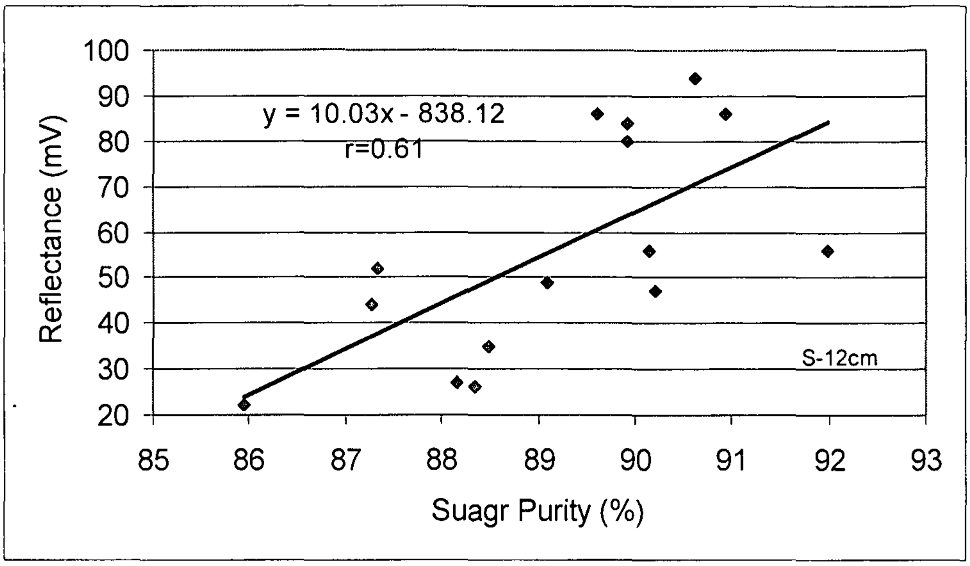

Figure B.1: Relationship between Sugar Purity and Reflected Light at a 18 cm Sample Distance

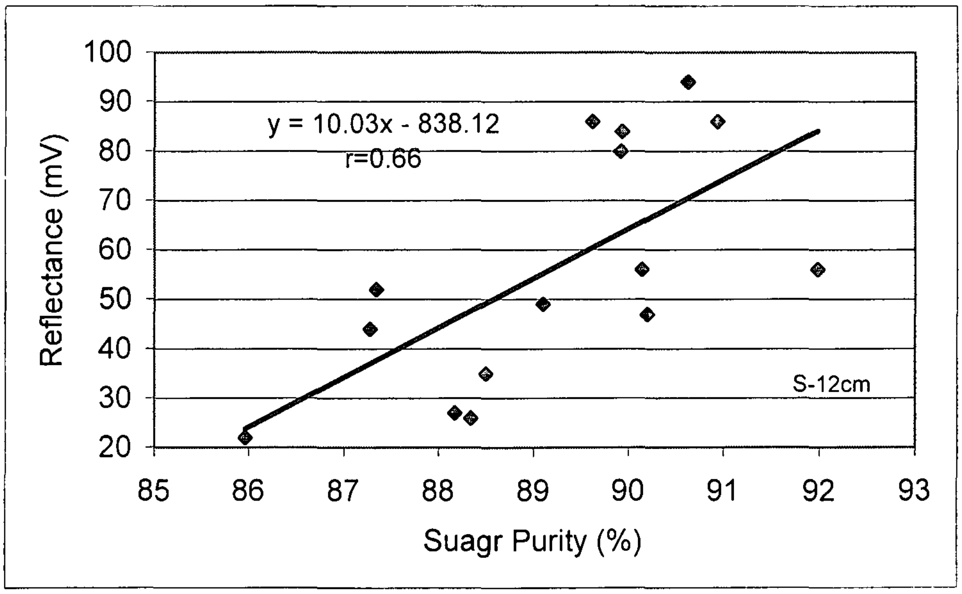

Figure B.2: Relationship between Sugar Purity and Reflected Light at a 12 cm Sample Distance

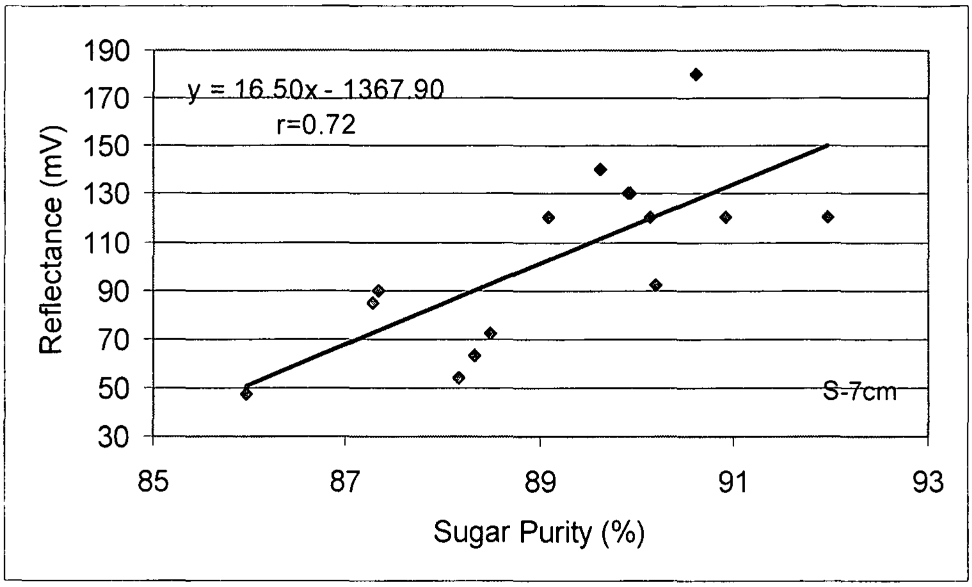

Figure B.3: Relationship between Sugar Purity and Reflected Light at a 7 cm Sample Distance

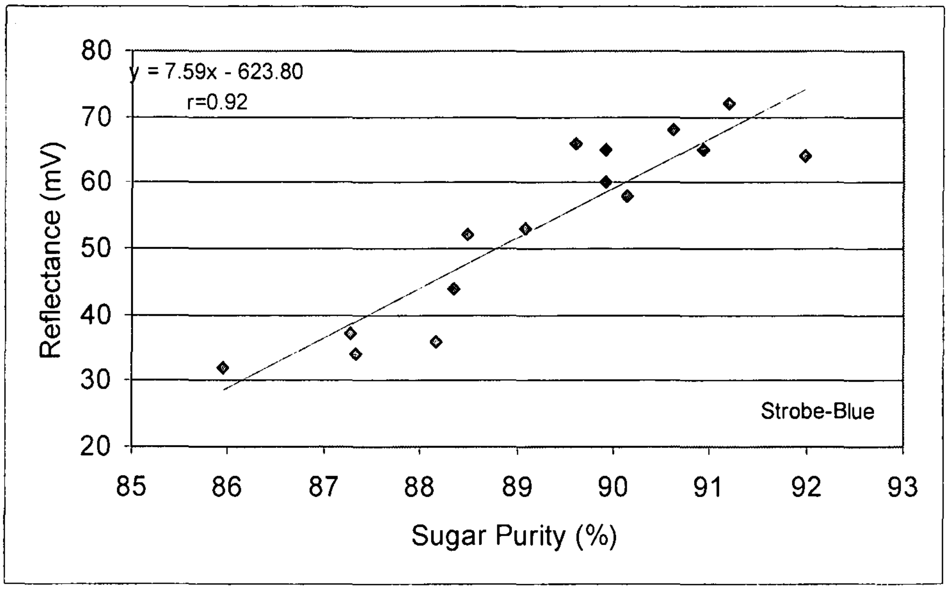

Figure B.4: Relationship between Sugar Purity and Reflected Light , using a Blue Filter

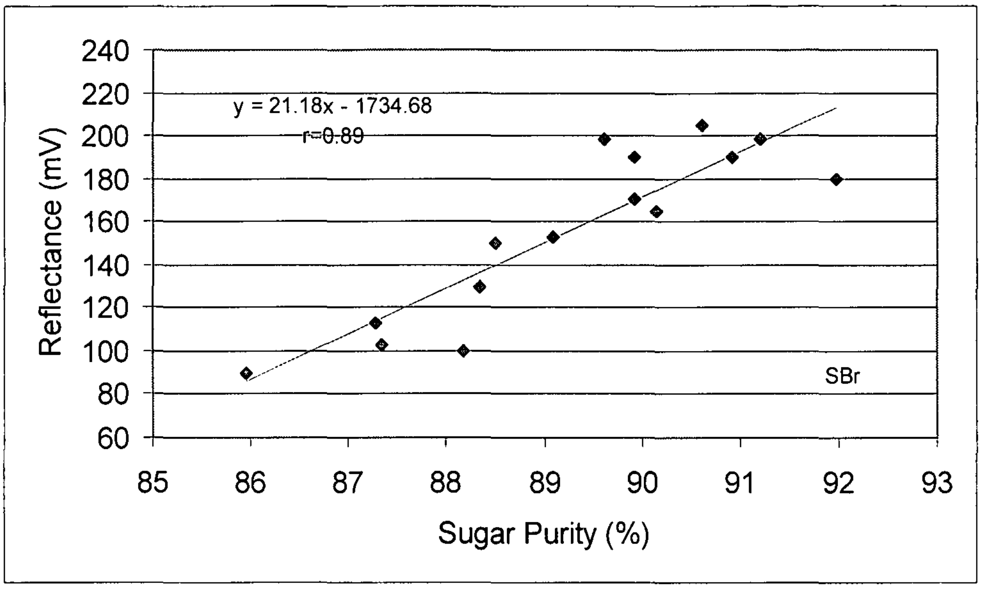

Figure B.5: Relationship between Sugar Purity and Reflected Light using a Brown Filter

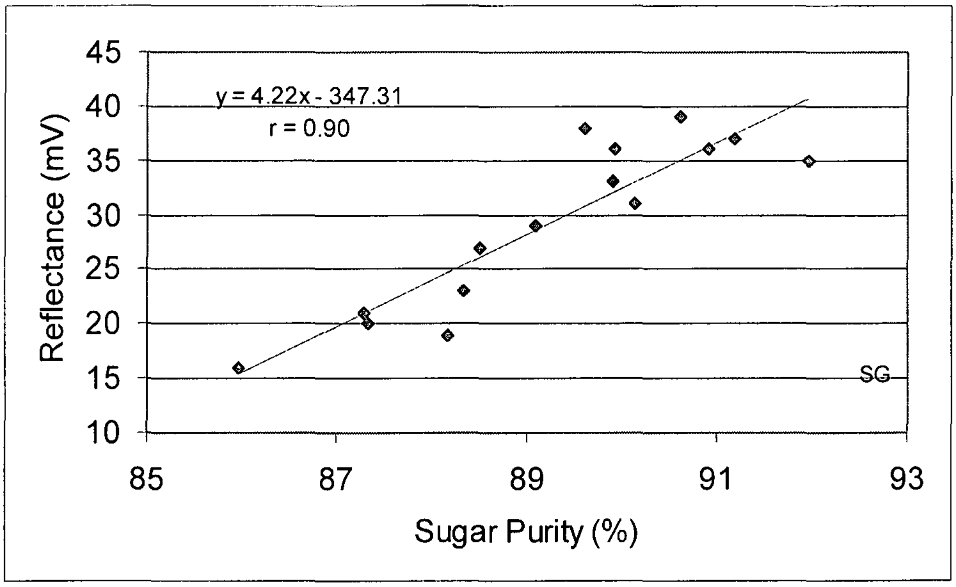

Figure B.6: Relationship between Sugar Purity and Reflected Light using a Green Filter

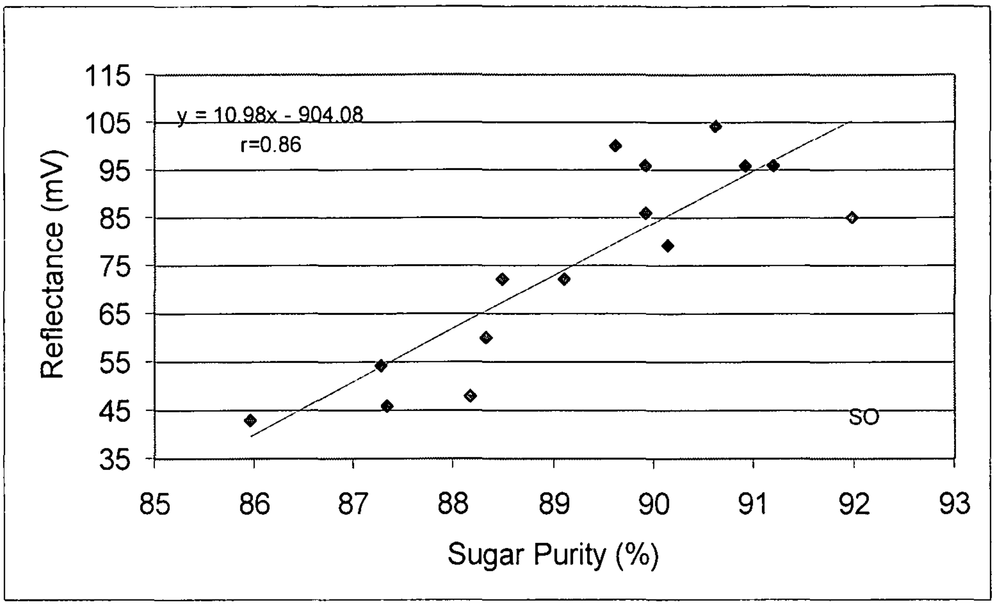

Figure B.7: Relationship between Sugar Purity and Reflected Light , using an Orange Filter

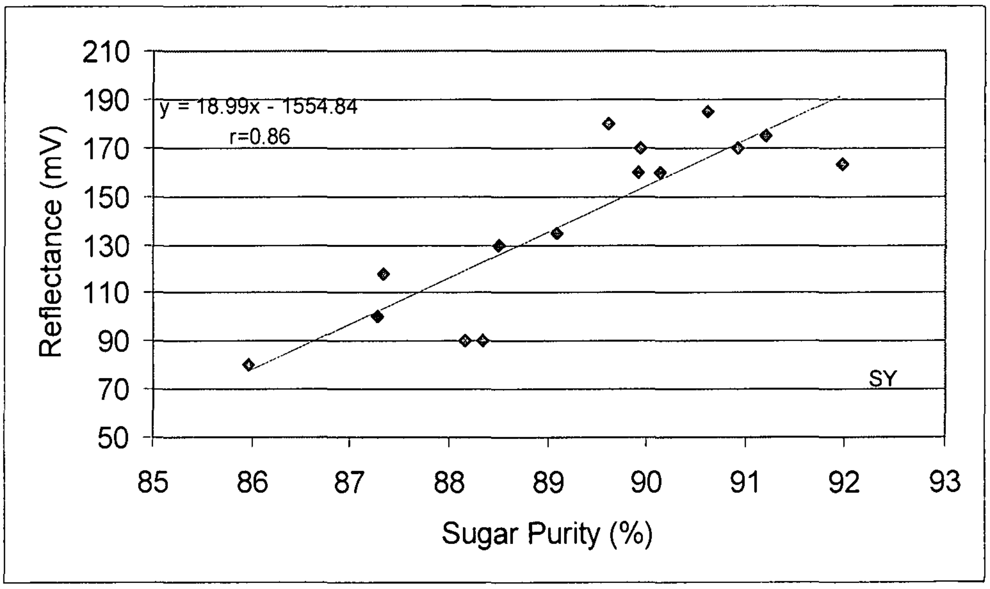

Figure B.8: Relationship between Sugar Purity and Reflected Light , using a Yellow Filter

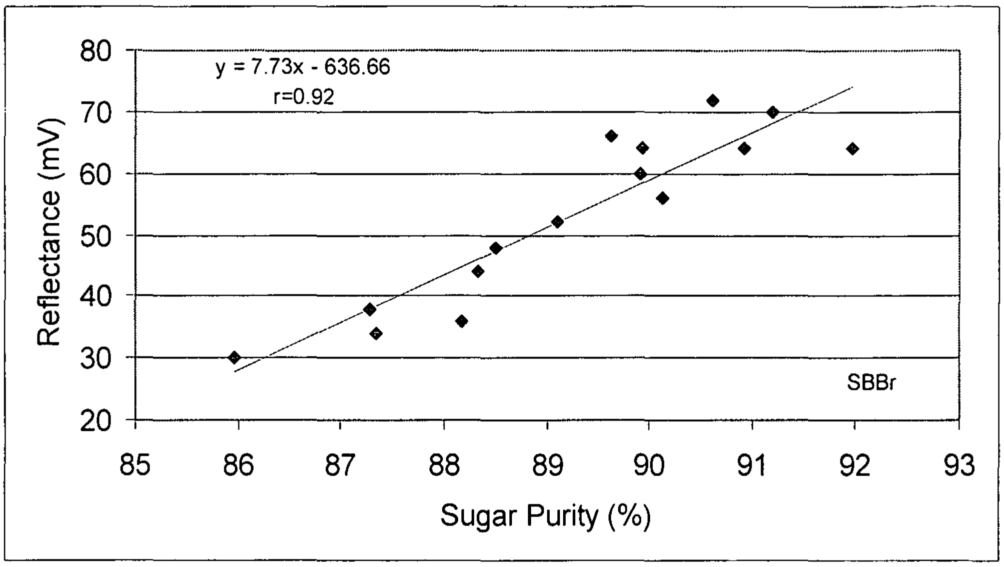

Figure B.9: Relationship between Sugar Purity and Reflected Light, using a Blue and Brown Filter

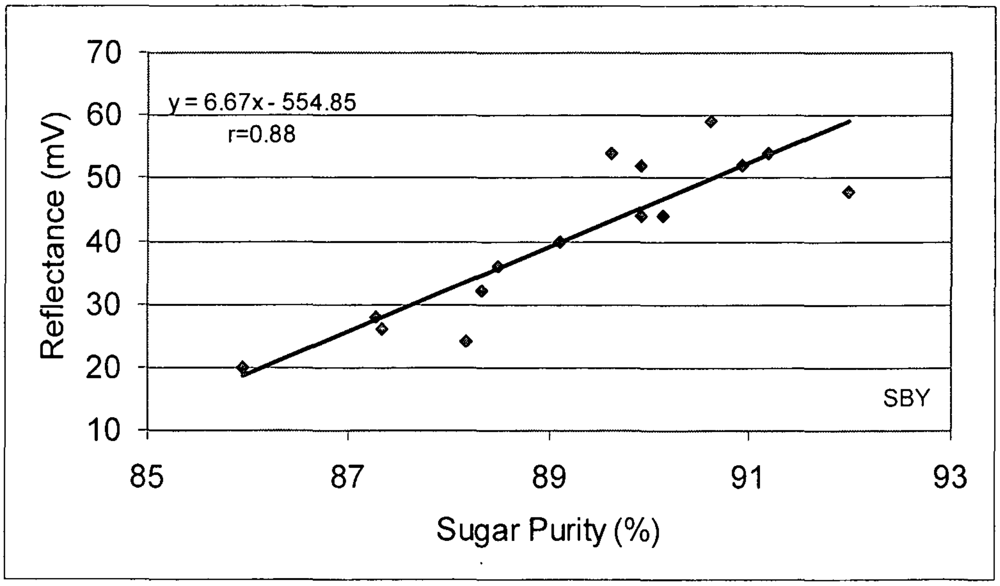

Figure B.10: Relationship between Sugar Purity and Reflected Light , using a Blue and Yellow Filter

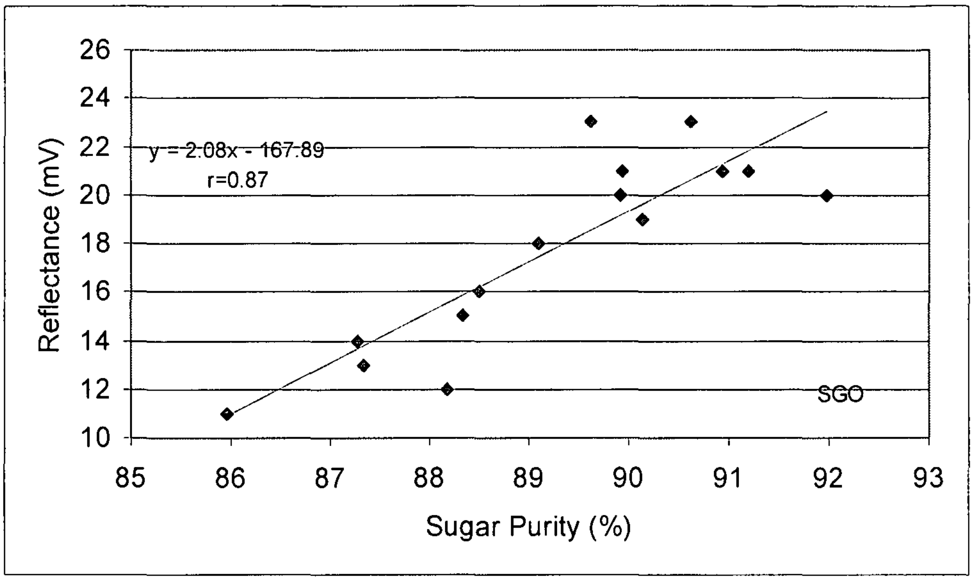

Figure B.13: Relationship between Sugar Purity and Reflected Light , using Green and Orange Filters

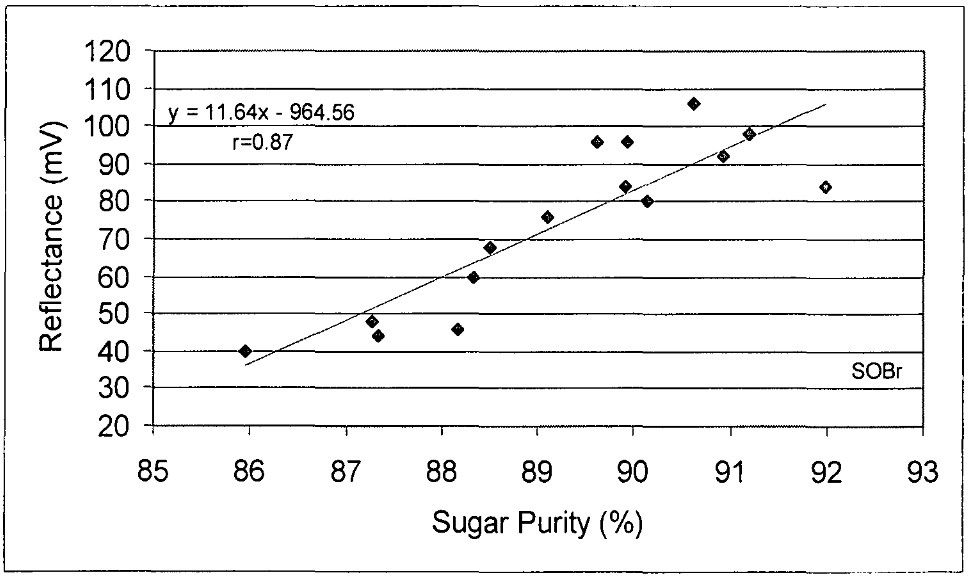

Figure B.14: Relationship between Sugar Purity and Reflected Light , using an Orange Brown Filter

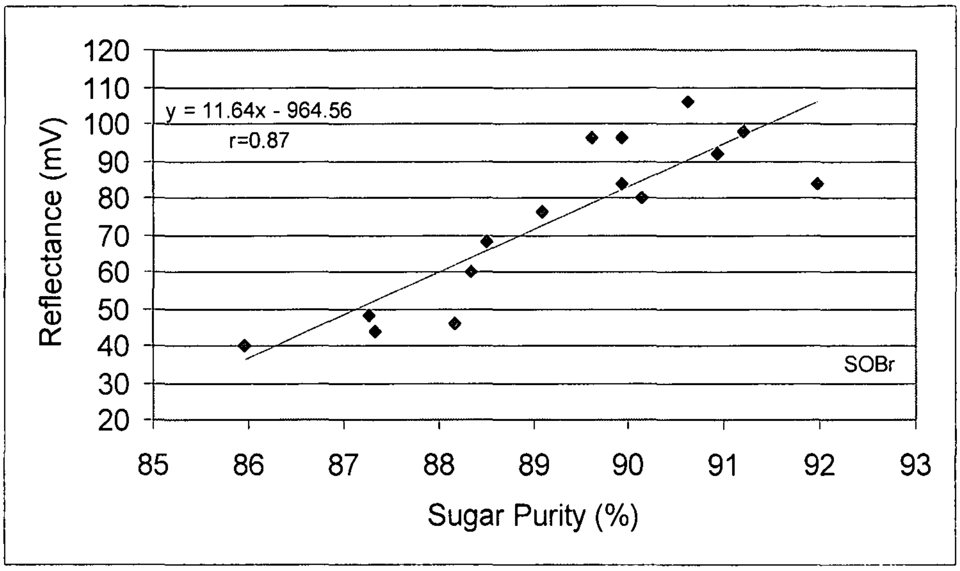

Figure B.15: Relationship between Sugar Purity and Reflected Light , using Green and Brown Filters

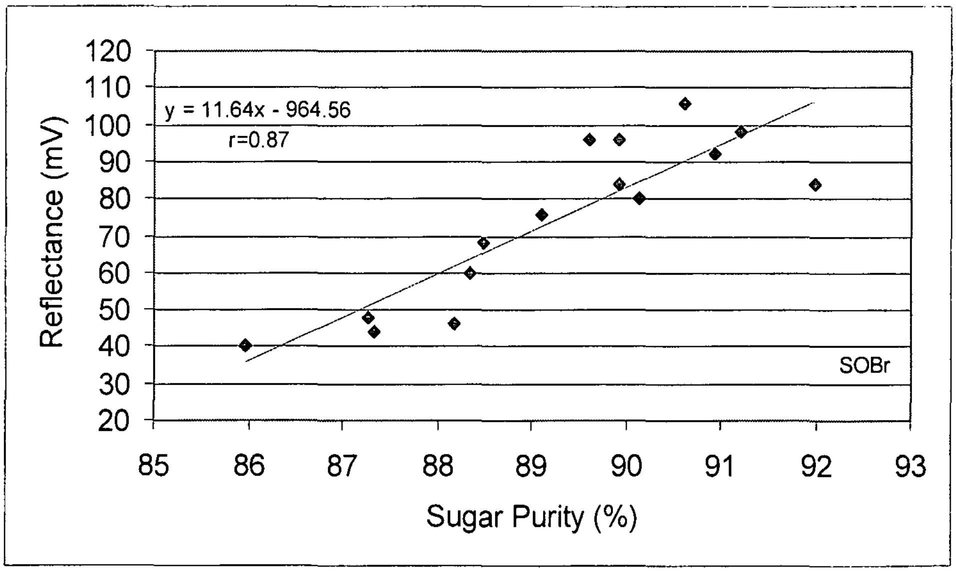

Figure B.16: Relationship between Sugar Purity and Reflected Light , using Orange and Brown Filters

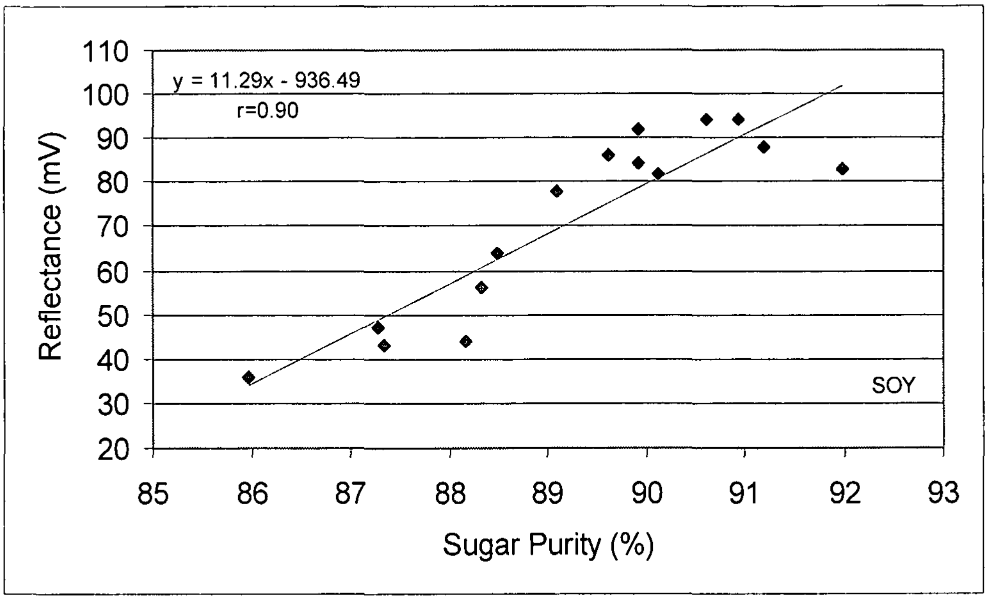

Figure B.17: Relationship between Sugar Purity and Reflected Light using Orange and Yellow Filter

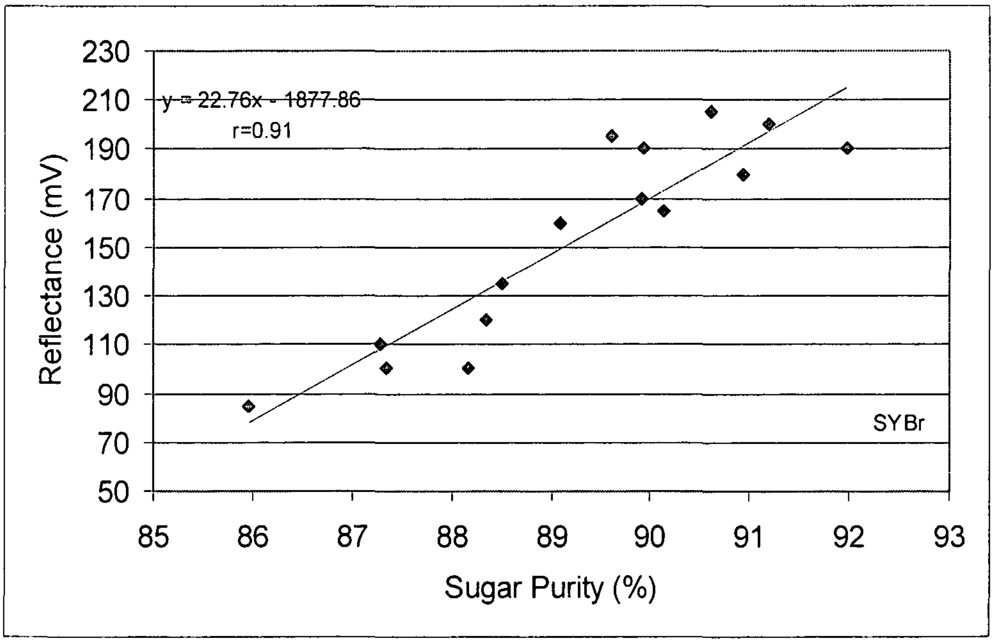

Figure B.18: Relationship between Sugar Purity and Reflected Light using Yellow and Brown Filters

Appendix C

Incandescent Light (12W)

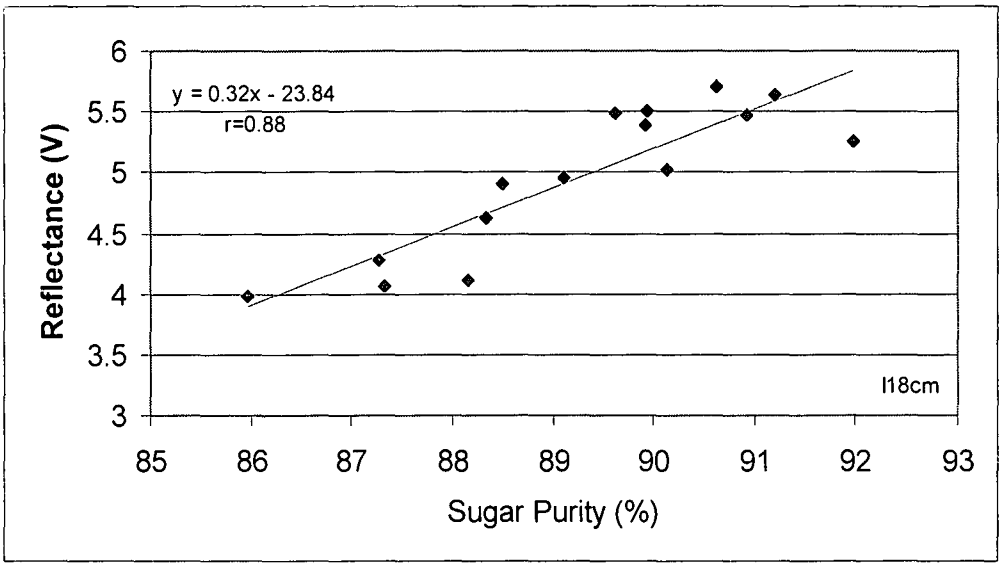

Figure C.1: Relationship between Sugar Purity and Reflected Light at a 18 cm Sample Distance

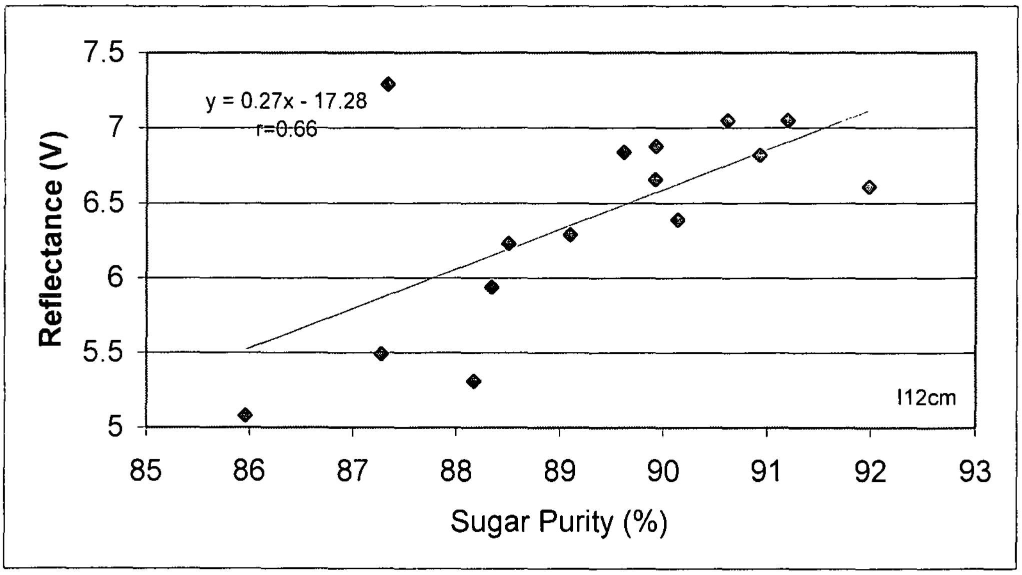

Figure C.2: Relationship between Sugar Purity and Reflected Light at a 12 cm Sample Distance

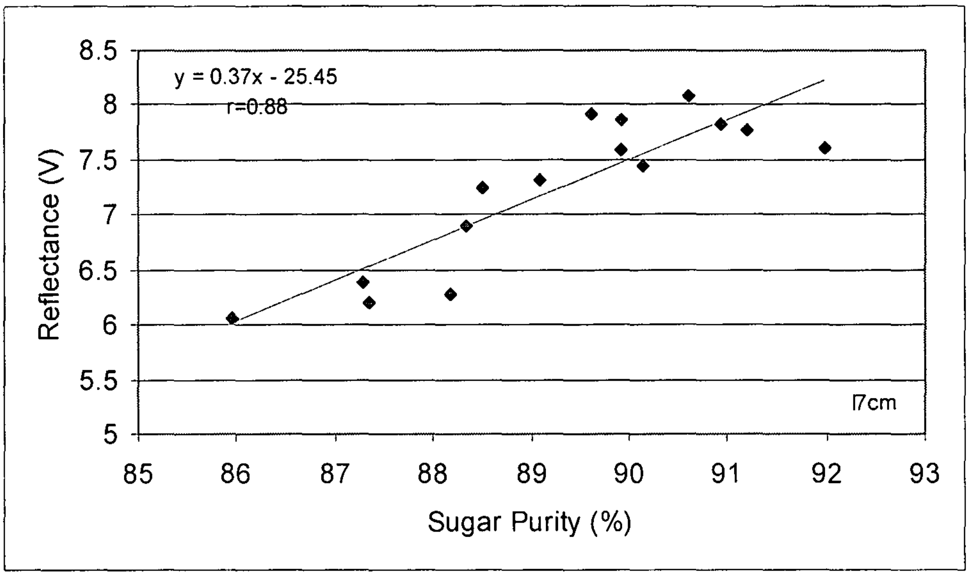

Figure C.3: Relationship between Sugar Purity and Reflected Light at a 7 cm Sample Distance

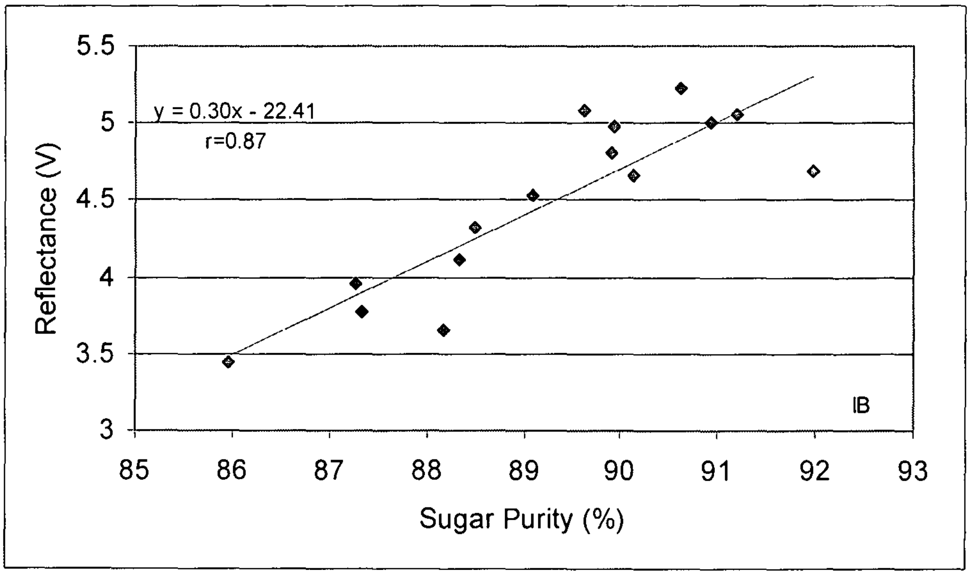

Figure C.4: Relationship between Sugar Purity and Reflected Light , using a Blue Filter

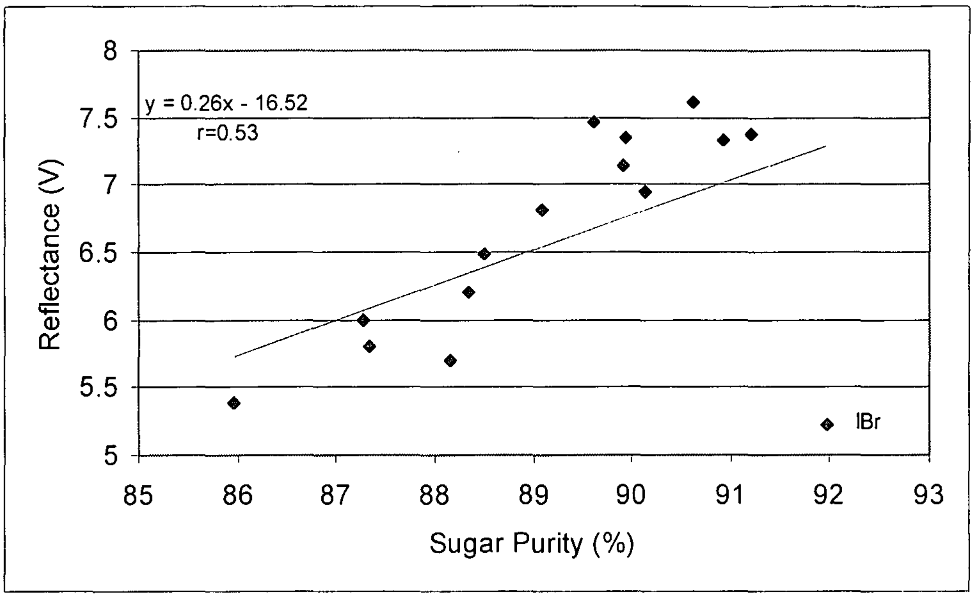

Figure C.5: Relationship between Sugar Purity and Reflected Light , using a Brown Filter

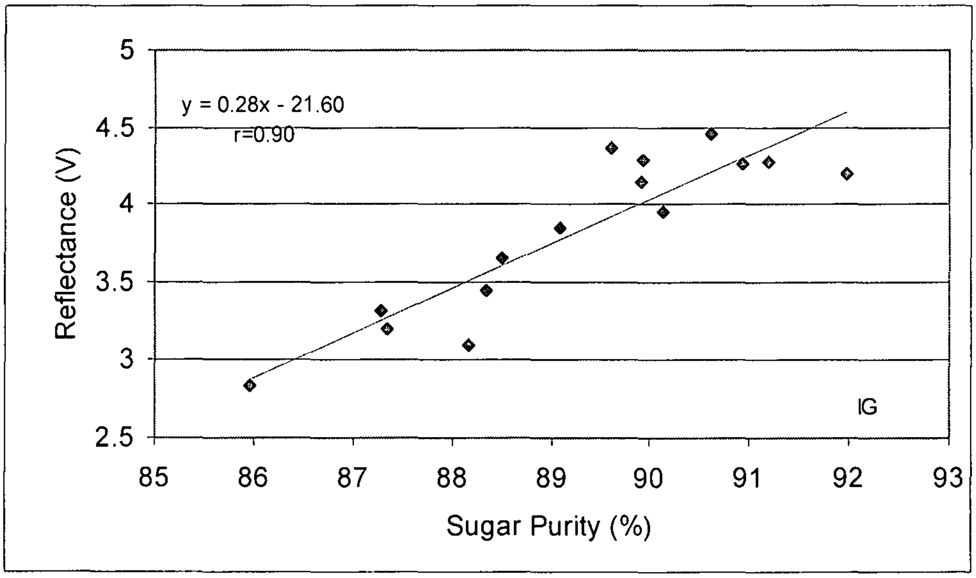

Figure C.6 Relationship between Sugar Purity and Reflected Light , using a Green Filter

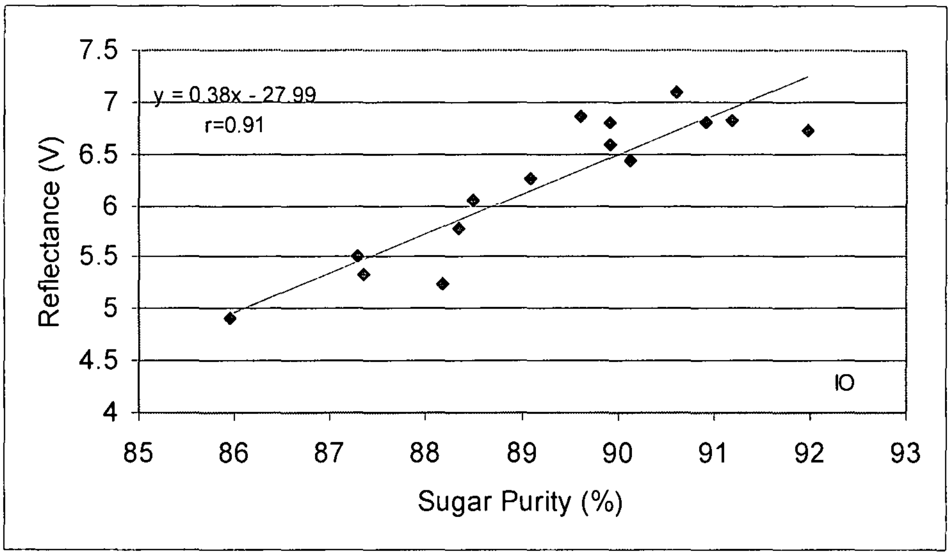

Figure C.7: Relationship between Sugar Purity and Reflected Light, using an Orange Filter

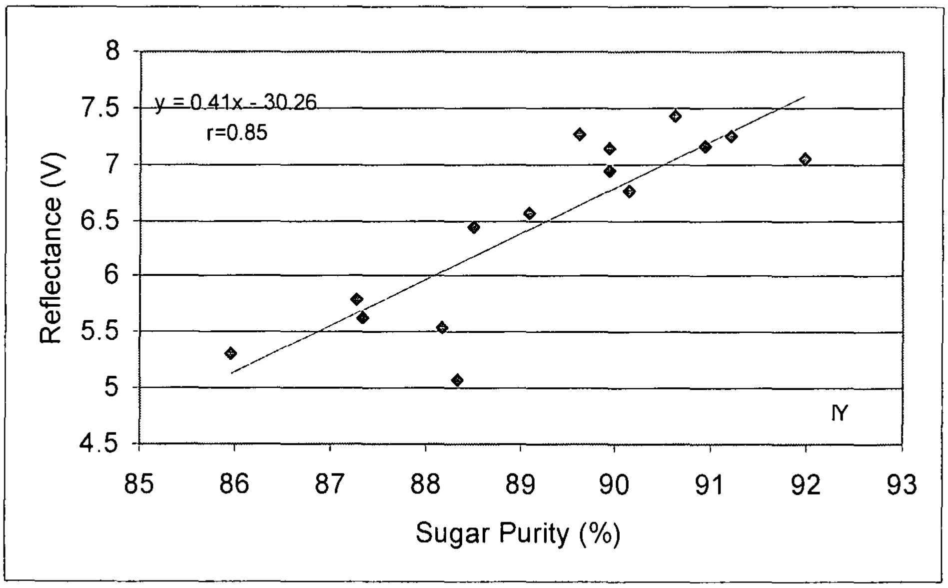

Figure C.8: Relationship between Sugar Purity and Reflected Light, using a Yellow Filter

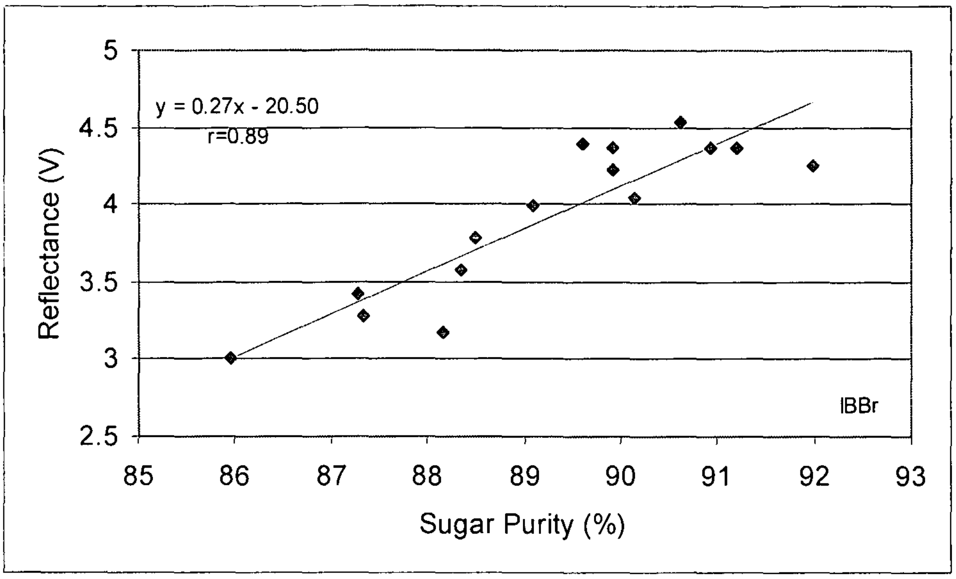

Figure C.9: Relationship between Sugar Purity and Reflected Light, using a Blue and Brown Filter

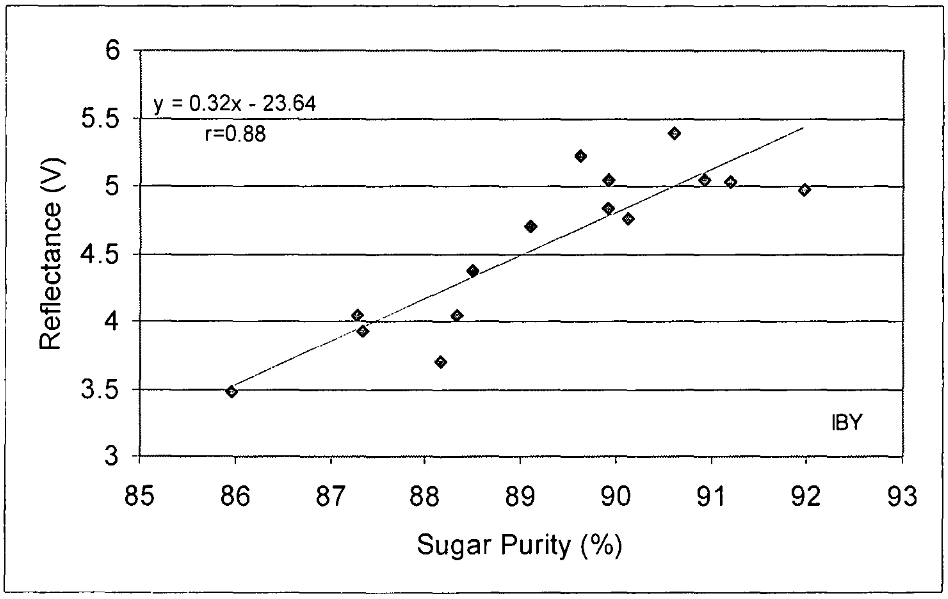

Figure C.10: Relationship between Sugar Purity and Reflected Light , using a Blue and Yellow Filter

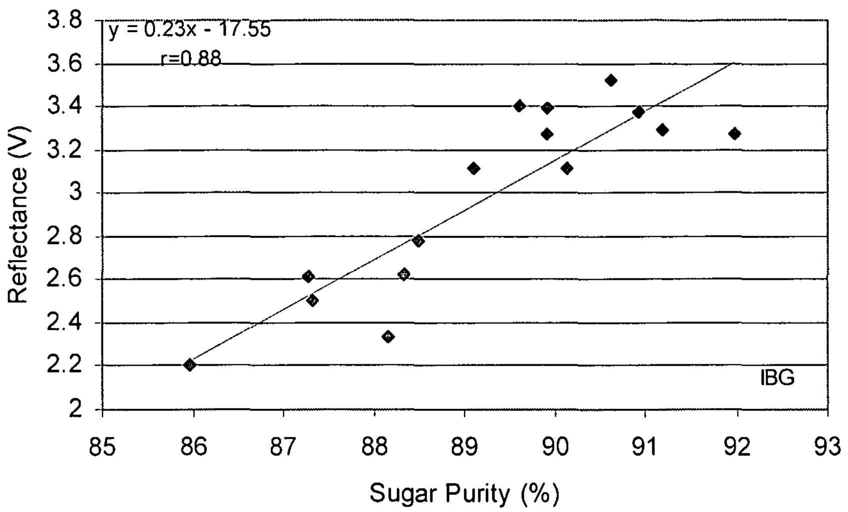

Figure C.11: Relationship between Sugar Purity and Reflected Light , using Blue and Green Filters

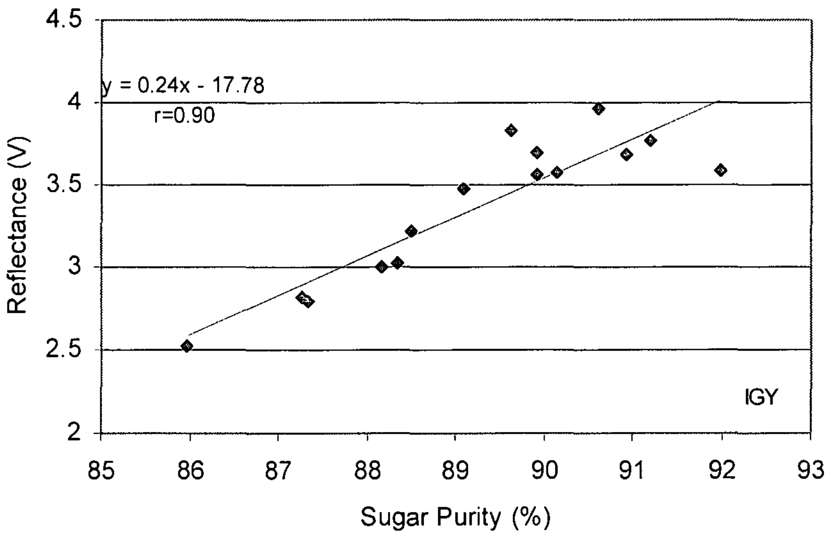

Figure C.12: Relationship between Sugar Purity and Reflected Light , using a Green and Yellow Filters

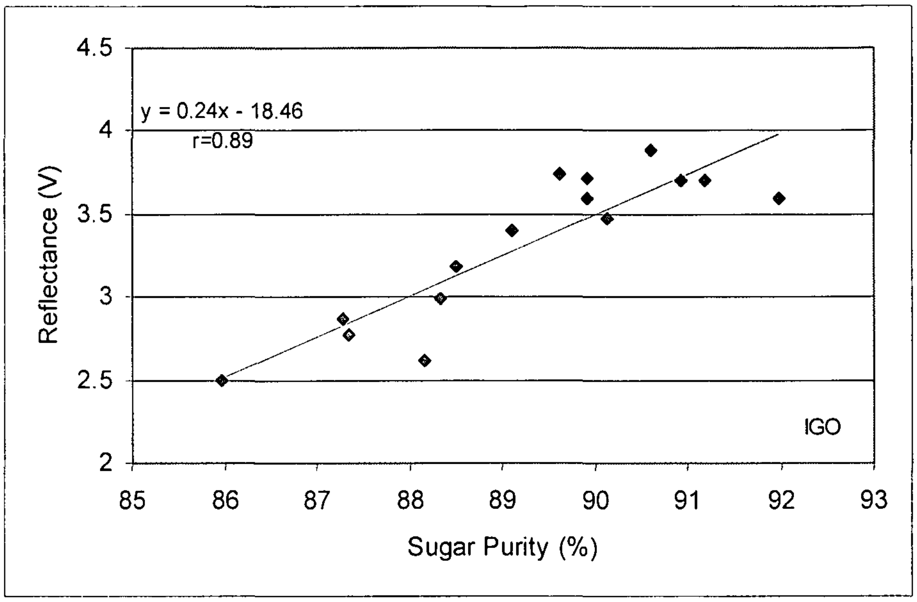

Figure C.13: Relationship between Sugar Purity and Reflected Light , using Green and Orange Filters

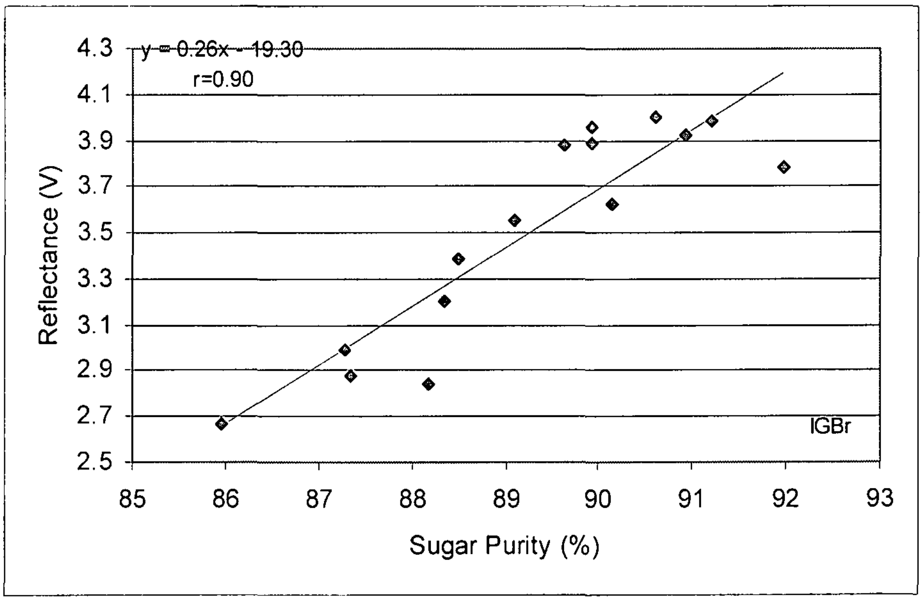

Figure C.14: Relationship between Sugar Purity and Reflected Light , using Green and Brown Filters

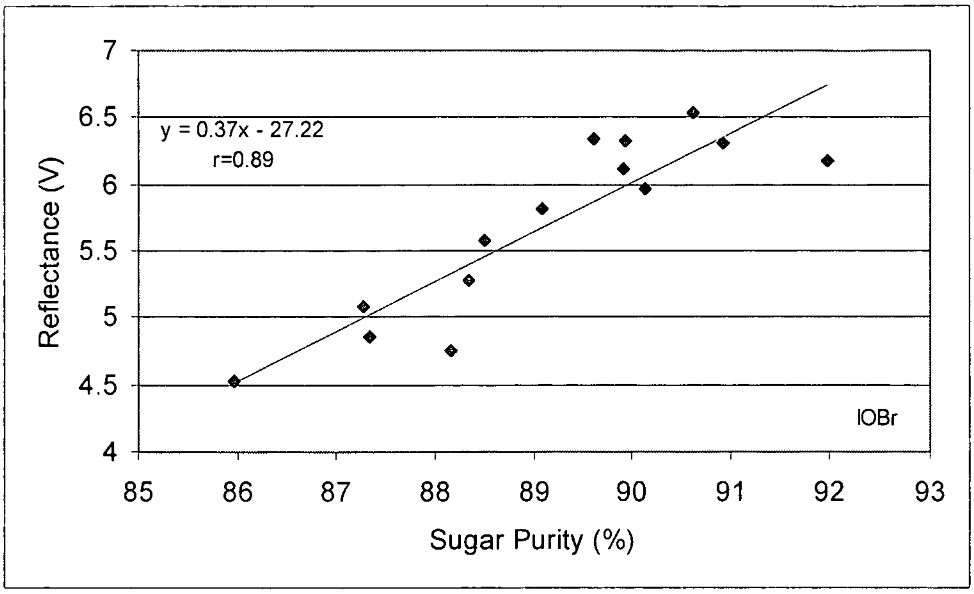

Figure C.15: Relationship between Sugar Purity and Reflected Light , using an Orange Brown Filter

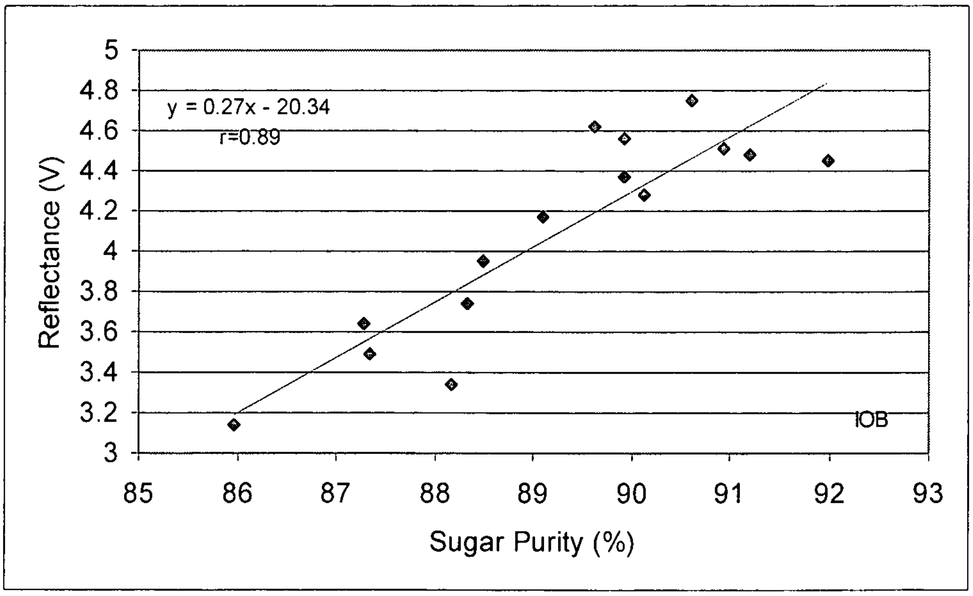

Figure C.16: Relationship between Sugar Purity and Reflected Light , using Orange and Brown Filters

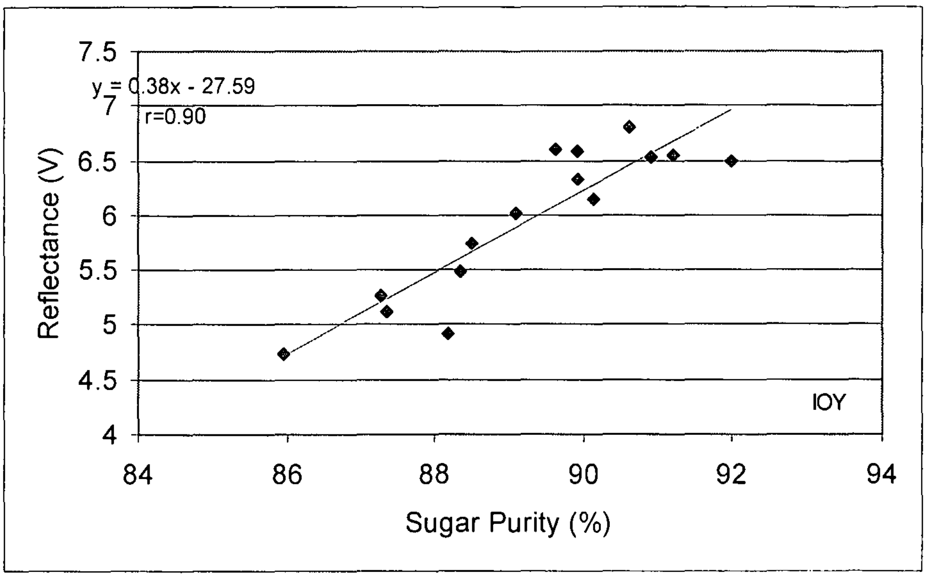

Figure C.17: Relationship between Sugar Purity and Reflected Light , using Orange and Yellow Filter

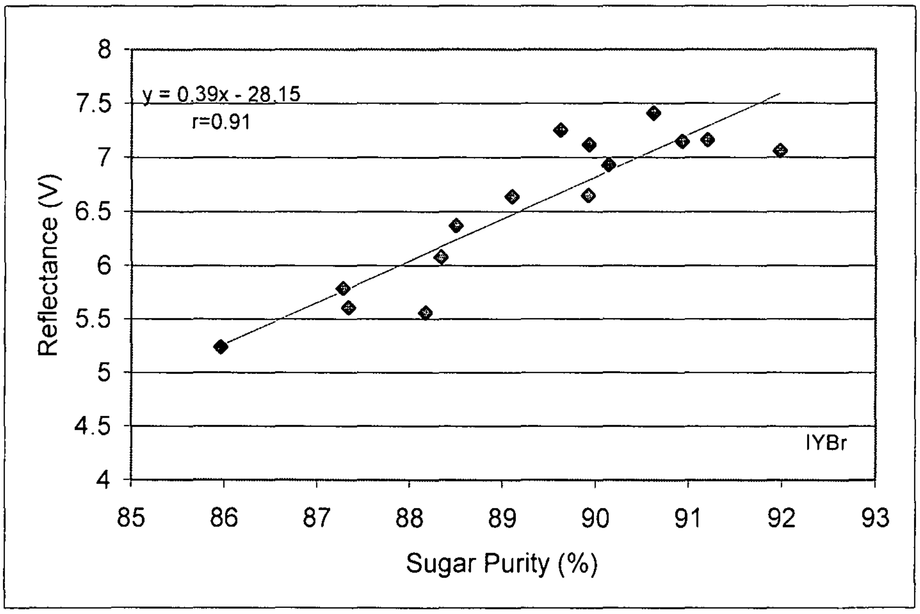

Figure C.18: Relationship between Sugar Purity and Reflected Light , using Yellow and Brown Filters

Appendix D

Incandescent Light (35W)

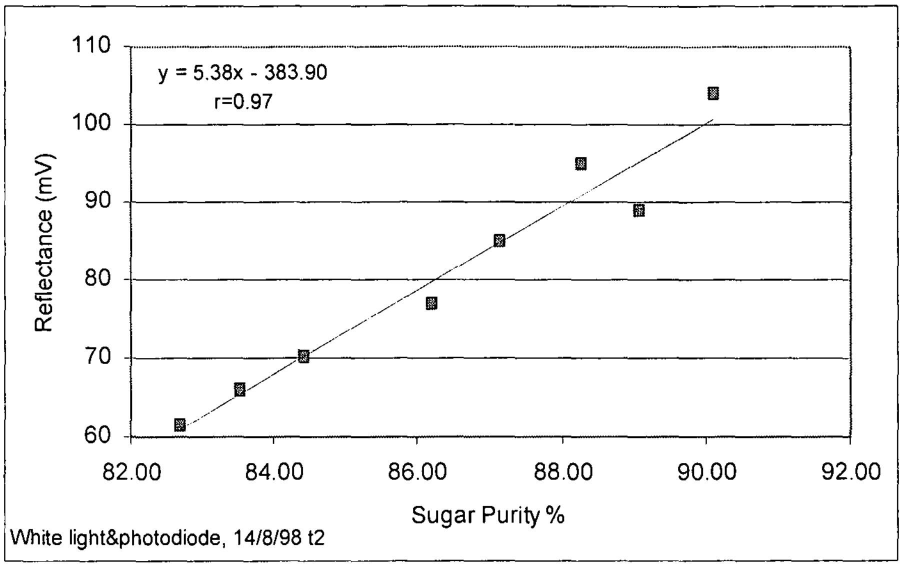

Figure D.1: Relationship between Sugar Purity and Reflected Light , using Incandescent Light of 35 W, Trial 2

Table D.1: Raw Data for the Incandescent Lamp and LDR Trials.

Purity (%)	Trial 1 (kΩ)	Trial 2 (kΩ)	Average (kΩ)
81.59	15.5	15.8	15.6
82.10	15.3	15.5	15.4
83.01	14.7	14.8	14.8
83.54	13.3	13.2	13.2
84.43	12.8	13.6	13.1
85.25	11.5	11.7	11.6
86.52	10.2	10.1	10.0
87.15	10.4	10.3	10.5
88.29	7.9	8.1	8.2
89.09	7.9	8	8.2
89.90	7.3	7.3	7.7

Table D.2: Incandescent Motion Trials Raw Data

Sugar Purity (%)	Stationary (kΩ)	Spinning (kΩ)	Stationary (kΩ)	Spinning (kΩ)	Average Stationary (kΩ)	Average Spinning (kΩ)
81.59	15.5	15.6	15.8	15.5	15.7	15.6
82.10	15.3	15.5	15.5	15.5	15.4	15.5
83.01	14.7	15	14.8	15	14.8	15.0
83.54	13.3	13.5	13.2	13.5	13.3	13.5
84.43	12.8	13.4	13.6	13.6	13.2	13.5
85.25	11.5	11.5	11.7	11.8	11.6	11.7
86.52	10.2	10	10.1	10.1	10.2	10.1
87.15	10.4	10.2	10.3	10.2	10.4	10.2
88.29	7.9	8.1	8.1	8.1	8.0	8.1
89.09	7.9	8.1	8	8.1	8.0	8.1
89.90	7.3	7.5	7.3	7.6	7.3	7.6

Table D.3: Incandescent Steam Simulation Trials - Raw Data

Sugar Purity (%)	No Steam (kΩ)	Steam Test 1 (kΩ)	Steam Test 2 (kΩ)	Average Steam (kΩ)
81.59	15.6	16.1	16.4	16.3
82.1	15.4	16.3	16.2	16.3
83.01	14.9	15.5	15.8	15.7
83.54	13.0	14	14	14.0
84.17	14.1	14.6	14.5	14.6
84.43	12.9	14	14.1	14.1
85.25	11.6	11.9	11.5	11.7
86.52	9.7	10.5	10.5	10.5
87.15	10.9	10.4	10.6	10.5
88.29	8.5	8.4	8.3	8.4
89.09	8.7	8.5	8.5	8.5
89.9	8.4	8	8	8.0

Appendix E

Red LED Light Trials Data

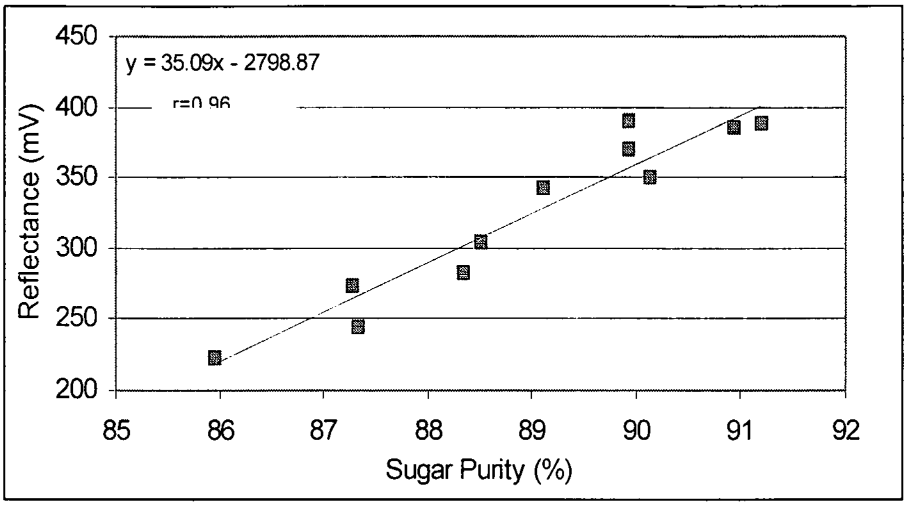

Figure E.1 : Relationship between Sugar Purity and Reflected Light , using a Red LED at 12 Candela.

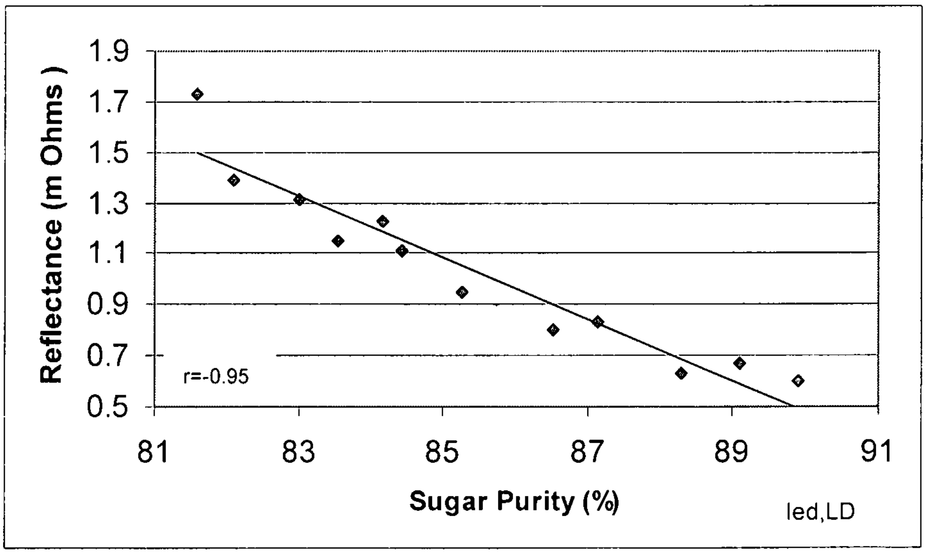

Figure E.2 : Relationship between Sugar Purity and Reflected Light , using a Red LED and :LDR

Table E.1: Raw data for the Motion Trials

Sugar Purity (%)	Stationary (mΩ)	Spinning (mΩ)	Stationary (mΩ)	Spinning (mΩ)	Average Stationary (mΩ)	Average Spinning (mΩ)
81.59	1.73	1.74	1.73	1.75	1.73	1.75
82.1	1.45	1.45	1.39	1.4	1.42	1.43
83.01	1.27	1.28	1.31	1.3	1.29	1.29
83.54	1.19	1.17	1.15	1.17	1.17	1.17
84.17	1.25	1.27	1.23	1.25	1.24	1.26
84.43	1.1	1.09	1.11	1.1	1.11	1.10
85.25	0.96	0.93	0.95	0.94	0.96	0.94
86.52	0.8	0.79	0.8	0.82	0.80	0.81
87.15	0.82	0.82	0.83	0.85	0.83	0.84
88.29	0.63	0.62	0.63	0.64	0.63	0.63
89.09	0.69	0.67	0.67	0.66	0.68	0.67
89.9	0.6	0.58	0.6	0.6	0.60	0.59

Table E.2: Raw data for the Steam Simulation Trials

Sugar Purity (%)	**No Steam** (mΩ)	**Steam Test 1** (mΩ)	**Steam Test 2** (mΩ)	**Average Steam** (mΩ)
81.59	1.73	1.81	1.76	1.79
82.1	1.45	1.38	1.39	1.39
83.01	1.27	1.33	1.35	1.34
83.54	1.19	1.13	1.12	1.13
84.17	1.25	1.2	1.23	1.22
84.43	1.10	1.1	1.09	1.10
85.25	0.96	0.93	0.95	0.94
86.52	0.80	0.81	0.83	0.82
87.15	0.82	0.83	0.84	0.84
88.29	0.63	0.64	0.64	0.64
89.09	0.69	0.66	0.67	0.67
89.9	0.60	0.58	0.59	0.59