UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

EVALUATION OF COMMERCIAL PURGE COMPOUNDS ON A LABORATORY FILM BLOWER

by

Morgan Govender

Submitted in partial fulfilment of the requirements for the degree

Master of Science

in the Faculty of Natural and Agricultural Science

University of Pretoria

Pretoria

May 2003

Declaration

I, Morgan Govender declare that this thesis is my own work, except where specifically acknowledged in the text. I would also declare that neither this thesis nor any part thereof has been submitted by me for degree purposes at any other university.

……………………………

M. Govender

Problem Statement

The ideal situation, for mass-producing plastic products, is to have machines that are dedicated to the continuous manufacture of a single product. Because the local market is limited, South African plastic manufacturers have to make many different products on any given machine. Sometimes, machines are not even used continuously. With machines staying idle for any length of time, thermal degradation of the residual material can become a problem. It often leads to carbonaceous deposits on the metal walls that may lead to subsequent flaws or blemishes in the final product. Purging compounds are therefore widely used in South Africa to overcome such problems.

In industry, the effectiveness of a purging compound is determined by a visible observation of the extrudate. A visible observation does not necessary mean a clean machine, as it does not take into account carbonaceous deposits that adhere to the metal surfaces. This method of analysis is not only ineffective, but also a time consuming process that results in a significant amount of scrap material. The processing of cables is an example that requires a much more stringent method of analysis, as single defects can result in meters of processed material being rejected. For these conditions, processors require the purge compound to have an additional feature viz., no adhesion. For processors of cables, purging involves the use of a purging compound followed by disassembling and cleaning of the extruder screw and barrel. Under such conditions, the purging compound is required to turn into a dry paste that does not adhere to the metal components, making it easy to disassemble and clean the screw. The adhesion of purging compounds to the metal surfaces of the processing equipment is a major problem.

ABSTRACT

Purging compounds allow for rapid colour and material changes in plastics converting machines. They have both a cleaning and a purging action. The cleaning action refers to the removal of contaminants, e.g. carbon deposits, from the die, barrel and extruder-screw surfaces. This mechanism relies on conventional detergency in combination with high wall shear stresses. The purging action refers to the observed narrowing in the residence time distribution and is less well understood. The action of a purge compound may encompass both the cleaning and purging mechanisms in order to achieve the desired effect.

In industry the effectiveness of a purge is determined by a visual observation of the extrudate. Therefore, a scientific method was required to quantitatively determine the efficiency of each purging mechanism under a set of fixed experimental conditions. In this study, a method was developed using a laboratory film-blower, which made use of a phthalocyanine blue pigment to impart colour to the film produced. The method was used to test the efficiency of various commercial purge compounds in switching the colour of film from blue to clear. The analysis was achieved by measuring the residual pigment concentration in the blue polymer film using a UV-Visible spectrophotometer.

Commercial purge compounds function by means of various mechanisms such as filler abrasion, solvent dissolution, the dislodging of deposits with the aid of surfactants, etc. This study also considered the use of slip additives as an additional purging mechanism.

In proposing that slip additives can contribute to a purging action, several slip additives where tested in polyethylene (PE), polypropylene (PP) and acrylonitrile butadiene styrene (ABS). The slip additives polypropylene wax and polyamide showed a significant increase in the MFI of PE whereas the additives polar wax and polyamide exhibited a slight increase in MFI of PP. Three additives, namely, polyamide, polypropylene wax and polar wax had showed noticeable improvement on the MFI of ABS. The slip additives that showed a significant improvement in polyethylene were tested together with six different commercial purge compounds. These compounds were tested for their colour change efficiency using polyethylene and switching from blue to clear in a laboratory film blower. It was found that the slip mechanism contributes very little to the purging action.

Polymeric materials tend to adhere to hot metal surfaces. When the material continues to adhere to the metal after cooling down, cleaning of the processing equipment becomes very difficult. A purge manufactured by the CSIR, Pretoria, exhibited this problem. This study also covers an investigation into overcoming the adhesion problem of this purging compound.

TABLE OF CONTENTS

Chapter 1: Literature Review 1

1.1 Purging and Purging Compounds 2

- 1.1.1 Background 2
- 1.1.2 Purging Compounds 3
- 1.1.3 Mechanisms of Purging and Cleaning 4
    - a. Flushing 4
    - b. Scouring 5
    - c. Penetrating/Detergency 5
    - d. Chemical 6

1.2 Melt Flow Index (MFI) 6

- 1.2.1 Methods of Measuring Melt viscosities 6
    - a. Cone and Plate Rheometer 7
    - b. The Melt Flow Index Tester 10
    - c. The Capillary Rheometer 13

1.3 Melting and Thermal Properties of Polymers 15

- 1.3.1 Processing Properties of Polymers 15
- 1.3.2 Viscous Properties of Polymer Melts 17
- 1.3.3 Effect of Slip Additives on the Polymer Flow Pattern 19

1.4 Film Blowing 20

1.4.1 The Process of Film Blowing 21

1.4.2 Materials used in Film Blowing 23

1.4.3 A Literature Review on the Modelling of Film Blowing 25

a. The Seventies: Foundation work 25

b. Schenkel Group at IKT, Stuttgart 26

c. Approaches of Other Groups during the Eighties 27

d. The Experimental Approaches lead by White 28

e. Work Done by Campbell and his Group through the Nineties 29

1.5 Spectroscopy 30

1.5.1 Background 30

1.5.2 The Absorption of Radiation 31

1.5.3 Beer's Law 32

Chapter 2: Experimental 35

2.1 Analysis of CSIR Purge 35

2.1.1 Starting Materials 36

2.1.2 Experimental Procedure 36

2.2 MFI Testing 38

2.2.1 Starting Materials 38

2.2.2 Experimental Procedure 39

2.2.3 Calculation of MFI 40

2.3 Extrusion Trials 41

2.3.1 Blue EVA Master-batch 42

2.3.1.1 Experimental Procedure 42

2.3.2 Phthalocyanine Blue Pigment 42

2.3.2.1 Experimental Procedure 42

2.3.3 Commercial Purging Trials 44

2.3.3.1 Experimental Procedure 44

2.4 Determination of Concentration using Beer's Law 45

2.5 Absorbance Analysis via UV-Visible Spectroscopy 46

Chapter 3: Results and Discussion 47

3.1 Adhesion of the CSIR Purge 47

3.2 Results of MFI Testing 50

3.2.1 MFI Analysis of Polypropylene (PP) 50

3.2.1.1 Analysis of PP at a Temperature of 190°C 50

3.2.1.2 Analysis of PP at a Temperature of 210°C 54

3.2.1.3 Analysis of PP at a temperature of 230°C 55

3.2.2 MFI Analysis of Acrylonitrile Butadiene Styrene (ABS) 57

3.2.2.1 Analysis of ABS at a Temperature of 210°C 57

3.2.3 MFI Analysis of Linear Low Density Polyethylene (LLDPE) 60

3.2.3.1 Analysis of LLDPE at a Temperature of 190°C 60

3.3 Purging Trials 65

3.3.1 Results of Purge Trials Using a Blue EVA Master-batch 65

3.3.2 Results of Purge Trials Using a Phthalocyanine Blue Pigment 69

Chapter 4: Conclusion 76

4.1 Conclusion 76

References 78

Appendices

Appendix A: Polypropylene 82

Appendix B: Acrylonitrile Butadiene Styrene 90

Appendix C: Linear Low-Density Polyethylene 94

Appendix D: Purging Trials 102

CHAPTER 1

LITERATURE REVIEW

This literature review encompasses the different aspects covered in this study. Purging compounds are widely used in South Africa and elsewhere and this review looks at the reason for using purging compounds and gives a background on different types of purging mechanisms involved. In this study it is postulated that slip flow patterns can contribute to a purging action. In order to measure the effect of slip additives on polymers, research was done on the different methods available for measuring polymer melt viscosity. The melt flow index is one such method that was used in this study. Some background is also given of the other different types of apparatus and methods that can be used. There is also a brief look at the melting and thermal properties of polymer melts and the effect of slip additives on changes in their flow patterns.

In industry, the effectiveness of a purging compound is determined by a visible inspection of the extrudate. This is usually done after several hours of purging and is not only time consuming but also inconclusive. Therefore, to quantitatively compare different commercial purges, a new method was required. A scientific method was developed to measure the effectiveness of the various commercial purges as well as that of the slip additives. The technique used in this method is based on film blowing. Therefore a historic review is provided on the development of film blowing. The analysis of the polymeric film produced by this method was done with the aid of a UV-Visible spectrophotometer. The literature review also gives some background on the absorption of radiation and the generation of a spectrum.

1.1 Purging and Purging Compounds

1.1.1 Background

According to Galli (Galli, 1987), there is no aspect of polymer processing that is practised more and understood less than purging. Purging has been practised as long as polymers have been processed, but is still a long way from being a science.

The US thermoplastic resin industry processes approximately 7.75 million tons of thermoplastic resin per year. When these organic molecules are subjected to the high temperatures (300°C – 500°C) and pressures (up to several tons per square millimetre) associated with extrusion and moulding processes, there is some tendency for degradation of molecules to occur (Galli, 1987). Although antioxidants and heat stabilisers are usually added to polymers, a degree of degradation is inevitable.

In particular, polymeric materials also decompose when in contact with hot metal surfaces over a period of time. Continued accumulation of such decomposed polymer residue may impede further production. When changing from one grade of polymer to another or from one pigmented polymer to a different pigmented polymer, it becomes desirable to thoroughly clean the processing equipment in order to avoid contamination of the second polymer.

Initially, various approaches have been utilised to clean the equipment but none of them have been entirely adequate. One solution is to dismantle the equipment and subject it to cleaning via brushing and abrasion. Periodic cleaning by mechanical means such as by wire brush or scraping is not only time consuming and unnecessarily labour intensive. It can also result in unnecessary erosion or damage to processing equipment. Under such conditions, it become desirable to provide for a cleaning process that avoids lengthy delays and lost production time. When it became a major quality problem, the processing equipment had to be cleaned. This lead to the development of specially formulated purging compounds.

1.1.2 Purging Compounds

Purging compounds are widely used in South Africa and elsewhere for facilitating rapid colour and material changes as well as for cleaning plastic processing machinery (Galli, 1987; Botros, 1996). They have both a cleaning and a purging action. The *cleaning function* refers to the removal of contaminants that tend to stick to the walls of the processing equipment, e.g., additive residues and carbonised deposits. Removal of such wall deposits can be achieved via a scrubbing or abrasion mechanism (Scheibelhoffer *et al.*, 1995; Leung *et al.*, 1993). However, such products may also cause undesirable erosive wear to the processing equipment. An alternative is to use polymers with a higher softening point and a higher melt viscosity than the material in normal use, e.g., glassy polymers like poly (methyl methacrylate) (Miller, 1975). This gives rise to a scuffing cleaning effect in the extruder. Walsh *et al.* (1999) proposed the use of solvents but this may pose a fire hazard at the high processing temperatures usually employed in plastics conversion.

Modern purge formulations, however, tend to exploit surface chemistry (Cohen and Gutoff, 1992; Bailey, 1989; Fujii *et al.*, Kmiec, 1992; Obama *et al.*, 1992). This mechanism relies on conventional detergency in combination with high wall shear stresses (Ross and Morrison, 1988; Cohen and Gutoff, 1992). Appropriately chosen surfactants with a high affinity for wetting metal surfaces are employed. They tend to loosen deposits by a wetting and penetrating action. Lifting and removal of the solid contaminants is further aided by high wall shear stresses.

The *purging action* refers to the ability of the additive to aid rapid colour changeover. This implies a narrowing of the residence time distribution. Purging agents provide economic advantages by reducing both downtime and raw material wastage. Many different commercial formulations are available, but their mechanism of action is not well understood. Developing such an understanding may assist the development of improved formulations. One such starting point is a better understanding of the different mechanisms involved in purging.

1.1.3 Mechanisms of *Purging* and *Cleaning*

Purging compounds are divided into four basic categories, based upon their mechanism of action. Some, however, may exercise more than one mechanism.

a. Flushing

This type of mechanism is usually achieved by running virgin polymer through the processing equipment. Flushing does not accomplish any heavy duty purging, and usually does not involve any added ingredients. It simply attempts to replace what is in the barrel. There are many sources for such material, sometimes labelled for purging. This method suffers from the disadvantage of being time consuming. Another disadvantage of this method is that it is wasteful of polymer (Kmiec, 1992). The purged polymer is routinely discarded due to the contaminants it contains. Apart from these disadvantages, the virgin polymer does not completely remove decomposed carbon deposits. Flushing does not have any cleaning actions and can be considered as a purging action as it may reduce the residence distribution time.

b. Scouring

A long-established step up from flushing has been to add abrasives to the material. Scouring contributes to the cleaning function rather than a purging function. It increases the cleaning action as compared to the flushing type, and thus should consume less time and material. Scouring uses abrasive particles, e.g., silica (Scheibelhoffer *et al.*, 1995; Leung *et al.*, 1993). However, such products may also cause undesirable erosive wear to the processing equipment. A less abrasive alternative to scouring is the use of a resin with a higher softening point and higher melt viscosity than the material in normal use, e.g. glassy polymers such as poly (methyl methacrylate) (Miller, 1975). This gives rise to a scuffing cleaning action in the extruder.

c. Penetrating / Detergency

This type is also described as lubricants (Galli, 1987). They are usually concentrates (liquids and powders) that are added at low dosages. The predominant mechanism appears to be penetration of the purge between metal and residues to encourage release. This mechanism includes the release of gases to expand material volume into dead spots, neutralisation of acids, and reduction in viscosity. This mechanism relies on conventional detergency in combination with high wall shear stresses (Ross and Morrison, 1988; Cohen and Gutoff, 1992). Appropriately chosen surfactants with a high affinity for wetting metal surfaces are employed. They are able to loosen deposits by a wetting and penetrating action. Lifting and removal of solids contaminants is further aided by high wall shear stresses. Sodium silicates are often used for the sole function of a wetting agent.

d. Chemical

The concept of chemical cleaning was introduced to purging specially by depolymerising the residual polymer to reduce its viscosity and thus increase its flushability. Most purges that work by this mechanism contain a thermally degradable nitrogen compound as the depolymerising agent (Galli, 1987). In order for the mechanism to operate, the purge must first go through a soak cycle in the machine, with the time required varying with the type of polymer.

1.2 Melt Flow Index

1.2.1 Methods of Measuring Melt Viscosities

There are two commonly used methods of measuring polymer-melt viscosities, namely rotational and capillary. In the rotational type, melt is sheared between rotating surfaces. The rate of shear is derived from the relative speed, while the shear stress is obtained from the torque required to maintain the motion.

In the capillary type, polymer melt is forced to flow along a small tube. A rate of shear is derived from the steady rate of flow achieved, while the associated shear stress is calculated from the measured pressure gradient along the tube. The different types of instruments use to measure melt viscosity that is described in this study include:

- Cone and plate Rheometer
- Melt Flow Index (MFI) Tester
- Capillary Rheometer

a. The Cone and Plate Rheometer

In this type of rheometer, a nearly flat cone is mounted with its axis normal to the plate as shown in Figure 1.1(a). Both the cone and the plate are usually composed of steel. The plate is heated to the required temperature and the cone is enclosed to minimise heat losses to the surroundings.

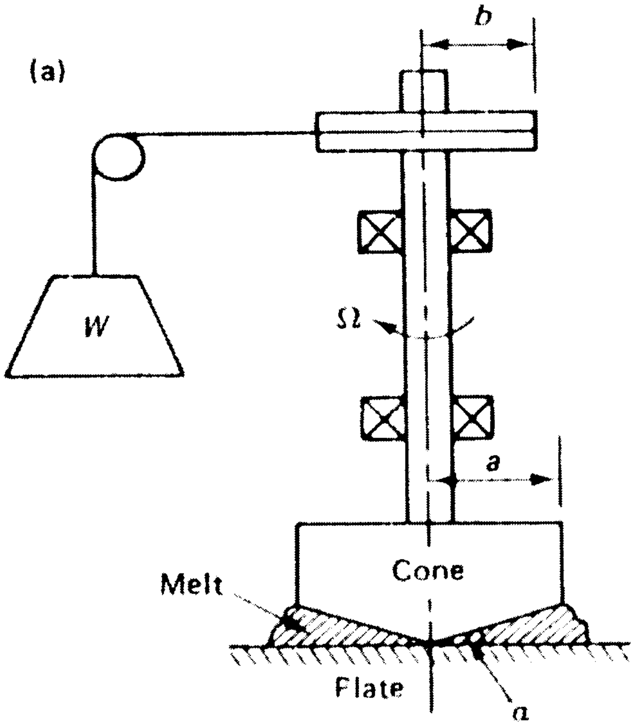

Figure 1.1(a): A Cone and Plate Rheometer (Fenner, 1985) with simple weight used to apply a known torque.

The shaft on which the cone is mounted is supported by bearings. It may either be driven at a constant speed and the applied torque measured or a known torque may be applied by a simple weight, as illustrated in Figure 1.1a, on a string and pulley arrangement. In this case, the speed of rotation is measured, often with the aid of an angular scale on the cone shaft.

Experimentally the procedure can be outlined as follows: The cone is raised from the plate, a sample of solid polymer in either granule or powder form is placed on the plate. Sufficient time is allowed for it to melt and reach the required temperature before the cone is lowered and its tip brought just in contact with the plate. A particular load *W* is applied to turn the cone, and the steady speed of the rotation, *Ω*, achieved is measured. The geometric parameters of the apparatus that need to be known are the cone angle, *α*, which normally lies between 1° and 5°, the radius of the cone, *a*, and the distance from the cone axis, *b*, at which the load is applied, all of which is shown in Figure 1.1(b).

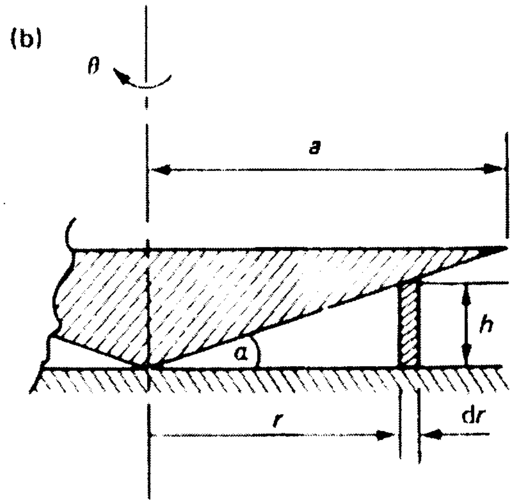

Figure 1.1(b): A section through the melt flow zone of a Cone and Plate Rheometer (Fenner, 1985)

The required shear rate and the stress may be derived from a simple analysis of the melt flow. When considering a small annular of melt, as shown in the diagram, its radius width is *dr* and it lies at a radius *r* from the cone axis.

Provided the cone angle is small, this element is effectively subjected to a simple shear flow, as described for polymer between two parallel plates. The relative velocity between the surfaces bounding the element is *rΩ*, where for steady conditions

$$\Omega = \frac{d\theta}{dt} \tag{1.1}$$

In this expression, t is the time and θ the angular displacement of the cone. Hence, from the velocity between two parallel plates i.e. $\dot{\gamma} = \frac{du}{dy} = \frac{U}{H}$, the shear rate in the element is

$$\dot{\gamma} = \frac{r\Omega}{h} = \frac{r\Omega}{r\tan\alpha} = \frac{\Omega}{\tan\alpha} \approx \frac{\Omega}{\alpha} \tag{1.2}$$

where h is the height of the element.

Although the approximation of tanα to α is only valid for small angles and α must be small in order to ensure that the flow can be treated as simple shear. The most important feature of the final expression for shear rate is that it is independent of the radius. If the shear rate is constant through the sample, then so is the shear stress, τ. The torque applied to the typical element of melt is the product of this stress, the area of the element in the plane of the plate, $2\pi r dr$, and its distance from the axis of rotation, r. Hence the total torque applied to the cone is

$$\tau \int_0^a 2\pi r^2 dr = \frac{2}{3}\pi a^3 \tau \tag{1.3}$$

Now, this torque is equal to the product of the applied load, W, and the radius of the application, b, giving the following expression for the shear stress

$$\tau = \frac{3Wb}{2\pi a^3} \tag{1.4}$$

In practise, the value for W used to find τ may need to be corrected for frictional losses found by repeating the experiment in the absence of the polymer. The viscosity can be calculated as a ratio of shear stress to shear rate. This procedure can be repeated using different applied loads and temperatures.

Advantage:

- The principle advantage of the cone-and-plate rheometer is that it is simple to use and gives stresses and shear rates directly. Because these are constant throughout the flow, the above derivations are equally valid for Newtonian and non-Newtonian materials.

Disadvantage:

- It also has a limited range of shear rate that can be covered. A minimum shear rate is reached when the applied torque is of the same order of magnitude as that required to over-come friction in the bearings. The maximum shear rate however, is limited to the tendency for cavities to form in the melt near the edge of the cone, invalidating the simple shear flow assumption (Fenner, 1985).

b. The Melt Flow Index Tester

The melt flow index (MFI) test is of the capillary type and involves the use of a short capillary die at the bottom of a heated barrel. Solid polymer is fed into this barrel and, after allowing time for it to reach the required temperature, a simple piston carrying a dead weight is added. Figure 1.2 is an illustration of a MFI tester. The melt-flow index is expressed as the weight of material in grams extruded over a period of ten minutes.

Both the test temperature and the size of the weight depend on the material concerned. For example, the most commonly used conditions for determining the MFI of polyethylene are 190°C and a weight of 2.16 kg as per ASTM standard D1238. Together with the apparatus, two removable weights are provided, which with that of the piston in one case total 2160 gram (g) and in the other 5000 (g). Likewise, two alternative dies are used, one of internal diameter 2.095 millimetres (mm) and the other 1.180 mm. Both are 8 mm long and made of hardened steel.

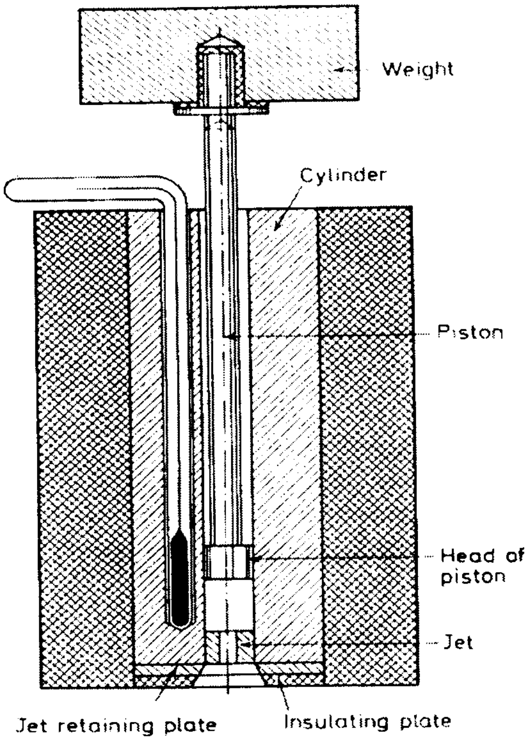

Figure 1.2: Illustration of a Melt Flow Index Tester (Fenner, 1985)

Experimentally, the test procedures can be divided into three different methods:

1. The first standard procedure (A) uses the die of diameter of 2.095 mm with a load of 2160 g. This method is used for materials of MFI in the range of 1 to 25. Prior to each experiment, the apparatus has to be thoroughly cleaned to avoid variations in the results. When clean, the apparatus is kept at 190°C ± 0.5°C for 15 minutes before use (Ives, 1971).

$$\boxed{\text{MFI (A)} = \frac{600 \text{ x average weight of cut-off in grams}}{\text{Interval of time in seconds}}} \qquad (1.5)$$

Thereafter, a sample of about 5 g is inserted into the top of the cylinder, within a period not exceeding one minute, and the piston is inserted. After the sample has melted, the weight is added and the molten material is extruded through the die. The rate of extrusion is measured by cutting of the extrudate at the die at suitable time intervals. Several such 'cut-offs' can be taken, all when the piston head is between 50 mm and 20 mm above the upper end of the die (as marked by scribed marks on the piston). The first cut off and any containing air bubbles are ignored. Several samples are taken, measured to the nearest milligram and the average taken.

2. Procedure (B) uses the same load (2160 g) but a smaller die, of diameter 1.180 mm. It is for materials of MFI between 25 and 30. The actual test is carried out as above, the result being calculated as follows:

$$\boxed{\text{MFI (B)} = \frac{600 \text{ x average weight of cut-off in grams}}{\text{Interval of time in seconds}} \text{ x conversion factor}} \tag{1.6}$$

The conversion factor is defined as the ratio of the average weight of cut off, using a larger die and a time interval of 30 seconds, to the average weight of the cut off using a smaller die and the same time intervals (Ives, 1971).

3. For materials of MFI below 1, procedure (C) is used, in which the die of 2.095 mm diameter is again employed, but this time with a load of 5000 g.

   This procedure is as previously described but using the equation (C) below.

$$\boxed{\text{MFI (C)} = \frac{150 \text{ x average weight of cut-off in grams}}{\text{Interval of time in seconds}}} \tag{1.7}$$

This time, the value corresponds to the amount extruded in two and a half minutes under specific conditions. These conditions are however, extended for PP and ABS by raising the temperature to 230°C whilst using the die of 2.095 mm.

Advantages:

- The main advantage of the melt flow index method is that it is a standard one widely used in the plastics industry
- It is also a simple measure of flow properties

Disadvantage:

- The melt flow indices of materials vary inversely to their viscosities and because the capillaries are so short, it is not possible to derive reliable values of viscosity from these indices.

c. The Capillary Rheometer

Capillary rheometers, which are sometimes called ram extruders, can be regarded as refinements of the apparatus for measuring melt flow indices. The capillary is generally much longer and the rates of flow of the melt can be varied over wide ranges. Two main types of instruments are used viz. the constant-rate and constant-pressure types. In the constant rate type illustrated in Figure 1.3 (a), a rigid piston is driven towards the capillary at a constant velocity, *V*. Figure 1.3 (b) illustrates a constant-pressure type apparatus.

In the constant-rate instrument, a rigid piston is driven towards the capillary at a constant velocity, *V*. A different piston arrangement is used in the constant-pressure type where gas, usually nitrogen, is applied under pressure to the small floating piston on top of the melt. In either type, the pressure in the melt is measured either at the piston or by means of a transducer in the barrel wall just before the entrance to the capillary.

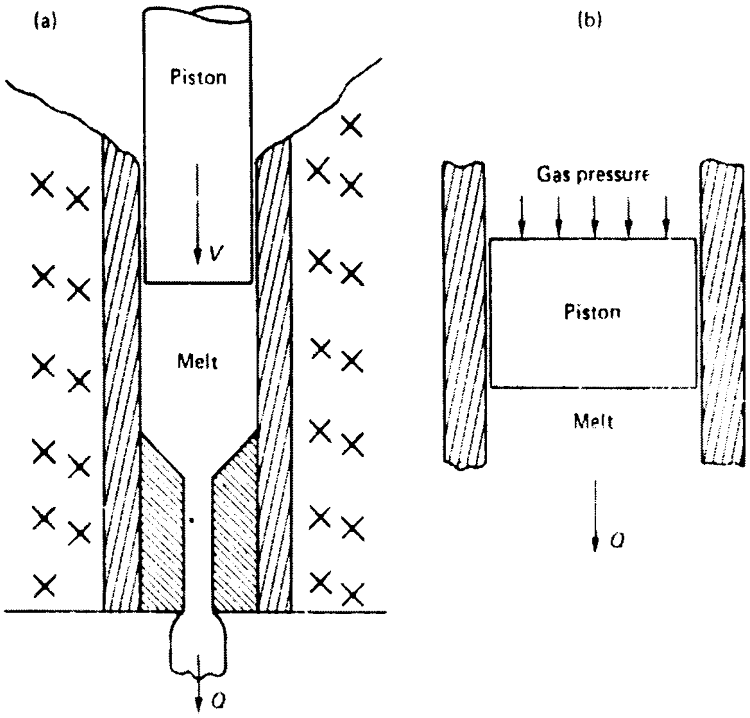

Figure 1.3: Illustration of the different types of Capillary rheometers viz., Constant-rate (a) and Constant-pressure (b) (Fenner, 1985)

The volumetric flow rate, Q, may be obtained in the constant-rate type as the product of piston velocity and barrel cross-sectional area, while in the constant-pressure type it must be measured directly. The mass flow rate can be measured more readily, by weighting a sample collected over a known time interval. The constant-pressure type of instrument requires knowledge of polymer-melt density at the temperature of the test. With the constant-rate type, however, weighing the extrudate provides a useful means of measuring melt density in addition to viscosity.

Advantages:

- Pressures up to ten times those available with compressed gas can be obtained, and that truly constant piston velocity is easier to achieve experimentally than a gas pressure.
- Shear stress and shear rates can be derived from an analysis of flow in the capillary.

1.3 Melting and Thermal Properties of Polymers

1.3.1 Processing Properties of Polymers

Unlike conventional materials that exhibit a distinct phase change from solid to liquid at their melting points, semi-crystalline polymers undergo an equivalent change over a finite temperature range. Below this range, their behaviour is that of elastic solids showing some viscoelasticity in the form of time-dependant properties. Above the melting range, polymers may be regarded as highly viscous liquids exhibiting some elastic effects (Fenner, 1985).

A typical plot of specific enthalpy against temperature for a polymeric material is illustrated in Figure 1.4. The melting temperature range, which is typically in the order of 10°C, normally occurs between 100°C and 300°C, depending on the material concerned. For processing, the minimum satisfactory temperature is generally some 10-20°C above the upper limit of this melting range. Maximum processing temperatures may well be imposed by susceptibility to thermal degradation. The portions of the enthalpy curve in the solid and melt regions are not normally either straight lines or parallel to each other (Fenner, 1985). This means the specific heats of solid and melts, which are given by the gradients of the relevant portions of the curve, are not equal and may be significantly temperature dependant.

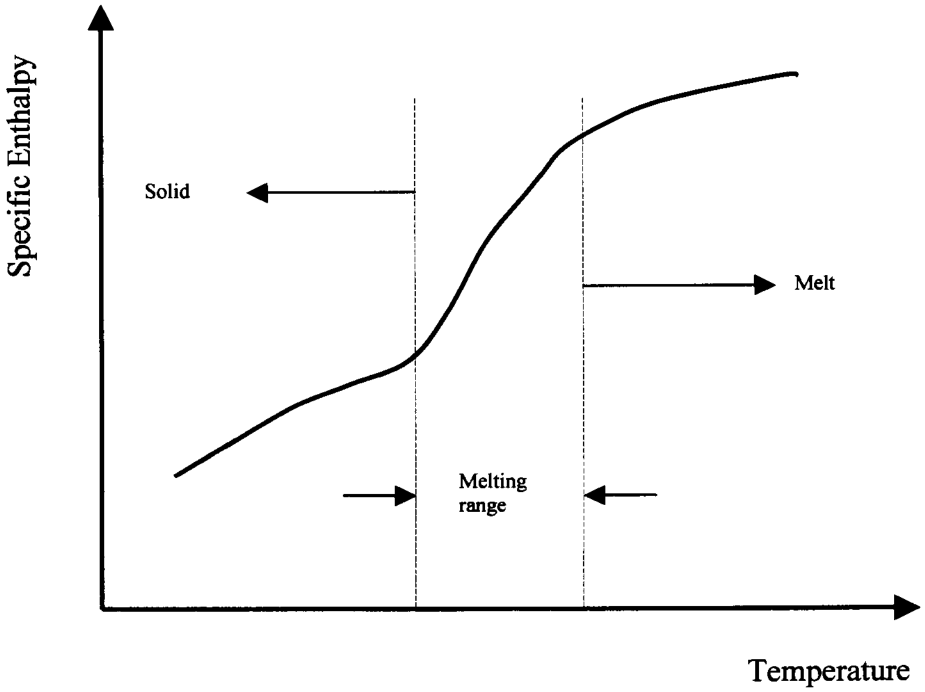

Figure 1.4: Typical enthalpy – temperature curve for a semi-crystalline polymer (Fenner, 1985) showing polymer processing conditions.

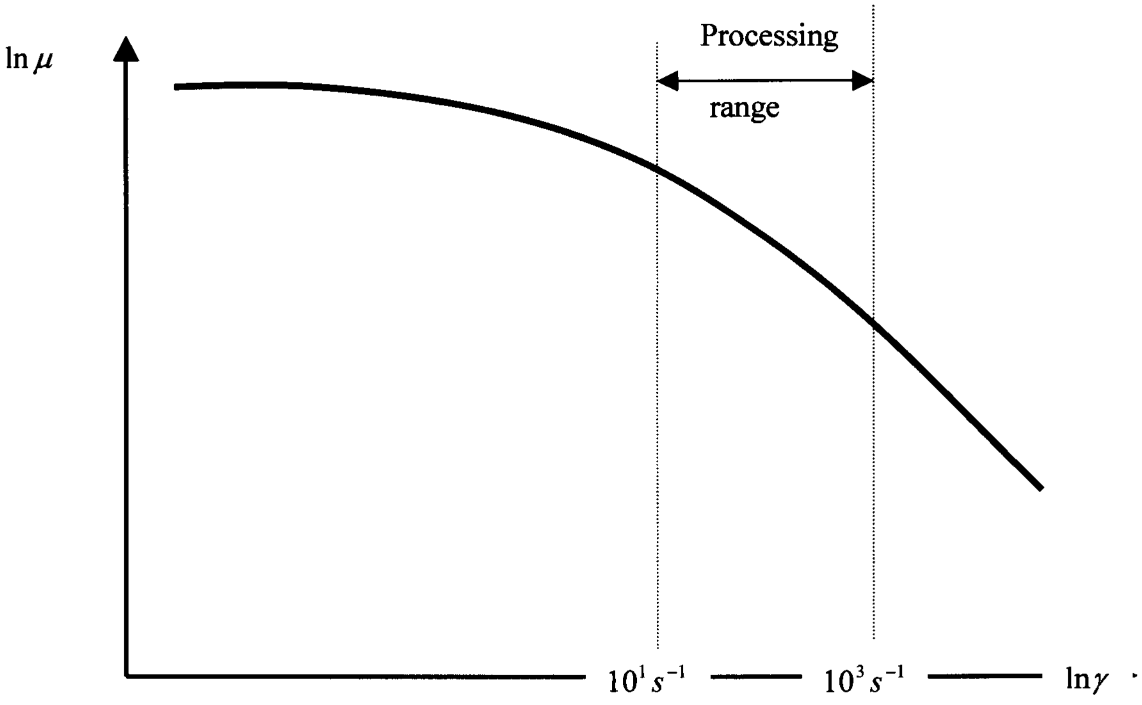

Figure1.5: Illustration of a typical flow curve for a polymer melt also showing the processing range for polymers (Fenner, 1985).

Within the melting temperature range the change of enthalpy is smooth compared to the abrupt increase at the melting point associated with the latent heat of fusion of conventional materials.

Measurements of polymer melt viscosity over wide ranges of shear rate show results of the form illustrated in Figure 1.5. Viscosity and shear rate are plotted on logarithmic scales to form the flow curve of the material. When sheared at low rates, typically less than $10^{-1}s^{-1}$, the melt behaves in a Newtonian manner, at higher rates of shear, however, particularly over the range 10^{1}-10^{3} s^{-1} which is relevant to most processing operations, melt viscosity decreases substantially with increasing shear rates. The melt behaviour at high shear rates is indicative of shear-thinning materials.

1.3.2 Viscous Properties of Polymer Melts

In addition to being very viscous under processing conditions, typically at least a thousand times more than, for example lubricating oils, polymer melts are also non-Newtonian, that is, their viscosities depend not only on temperature and pressure, but also on the rate at which the material is deformed. The viscosity of the polymer melt also has to be taken into consideration during processing (Fenner, 1985).

Consider the simple shear flow between flat parallel plates as illustrated in Figure 1.6. The upper plate moves at a velocity U relative to the lower one in the direction of the x coordinate with coordinate y being normal to both plates. The velocity of the flow, u, is proportional to the distance y above the stationary plate, and the constant shear rate is

$$\dot{\gamma} = \frac{du}{dy} = \frac{U}{H} \tag{1.8}$$

Here H is the distance between the plates. A shear stress, τ, applied in opposite direction as shown in Figure 1.6, maintain the shearing motion, and viscosity is defined as the ratio of stress to shear rate

$$\mu = \frac{\tau}{\dot{\gamma}} \tag{1.9}$$

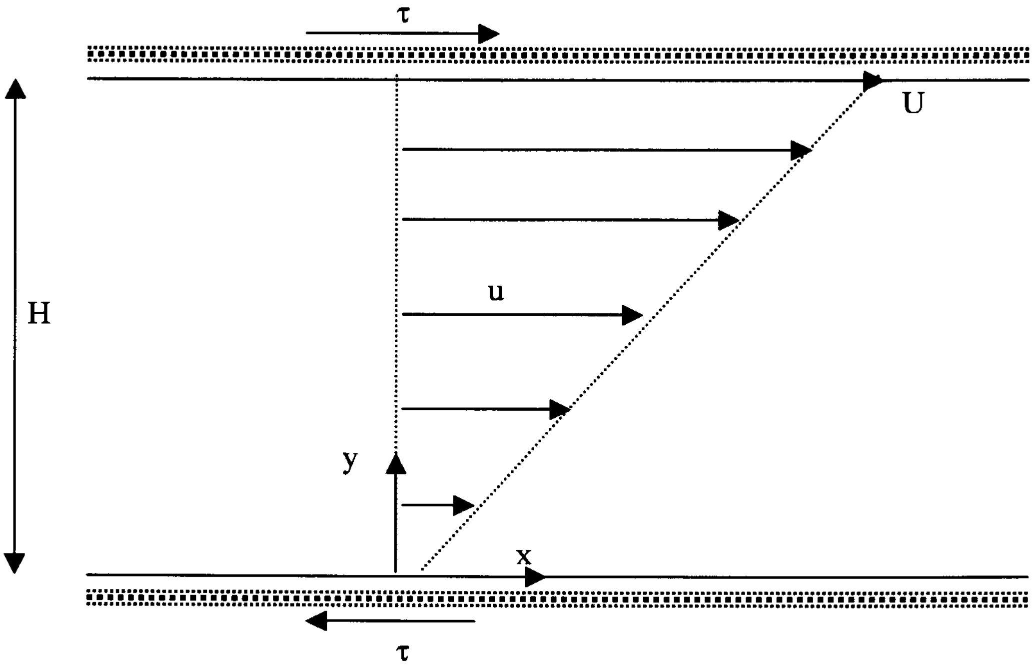

Figure 1.6: Illustration of simple shear flow between flat parallel plates (Fenner, 1985)

The velocity profile of the simple shear flow between parallel plates as illustrated in Figure 1.7, can be visualised as the flow in a single screw extruder where one of the walls are travelling at a constant velocity towards the discharge direction (Gogos *et al.*, 1987). Conceptually, the helical screw of the extruder results from the twisting of the stationary part of this rectangular duct around a solid cylinder. The screw flights define the sidewalls of the rectangular duct (Govender *et al.*, 2002). The extruder barrel then corresponds to the moving wall. This motion arises from the rotation of the screw that sets up a relative motion of the barrel wall, at an angle defined by the screw pitch, with respect to the screw defined flow channels.

This velocity vector can be decomposed into velocity components parallel to and perpendicular to the rectangular duct. The latter gives rise to a circular flow pattern while the former induces a drag flow pattern in the transport direction. It is this dragging action of the barrel wall that gives rise to the forward pumping action of the extruder and the generation of pressure. It applies to the particulate bed of polymer pellets being fed into the extruder, the transition region where drag induced melting is effected as well as the polymer melt in the front section of the extruder.

1.3.3 Effect of Slip Additives on the Polymer Flow Pattern

The theoretically predicted flow enhancement in pressure flows, due to the presence of slip additives that accumulate at the polymer-metal interface, is presented in Table1.1 (Ricco *et al.*, 2002). For low volume fractions slip additives and flow through a circular capillary, a linear increase in the flow rate with the volume fraction slip additive is predicted:

Table 1.1: Theoretical flow enhancement by slip agents in various geometries

Flow situation	**$U_{max})_{slip}/U_{max}$**	**$<U>_{slip}/<U>$**
Pressure Flow in a pipe	$1 + \varphi\left(\frac{\mu_p}{\mu_s} - 1\right)$	$1 + \left[1 - (1-\varphi)^2\right]\left(\frac{\mu_p}{\mu_s} - 1\right)$
Pressure flow in a parallel plat channel	$1 + \left[1 - (1-\varphi)^2\right]\left(\frac{\mu_p}{\mu_s} - 1\right)$	$1 + \left[1 - (1-\varphi)^3\right]\left(\frac{\mu_p}{\mu_s} - 1\right)$

It implies that slip additives reduce the effective resistance-to-flow of the die. Kemblowski and Sek (1981) previously found that such a reduction in the resistance to flow through the die-head of the extruder narrows the residence time distribution. Figure 1.8 (a) is the resultant velocity profile of a polymer melt without any slip additive.

Consider now the effect of a small amount of fluid that is incompatible with the polymer melt. Figure 1.8 (b) illustrates how the velocity profile is changed in the presence of this incompatible fluid. The accumulation of the fluid as a thin layer at the channel walls results in an effective slip flow situation for the main flow. It is clear that as a flatter velocity develops the bulk flow portion approaches plug flow. This implies that the residence time distribution should also be narrowed especially where the slip additive has no affinity for the polymer melt.

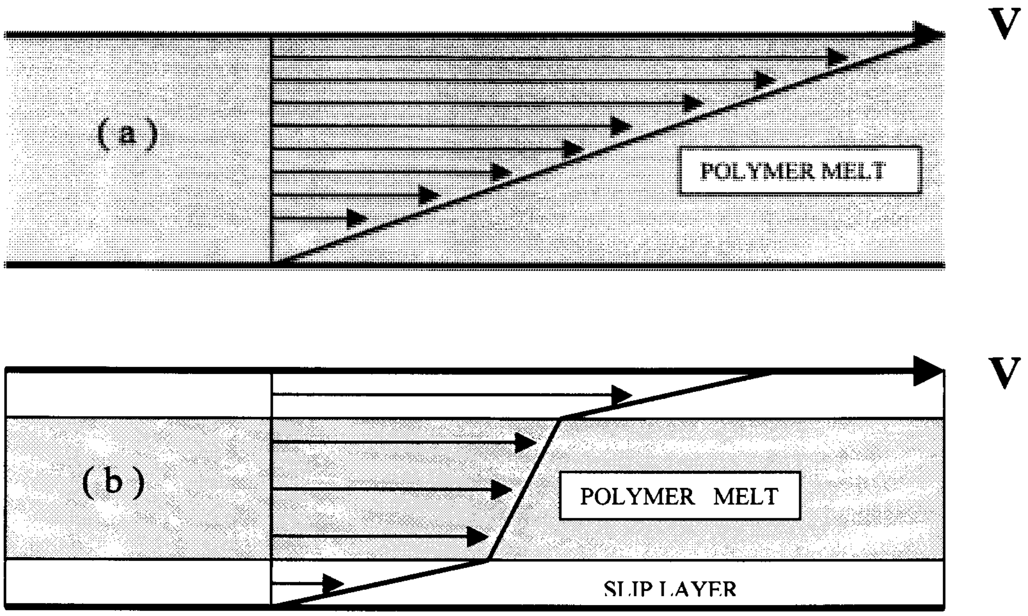

Figure 1.8: The anticipated effects of an incompatible, low viscosity fluid on the fully developed velocity profiles of a high viscosity polymer melts. It is assumed that the slip additive fluid accumulates at the polymer-metal interface.

1.4 Film Blowing

A brief overview on the development of film blowing through the years is given as an insight into this processing technique. This overview is researched because film blowing is one of the techniques used in this study to characterise purging efficiency.

Tubular films produced by this method were used as a technique to determine the efficiency of the tested purging compounds.

1.4.1 The Process of Film Blowing

The tubular film blowing process is one of the oldest polymer processing techniques. The most common method of producing thermoplastic film is via the tubular film blowing process (Fenner, 1985), a general view of which is shown in Figure 1.9. Tubing is usually produced by the film blowing of low density and high-density polyethylene in widths from a few centimetres to metres. Films can also be made from polycarbonate, cellulose acetate and other thermoplastics (Schenkel, 1966) but not by film blowing.

The processing equipment used in film blowing is a development from the basic extruder containing a specialised die. Melt from the extruder is turned through a right angle and vertically upwards in the form of a thin tube. This tube is expanded by internal air pressure to form a bubble, and stretched in the direction of the flow by means of powered nip rollers, which also close the bubble (Fenner, 1985).

The flattened film is then wound on to a reel. Cooling of the melt once it has left the die is accomplished by the flow of air from a cooling ring directed onto the bubble. Solidification occurs at a freeze line, which is often observable near where the maximum bubble diameter is first reached.

In 1939, the first production plants for the extrusion of tubular film from polyethylene were built in the U.S.A. Only narrow film widths were then produced, with the main differences being in the working direction and in the take-off systems. Nowadays, films of infinite length can be made with a width varying from a few centimetres to several metres. Initially, the film thickness could range between 15 and 500 μm. The advances in technology can nowadays produce film of thickness between 4 and 2500 μm.

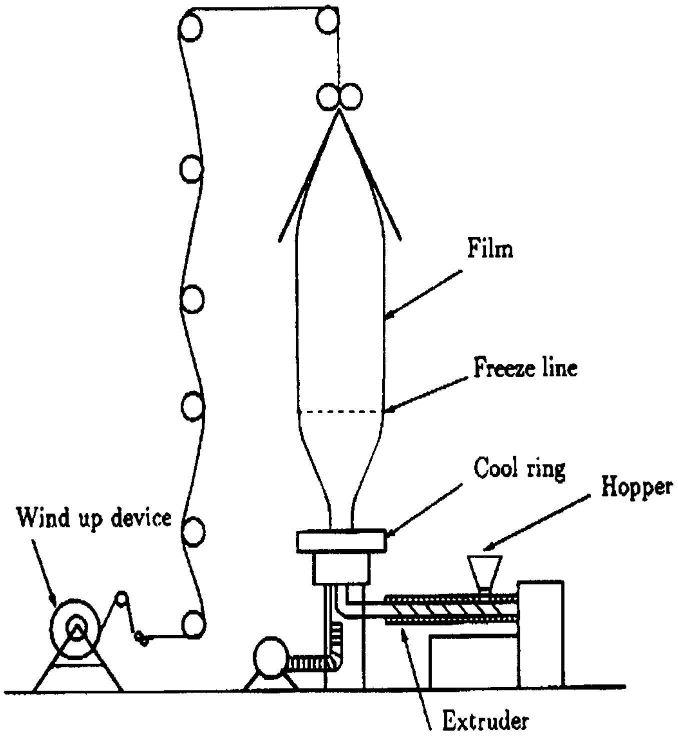

Figure 1.9: An overview of the film blowing process

About 85% of the polyethylene film produced in the U.S.A. in 1960 was manufactured this way (Schenkel, 1966). Applications of polyethylene (PE) films can be found in e.g. carrier bags, shrink films, food wrapping, refuse bags and films for agricultural purposes.

Polyethylene feedstock is transported, pressurized and melted in an extruder. At the end of the extruder the melt is forced through an annular die. On leaving the die the melt is stretched vertically upwards in the form of a thin tube. During the time the polymer is in the molten state the film will be stretched in two directions.

Firstly, by blowing air through the orifice in the annular die the tube is inflated, where no air can escape because the nip rolls are pushing together. Due to this inflation, the film is being stretched in the so-called circumferential (or transverse) direction. At the end of the extrusion line, the extruded film is wound-up, causing elongation in the machine direction and yielding the so-called draw down. The height at which solidification of the melt begins is referred to as the freeze line height.

The ratio of bubble diameter at the freeze line height to the die diameter is known as the blow-up ratio (BUR), whilst the ratio of the haul-off rate to the natural extrusion rate is the draw ratio (DR). Processing plastic materials this way results in biaxially oriented films.

The ultimate film properties will depend on the polymer used and the processing conditions.

1.4.2 Materials used in Film Blowing

Polyethylene is a relatively old plastic and its development has led to many grades now being available. In 1993, the production of PE in Western Europe was estimated to be approximately 8.8 x 10^6 tonnes (Oonk, 1994). This amount is split into 4.4 x 10^6 tonnes Low Density Polyethylene (LDPE), 1.2 x 10^6 tonnes Linear Low Density Polyethylene

(LLDPE) and 3.2 x 10^6 tonnes High Density Polyethylene (HDPE). In 1993 in Western Europe, 74% of the LDPE and LLDPE were used for making films (Oonk, 1994). Although a small proportion of PE films are made by film casting, the most widely and frequently used process to make PE films is the tubular film blowing process.

The properties of all these grades vary and can be controlled by varying:

- The degree of short chain branching by the presence of a small amount of comonomer, e.g. hexene or octene
- The degree of long chain branching, e.g. by the nature of a free radical polymerisation process for LDPE
- The average molecular weight and the molecular weight distribution
- The presence of additives.

Low Density Polyethylene (LDPE) is the oldest of the three PE's. Because of the long chain branching in LDPE the degree of crystallinity of LDPE is limited to approximately 40%. Consequently, the density of LDPE is between 910 kg/m^3 and 935 kg/m^3. In high density polyethylene (HDPE) there is a virtual absence of chain branching. This is responsible for a higher degree of crystallinity, greater than 70%. The density of HDPE can range from 940 kg/m^3 to 970 kg/m^3.

The third type of PE is linear low-density polyethylene (LLDPE). Owing to the use of a small amount of C_4, C_6 or C_8 comonomers, LLDPE is a linear polymer with randomly distributed short branches of regular length and thus a limited crystallinity. The density of LLDPE can range from 915 kg/m^3 to 940 kg/m^3.

1.4.3 A Literature Review on the Modelling of Film Blowing

Despite numerous papers on experimental and theoretical research on the film blowing process, it is still not quite well understood how film properties relate to the polymer feedstock and processing parameters. This literature search concentrates on the various groups all over the world who worked on understanding and modelling the film blowing process. It is divided into the progress made by each group during their distinctive time.

In the early seventies, in England Pearson and Petrie (Pearson *et al.*, 1970a, 1970b, 1970c) created the foundation of the modelling of film blowing, followed by the group of Schenkel at the IKT in Stuttgart, Germany (Ast, 1976). In the eighties, it was mainly the group of White (at the time still in Knoxville, Tennessee, nowadays in Akron, Ohio (White *et al.*, 1988; Choi *et al.*, 1982) who was active in understanding the film blowing process, while in the nineties, Campbell and co-workers were the most published group (Cao *et al.*, 1990; Ashok *et al.*, 1992)

a. The Seventies: Foundation Work

Pearson and Petrie (1970a, 1970b, 1970c) derived and solved the equations for isothermal film blowing for a Newtonian fluid. Attention was placed on describing the bubble shape and film velocity. Petrie (1973) extended the model to isothermal viscoelastic film blowing using a constitutive model of the Oldroyd type. Due to numerical problems, he was not able to solve the resulting set of equations. In a later paper, Petrie (1975) solved the non-isothermal problem for a Newtonian fluid and the problem for a purely elastic fluid. The main outcomes of this research suggested that accurate modelling of the heat transfer and the use of a suitable viscoelastic constitutive equation was required.

In the same period, Han and Park (1975a) reported an experimental study of the film blowing process. They tried to use a film blowing line as a rheometer to determine extensional viscosities. In a subsequent paper, Han and Park (1975b) simulated the isothermal film blowing process for a generalised Newtonian model. The dimensional take-up force and the bubble pressure were used as fitting parameters to achieve reasonable agreement with experimentally observed bubble radii and film thickness profiles.

b. Schenkel Group at IKT, Stuttgart

Professor Schenkel was the supervisor of a number of theses on the film blowing process. One such investigation was by Ast (1976) who carried out experiments on cooling the film. In solving the energy equation, he was able to calculate the temperature profiles in the film during processing. The heat transfer coefficient was used as a parameter to determine the freeze line height.

Wagner (1976) reported the study on non-isothermal modelling with Newtonian, pure elastic and a Maxwell fluid. Interest in his work was the accurate measurement of the take-up force with a specially constructed device. For pure elastic and a Newtonian model, it was not possible to describe the kinematics of the film with the correct bubble pressure and take-up force. This was possible with one mode Maxwell model. However, to describe different experiments the relaxation time and the relative viscosities had to be altered. Apparently, the one mode Maxwell model is not suitable to model the film blowing process. Fisher (1983) used measured temperature and deformation profiles to calculate the stresses in the machine and transverse direction, which was compared with experimentally determined stresses. The constitutive equations he investigated were Wagner's non-linear integral equations. By using parameters as determined in shear and uniaxial elongation, the experimentally observed stresses were highly unpredictable.

c. Approaches of Other Groups during the Eighties

A similar approach to calculate stresses in the films was adopted by Gupta (1980). He introduced a modified Maxwell model in such a way that temperature effects were taken into account. Stresses calculated in the polymer melt under non-isothermal deformation proved to be higher than calculated with a temperature rate independent model. In trying to describe the stresses in the film for polystyrene, the axial stresses served as data to fit the proper relaxation time. The axial stresses were predicted well (Gupta, 1980). The calculated circumferential stresses, however, differed from the experimentally observed stresses. No decisive proof was given that a temperature rate dependant model should be used to model the film blowing processes, as was pointed out later by Luo and Tanner (1985).

Other efforts to incorporate the viscoelastic nature of polymer melt in the modelling the film blowing processes were reported by Luo and Tanner (1985) and Cain and Denn (1988). Cain and Denn (1988) calculated deformation and temperature profiles for a Newtonian, an Upper Convected Maxwell and a Marruci fluid. The set of equations was solved using a Newtonian banded matrix technique, in which the bubble pressure and the take-up forces were the unknowns. By solving the problem this way, fewer troubles with numerical instabilities were encountered. The most striking result of their calculations was that it produced multiple solutions for a pair of bubble pressure and take-up force values, which is unrealistic.

d. The Experimental Approaches lead by White

Choi, White and Spruiell (1980) investigated the orientation development in tubular film extrusion of polystyrene. The take-up force was measured with a tensiometer and birefringence of the films was experimentally determined. However, the tensiometer was not accurate due to the low tension in the film during tubular film blowing. In a later paper, Choi, White and Spruiell (1982) showed that, for HDPE, the crystalline biaxial orientation factors were unique functions of the stresses in the freeze line, as was later once more pointed out by White and Cakmak (1988) for HDPE, LLDPE, LDPE and PP.

White, Cakmak (1988) and later Simpson (1993) proposed a model for the crystalline morphology of the films. They concluded that crystallisation under the influence of stresses resulted in the formation of row – nucleated lamellae. Simpson also showed that the molecular orientation of the amorphous phase was mainly in the machine direction.

Kanai and White (1984 and 1985) together published a series of papers on film blowing. In the first paper, they reported on an experimental study on film blowing of LDPE, LLDPE and HDPE. The most notable result was that increasing the cooling rates did not affect the crystallisation temperatures, but only the crystallisation rates. Their second paper dealt with a theoretical model of the dynamics, heat transfer and crystallisation processes in tubular film blowing. A Newtonian model, with temperature dependence according to the Arrhenius equation and an exponential dependence on the crystallisation degree was done. Using this model it appeared that the bubble shape is most influenced by the activation energy, while the crystallinity retards the continued growth of the velocity and the thinning of the film.

e. Work done by Campbell and his Group through the Nineties

Cao *et al* (1990) introduced a viscoelastic plastic model, for which the traditionally kinematic boundary conditions were replaced by a rheological boundary condition, the so-called plastic elastic transition (PET). The main reason for introducing the new constitutive equation was the fact that existing equations predicted a continued increase of film velocity and a decrease of bubble radius once the freeze line was exceeded. Ashok and Campbell (1992) performed a two-phase simulation of tubular film blowing using a viscoelastic model. In this two phase modelling, the film was divided into a liquid part, a solid-liquid part and finally a solid part. Although the polymer can be partly in the liquid phase and partly in the solid phase across the film thickness, the temperature gradient in the radial direction is ignored. One of the major drawbacks of the model is that in simple shear flow the model reduces to the Upper Convected Maxwell model. Therefore, in simulation the film blowing process the flow in the annular die cannot be taken into account, since the normal stresses in the die would become too high to obtain reasonable results. In the simulation performed in the two-phase model, the pressure at the die, the initial angle and the initial hoop stress were therefore taken as parameters to be able to fit the correct bubble shapes. Moreover to avoid the so-called die swell problem, the calculations started approximately 6 cm above the die. Although the model has its limitations, the predicted deformations in the film blowing process were in good agreement with the experimentally observed deformations. This holds especially for the region above the freeze line.

In an investigation on the temperature profiles, Cao, Sweeney and Campbell (1990) set up experimentation to measure the bulk temperature of the film and the surface temperature simultaneously. Using an Infrared radiation technique with a wavelength of

3.43μm, the surface temperature was detected while with a wavelength of 1.8 - 3μm the bulk temperature was found. They reported temperature variations across the film thickness of 15°C for HDPE, immediately after the die exit. These temperature variations fade away as the distance from the die increases. At the freeze line height all these variations disappeared. This work suggests that simulations of the film blowing process needs incorporation of two-dimensional heat transfer.

1.5 Spectroscopy

1.5.1 Background

Spectroscopy is the use of absorption, emission, or scattering of radiation by matter to qualitatively or quantitatively study the matter or to study physical processes. The matter can be atoms, molecules, atomic or molecular ions or solids (Thomas, 1996). The analysis by spectroscopy is usually presented in the form of a spectrum. The term spectrum, a Latin word for image, was applied originally to the bands of colour obtained with a prism and white light. The meaning has been broadened considerably to indicate any range of electromagnetic frequencies and especially the characteristic absorption and emission pattern of any substance in a given frequency range (Thomas, 1996). Thus one may speak of the visible spectrum, meaning the colours of the rainbow; of the ultraviolet emission spectrum; or the infrared absorption spectrum. For purposes of this study, only absorption in the ultraviolet (UV) and visible (Vis) regions will be considered.

Spectrometry, particularly in the visible region of the electromagnetic spectrum, is one of the most widely used methods of analysis. The wavelength unit preferred for the UV and Vis regions of the spectrum is nanometer (nm).

The electromagnetic spectrum is arbitrarily broken down into different regions, according to wavelength. The various regions of the spectrum are shown in Figure 1.10. Analysis done in this study concentrated mainly in the UV-Visible region.

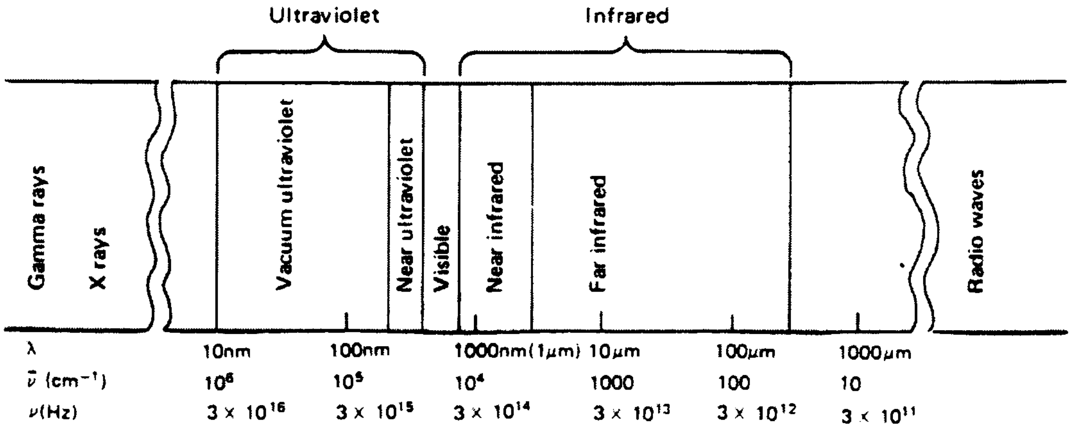

Figure 1.10: The Electromagnetic spectrum illustrating the different regions separated by wavelength (Christian, 1980)

The ultraviolet region extends from about 10 to 380nm, but for purposes of this study, the most significant region is from 200 to 380nm, called the near ultraviolet region. The visible region is actually a very small part of the electromagnetic spectrum, and it is the region of wavelengths that can be seen by the human eye, that is, the light appears as a colour. The visible region extends from the near ultraviolet region 380nm to about 780nm. A typical visible spectrum as seen in Figure 1.10 is produced by a UV Visible spectrophotometer. Such a spectrum is produced from the absorption or the transmission of electromagnetic radiation.

1.5.2 The Absorption of Radiation

Matter can capture electromagnetic radiation and convert the energy of a photon to internal energy. This process is called absorption. In this study, the absorbing specie is the phthalocyanine blue pigmented film. Energy is transferred from the radiation field to the absorbing molecule. The energy change of the absorber can be described as a transition or an excitation from a lower energy level to a higher energy level. Since the energy levels of matter are quantized, only light of energy that can cause transitions from one energy level to another will be absorbed.

Absorption spectroscopy is a way to study the energy levels of the atoms, molecules, and solids. The type of excitation depends on the wavelength of the light. Electrons are promoted to higher orbitals by ultraviolet and visible light, vibrations are excited by infrared light and microwaves excite rotations. An absorption spectrum is the absorption of light as a function of wavelength. The Beer-Lambert Law can be used to measure the concentration of an absorbing species in a sample.

1.5.3 Beer's Law

Beer-Bouguer-Lambert law, which described the amount of radiation absorbed by a sample, is commonly called Beer's Law. Considering the absorption of monochromatic radiation as shown in Figure 1.11. Incident radiation of radiant power P_o passes through a sample of an absorbing species at concentration c and path length b, and the emergent (transmitted) radiation has radiant power P. This radiant power is the quantity measured by spectrometric detectors.

Bouguer in 1729 and Lambert in 1760 (Knowles *et al.*, 1984) recognized that when electromagnetic energy is absorbed, the power of the transmitted energy decreases geometrically (exponentially). Since the fraction of radiant energy transmitted decays exponentially with the path length, we can write it in exponential form:

$$T = \frac{P}{P_o} = 10^{-kb} \tag{1.10}$$

Where k is a constant and T is the transmittance. The logarithmic form of this is:

$$\log T = \log \frac{P}{P_o} = -kb \tag{1.11}$$

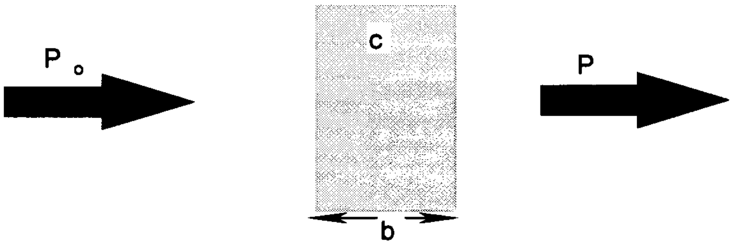

Figure 1.11: The absorption of monochromatic radiation by a specimen of concentration *(c)* and path length *(b)*.

In 1852, Beer and Bernard each stated that a similar law holds for the dependence of T on the concentration:

$$T = \frac{P}{P_o} = -k'c \tag{1.12}$$

Where k' is a new constant, or

$$\log T = \log \frac{P}{P_o} = -kc \tag{1.13}$$

On combining these two laws, we have Beer's Law, which describes the dependence of T on both the path length and the concentration,

$$T = \frac{P}{P_o} = 10^{-abc} \tag{1.14}$$

Where a is a combined constant of k and k', and

$$\log T = \log \frac{P}{P_o} = -abc \tag{1.15}$$

By omitting the negative sign on the right-hand side of the equation, defines a new term, absorbance:

$$A = -\log T = \log \frac{1}{T} = \log \frac{P_o}{P} = abc \tag{1.16}$$

Where A is the absorbance. The path length b is expressed in centimetres and the concentration c in grams per litre. The constant a is called the absorptivity and is dependant on the wavelength and nature of the absorbing material.

In an absorption spectrum, the absorbance varies with wavelength in direct proportion to a (b and c are held constant). The product of the absorptivity and the molecular weight of the absorbing species is called the molar absorptivity, ε. Thus

$$A = \varepsilon bc \tag{1.17}$$

c is now in moles per litre. The cell path length in ultraviolet and visible spectrophotometry is often 1 cm and thus ε has the units of cm^{-1} mole^{-1} litre.

CHAPTER 2

EXPERIMENTAL

2.1 Analysis of CSIR Purge

The aim of this set of experiments was to alleviate a problem experienced by manufacturers with regard to the adhesion of the purge to the metal surfaces of the extruder. Due to the local market being limited, South African plastic processors have to manufacture many different products on a single machine. If the type of material and colour between two consecutive products were the same, this would not be a problem. However, when manufacturing products like wire and cable coverings of different colours and composition, a single defect can result in meters of product being rejected. Under such conditions manufacturers disassemble the extruder in order to subject the screw to a thorough cleaning after purging using a purging compound.

The requirement under these circumstances is that the purging must be efficient and allow easy cleaning afterwards. By dismantling the extruder screw, processors prefer the purge to form a paste that does not adhere to the metal components and can be removed thereafter.

The purging compound manufactured at the CSIR experienced this problem. Although the purge compound was effective in its function, it tended to adhere to the metal components, making cleaning difficult. The adhesion of the purging compound was determined by dismantling of the extruder after purging. It was observed that the purge compound adhered significantly to the extruder screw was well as the barrel walls. The degree of adhesion made the cleaning thereafter extremely difficult.

There are several theories of adhesion and adhesive action with different approaches. They include those based on adsorption and wetting, diffusion, electrostatic interactions and chemisorption (Wake, 1978). In order to determine the cause of the adhesion, all additives used in to formulation as well as the additives for future formulations were tested in order to identify and replace the additives contributing to the adhesion.

2.1.1 Starting Materials

The adhesion tests were performed on mild steel plates. The plates were 120 mm in length and 30 mm in width. The plates had to be thoroughly degreased for each experiment. This was achieved using acetone. Some of the additives tested are shown in Table 2.1 and the others in Table 3.1. The additives were used as received. An *Instru* laboratory hot plate was used to heat and melt the additives onto the steel plates.

2.1.2 Experimental Procedure

All additives were tested for their adhesion to mild steel plates. Although polymer extruder screws and barrel walls are hardened and smooth, the use and preparation of the mild steel plates would give some indication of the degree of adhesion of each additive. The additives were added to cleaned mild steel plates at a temperature of 250°C and allowed to completely melt. They were then removed, and cooled overnight to room temperature before being tested. All additives were tested for the adhesion to the mild steel plates by checking the ease of removal. The degree of adhesion was rated on a scale from one to five, with five being extremely difficult to remove.

On analysis of the results obtained in the above experiments, additives showing the least adhesion to the metal plates were compounded at 200°C with the base polymer of the purge viz., LDPE at 10% by mass. These samples were then subjected to Lap-shear test for adhesion to determine the load at break and the influence of the base polymer on the adhesion of the additive. The Lap-shear test was performed according to ASTM Standard D3163. The test conditions were kept the same for all experimentation. The test conditions were as follows:

- Temperature @ 23°C and 50% Humidity
- Crosshead speed at 50 mm/min
- Grip distance of 330 mm
- Two to three samples were tested and the average taken

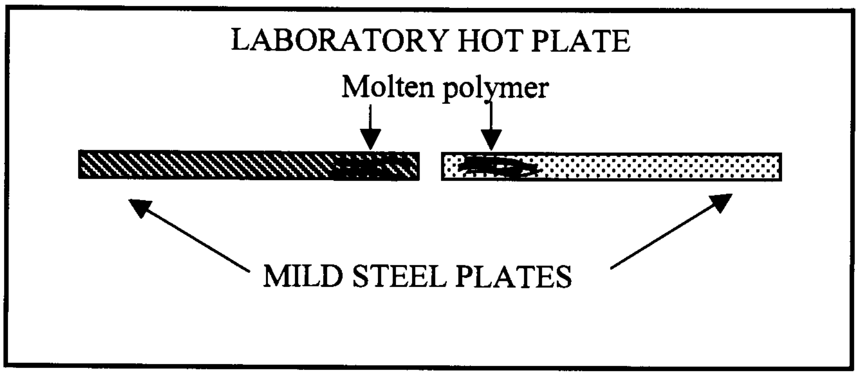

Figure 2.1: The preparation of mild steel plates for Lap Shear testing

The Lap shear sample preparation was as follows: After the metal plates were thoroughly cleaned and degreased, two plates were placed next to each other, longitudinally as shown in Figure 2.1. They were heated for five minutes in order to allow them to reach and maintain the required temperature of 250°C. The additives were then added to the plates and allowed to completely melt. Once molten, the plates were allowed to adhere to each other by bring the two plated together as shown in Figure 2.2. Pressure was applied to the adhering ends for approximately 2 to 3 minutes and the plates allowed to cool before being tested.

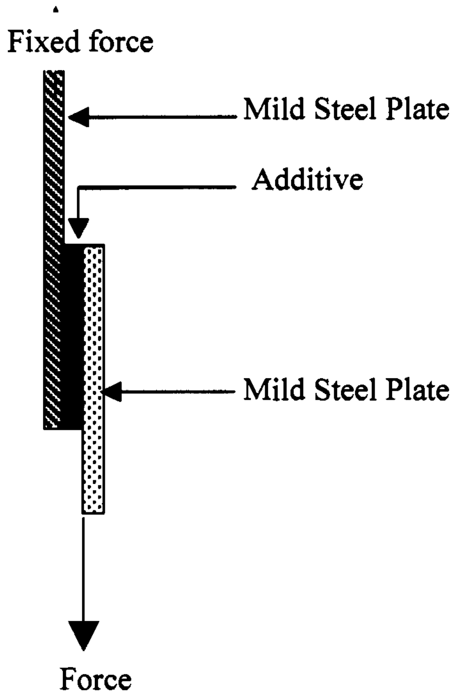

Figure 2.2: A typical sample prepared for Lap Shear Testing

2.2 MFI Testing

2.2.1 Starting Materials

All polymers and slip additives were used as received. Tubular film blowing was conducted using low-density polyethylene (grade XJF 46/60 ex Polifin) with a MFI of 2 g/10 min @ 190°C/2.16 kg and a density of 0.93 g/cm^3. Table 2.1 below lists the polymers and additives used in this study. In the initial experiments, the blue colour was imparted by a 70% blue EVA masterbatch (CSIR, Pretoria). Thereafter, further experiments were conducted using a phthalocyanine blue pigment powder supplied by Rolfes Pigments. In all the purging experimental procedures a 20% red colour masterbatch in EVA was used as a tracer.

Table 2.1: List of materials tested as polymer carrier or as slip agent.

Compound	Grade	Supplier
Linear low density polyethylene	AMS 1175	Affirm Marketing
Polypropylene	H504	Dow
ABS	Tarilac AG12AO	Affirm Marketing
Calcium stearate	Standard	Cupelite Products
Polyamide	Eurelon 930	Bayer
Polycaprolactone	Capa 656	Solvay
Fischer Tropsch wax	Sasol Wax C80	Schumann-Sasol
Polypropylene wax	PP 230	Clariant
Diethanolamine benzoate	VCI 8533	CSIR
Epoxy resin	Epikote 3002	Shell chemicals
Polyethylene wax	Luwax A	BASF
Polar wax	Aclyn 295 A	Clariant
Stearamide	Crodamide	Croda
Styrene-co-acrylic acid		Makeean Polymers

2.2.2 Experimental Procedure

The experimental procedure was conducted as per ASTM standard D1238. The effect of slip additives was evaluated using a standard MFI tester, as shown in Figure 1.2. The die used had a length of 8 mm and a capillary with diameter of 2.095 mm. Before any experiments were conducted the apparatus was thoroughly cleaned. Thereafter, the MFI tester was maintained at the required temperature for 10 minutes. Before testing of each sample commenced, the apparatus was purged, firstly, with the base resin and then with a small amount of the test sample. Sample preparation was as follows: polymer powder with an average particle size of 60 μm was blended with the slip additive in a high-speed grinder until homogenous. MFI values were then measured at different temperatures and using masses as per ASTM Standard D1238. The different temperature and weights used for each polymer is shown in Table 2.2. The suppliers of the resins used in this study viz., polypropylene, polyethylene and acrylonitrile butadiene styrene are shown in Table 2.1. The weight presented in Table 2.2 is the combination of the piston and the dead weight.

Table 2.2: Temperatures and Weights of the Polymers tested

Polymer Resin	**Temperature (°C)**	**Weight (kg)**
Polypropylene	190	2.16
	210	2.16
	230	2.16
Polyethylene	190	2.16
Acrylonitrile butadiene styrene	210	5.0

2.2.3 Calculation of MFI

A small amount ca. 6-8 g of sample was charged into the tester. Once molten the piston and weight were added and the molten sample was extruded through the die. Analysis of each sample was performed 4-6 times and the mean was taken as the MFI. The standard deviation was also calculated for each set of results. MFI experiments, which showed values with a standard deviation greater than 2%, were repeated. Cut-offs containing air bubbles were ignored. The MFI for each mass was determined using equation 1.5 shown below.

$$\boxed{\text{M.F.I. (A)} = \frac{600 \text{ x average weight of cut-off in grams}}{\text{Interval of time in seconds}}}$$

During the experimental, the masses were obtained in grams and the time in seconds. However, the MFI results are represented in (g/10 minutes) as per ASTM standard D1238.

2.3 Extrusion Trials

All extrusion trials were conducted using a 28 mm laboratory film blower with a L/D ratio of 22. The internal volume of the extruder was ca. 80 ml. The film extruder was fitted with three temperature controllers and their temperatures were set at 160°C, 180°C and 180°C, respectively. The screw speed was adjusted to give an extrusion rate of ca. 210 g/min. Film with a lay-flat diameter of approximately 100 mm was produced. This diameter was kept relatively constant for all experiments. The machine was allowed to settle down for a period of approximately 1 hour of film blowing before experiments commenced.

The initial purge trials were conducted using a 70% blue masterbatch in EVA to impart a blue colour to the produced films. The determination of the intensity of the blue films was achieved with the aid of an UV-Vis spectrophotometer at a wavelength of 635 nm. Initial results produced concentrations very similar to each other due to the ease at which the blue masterbatch was removed. This made analysis difficult in determining the efficiency, if any, of the slip additives. Thereafter, further experiments where conducted using a phthalocyanine blue pigment. The blue pigment afforded a means of differentiating the effectiveness of each purge as well as reproducibility in results. The consistency was due to the better coating of the extruder barrel wall by the pigment as compared to the blue EVA masterbatch.

2.3.1 Blue EVA Masterbatch

2.3.1.1 Experimental Procedure

Firstly, the machine was allowed to settle down for approximately an hour. The experimental procedure involved the extrusion of four extruder volumes (80 g each) of the blue masterbatch in order to obtain a consistent colour. An additional volume of blue separated by red tracers followed this. The next extruder volume contained a slip additive (5% by mass) followed by four extruder volumes of clear LDPE pellets. The extruder speed was kept constant at 60 rpm throughout the purge trial.

A standard (containing no purging compound), comprising of five extruder volumes of blue followed by four volumes of clear polymer was used for comparison. At the end of each extruder volume, three red tracer pellets were added. The red tracer was used for analysis purposes, to signal the end of one extruder volume and the beginning of the next.

The slip additives used in these experiments were chosen from the MFI values obtained for LLDPE at 190°C / 2.16 kg. However, due to inconsistency in results, further experiments where conducted with a phthalocyanine blue pigment instead of the blue EVA masterbatch.

2.3.2 Phthalocyanine Blue Pigment

2.3.2.1 Experimental Procedure

The smaller particle size of the pigment would ensure better coating of the barrel walls and would also be much more difficult to remove. The ability of the pigment to adhere to the barrel walls of the extruder also provides a better mechanism of determining the efficiency of the purging compounds in comparison to the standard and each other.

After the initial experimental runs using the blue pigment instead of the EVA masterbatch it became evident that the amount of pigment used would be critical in determining optimum efficiency of the various different purge compounds. The method development had to take into account the fact that different commercial purge compounds do not all use the same purging mechanism. Some commercial purges incorporate a variety of mechanisms and therefore the method used had to accommodate for all compounds tested.

The trials were conducted as follows: Before each test run at least 0.5 kg of clear polymer was extruded into film at an extruder speed of 60 rpm. A blend of pigment powder and LDPE pellets (XJF 46/60 from Sasol Polymers) was added into the extruder. A further minute was allowed after the addition of all the pigment mixture to ensure sufficient coating of the barrel walls. The purge was then added followed by seven extruder volumes (80 g each) of clear LDPE pellets (grade XJF 46/60). A red tracer pellet was added at the end of each extruder volume.

A series of experiments were conducted with varying amounts of pigment concentration. The pigment concentration was varied from 10% to 40%. A commercial purge based on a corrosion inhibitor was used in this set of experiments to determine the most effective level of pigment. An experiment using LDPE powder (grade XDG 33 from Sasol Polymers) instead of the LDPE pellets was also conducted under the same experimental procedure. The LDPE powder, average particle size of 60 μm, was blended with the pigment in a high-speed grinder. This analysis was carried out with a 40% dosage of pigment. For each experiment, a standard containing no purge was also run.

2.3.3 Commercial Purging Trials

2.3.3.1 Experimental Procedure

Several commercial purges, as well as two slip additives dosed at 5%, were evaluated in terms of their ability to aid switching from blue to a clear polymer. The trials were conducted as follows: Before each experiment at least 0.5 kg of clear polymer was extruded into film at an extruder speed of 60 rpm. A blend of 20% pigment and 80% LDPE powder (grade XDG 33 from Sasol Polymers) was added into the extruder. A further minute was allowed after the addition of all the pigment mixture to ensure sufficient coating of the barrel walls. The extruder speed was reduced to 20 rpm and the various purge compositions added. An additional three minutes were allowed after the addition of the purge mixture to ensure maximum effectiveness of the purge. Thereafter the screw speed was returned to the normal 60rpm setting. Seven extruder volumes (80 g each) of clear LDPE pellets (grade XJF 46/60) were added consecutively, with each extruder volume being separated by red tracer pellets.

The following commercial compounds were tested for their purging efficiency:

- Purge A: foaming Compound with slip agents used at a 10% dosage level;
- Purge B: solvent based system dosed at 5%;
- Purge C: surfactant (based on a corrosion inhibitor) added at 1% dosage;
- Purge D: a filled compound with a scuffing or abrasive action; and
- Purges E1 and E2: combination purges incorporating both surfactants and scuffing agents.

The purge dosage level of the commercial purges were suggested by the manufacturers and were obtained by blending the purges with LDPE pellets to make up a total of 80 g purge mixture. However, for purge B the mixture was increased to 160 g to avoid screw slip. The dosage levels were as follows: Purge A: 10%; Purge B: 4%; Purge C: 2.5%; Purge D: 100%; Purge E1: 100% and Purge E2: 50%.

Film samples were taken from just ahead of the red tracer i.e., corresponding to passing an extruder volume. Measuring the absorbance at 643 nm using an UV-VIS spectrometer monitored the change in the intensity of the blue colour of the film. The absorbance was normalised with respect to the pure blue film. Corrections were also made for film thickness variations based on the assumption that Beer's Law holds.

2.4 Determination of Concentration using Beers Law

Beers Law states that the absorbance is equal to the product of the concentration (*c*), path- length (*l*) and the molar absorptivity constant (*ε*), from equation 1.17:

$$A = \varepsilon c l$$

In order to obtain the concentration of the pigment in the polymer film, this equation can be arranged to give equation 2.1,

$$c = \frac{A}{\varepsilon l} \tag{2.1}$$

From equation 2.1, the concentration is directly proportional to the absorbance of the polymer film. Because the molar absorptivity, *ε*, is unknown, an apparent pigment concentration in the film was used in this study. It was defined in units of absorbance/cm. The absorbance of the polymer film was obtained using a Varian 650 UV-Visible spectrophotomer. For the analysis of solutions the path length (*l*), which usually is the path length travelled by the beam, equates to the path length of the cuvette in which the sample is contained. For purposes of this study, the path length is the distance travelled by the beam through the film. This was determined by measuring the thickness of each polymer film analysed, using an electronic digital micrometer (0-25 mm). The thickness of each polymer film representing the end of an extruder volume was determined at four different areas and the values averaged. A series of clear polymer films were analysed and it was found to have an apparent concentration of 14.8 ± 0.9 absorbance/cm. Therefore a concentration of 14.8 absorbance/cm was subtracted from the blue films in order to obtain the true concentration of the pigment.

2.5 Absorbance Analysis using a UV-Visible Spectrophotometer

In order to obtain the wavelength at maximum absorbance, a series of films containing the phthalocyanine blue were scanned between 400 and 700 nm. By scanning between these wavelengths using a survey scan function the maximum absorbance is attained at a wavelength of 635 nm. The wavelength of 635 nm was used for all further analyses.

From equation 2.1, the concentration of the pigment contained in the polymer film is directly proportional to the absorbance of the film. Absorbance analysis is usually performed on solutions of the analyte contained in a cuvette. For purposes of this study, the absorbance of the polymer film was determined by attaching the film to the exiting side of the cuvette holder. Film with a lay-flat of approximately 100 mm was cut into squares (approximately 80x50 mm). Four absorbance readings of two squares from either side of the film representing an extruder volume were taken and the average is presented.

CHAPTER 3

RESULTS AND DISCUSSION

3.1 Adhesion of CSIR Purge

All additives were tested in order to overcome the adhesion of the purging compound to the hot metal surfaces of the extruder. The additives and the base polymer, polyethylene were tested individually and then tested again after being compounded together. Most of the polymer additives tested exhibited some degree of adhesion. Table 3.1 presents not only the additives used in the purge formulation but also the base polymer viz., polyethylene. The adhesion of the additives to the mild steel plates were rated according to the following scale:

- 1- No adhesion
- 2- Limited adhesion
- 3- Adhesion-easily removed
- 4- Adhesion-removal with difficulty
- 5-Adhesion-could not be removed.

As is illustrated in Table 3.1, polyethylene on its own adheres significantly to the metal plate. The additives showing little adhesion i.e., scale rating of one and two where then compound at a level of 10% with polyethylene. These additives were then re-tested to investigate the effect of polyethylene on the adhesion of the additives. The result of the analysis is presented in Figure 3.1. From Figure 3.1, it is clear that the additives, which had previously shown minimum to no adhesion, now shows signs of significant adhesion to the metal plates.

Table 3.1: The scale of adhesion of the polymer additives tested

Purge Additive	Rating	Purge Additive	Rating	Purge Additive	Rating
Fischer Tropsch Wax	3	Dipenta-erythritol	4	FR RIO /AO / Escorene	5
GMS 900V	2	Dynapol s1359 chg 703113	5	MB BT 93	5
Epoxy resin	3	Dynapol s1426 chg 903240	5	Crodafos CS2A 80863	2
Calcium Stearate	2	Mica 325	5	Crodafos CS2A 73721	2
Anox 20	3	Orox PKA	5	Isopropanolamine Benzoate	2
Polypropylene wax	2	MB 45%	4	Polycaprolactone 656	5
Polyethylene wax	1	AP750 45% LLDPE	5	Polycaprolactone 650	5
Polyamide	5	AP 422 45%	5	Polar Wax	5
Polypropylene	1	Penta-erythritol 35%	5	Crodamide ER	3
Orox PK	2	Escorene LD 728.61	5	Purge containing EVA/$CaSO_4$ /Calcium Stearate	3
LLDPE	5	Antiox MB LLDPE	3	Purge C	3
Purge A	4	Mica 325 /Naugard P/LDPE	5	MB/LDPE/APP/Epoxy resin	4
Purge B	3				

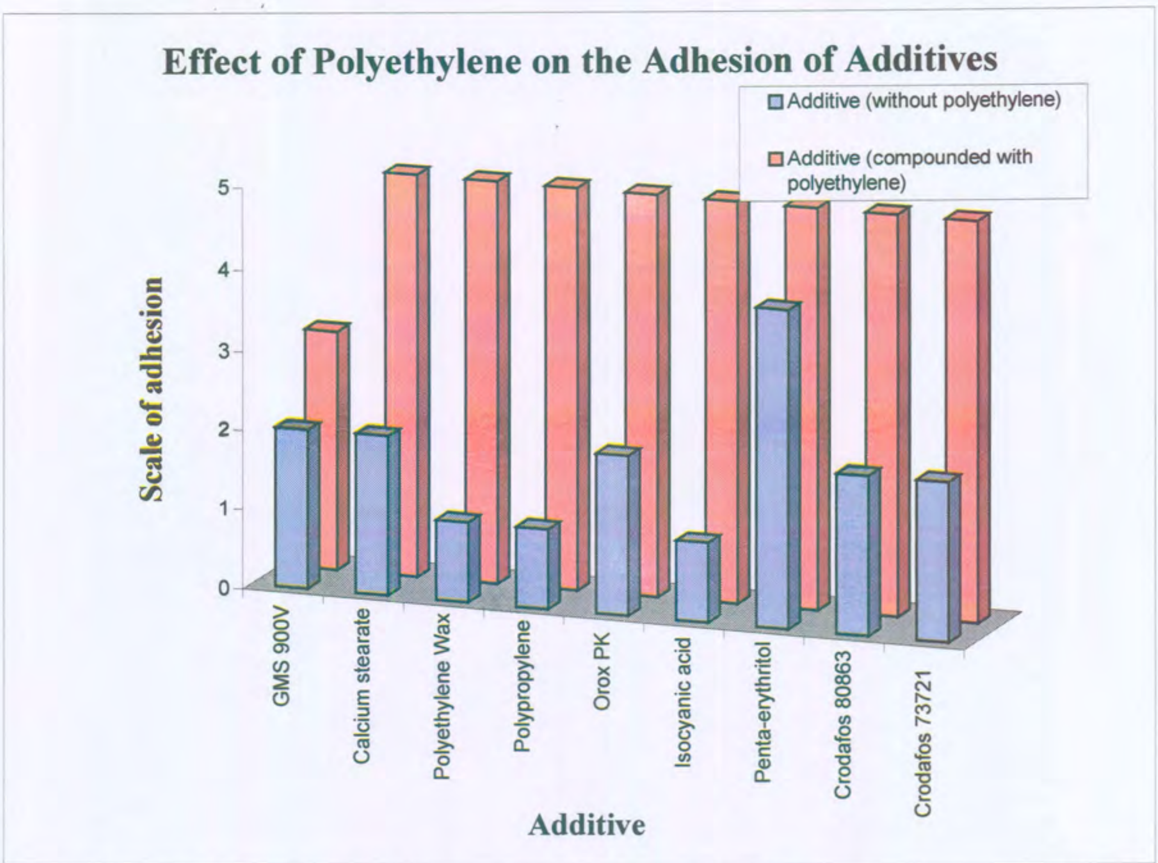

Figure 3.1: The increase in adhesion of additives (10%) after being compounded with polyethylene

Figure 3.1 illustrates the effect that the polyethylene polymer has on the adhesion of the additives used in the purge formulation. It is clear from Figure 3.1 that polyethylene increases the adhesion of the additives significantly. The additives where compounded with polyethylene at a level of 10% by mass. In order to overcome this problem, the base polymer was changed from polyethylene to polypropylene. The effect of this change in the formulation is illustrated in Figure 3.2. Figure 3.2 is an illustration of the load at break of the Lap-shear test conducted of the same additives presented in Figure 3.1. There is a significant decrease in the load at break between the old formulations, containing polyethylene, to the new formulation using polypropylene as shown in Figure 3.2.

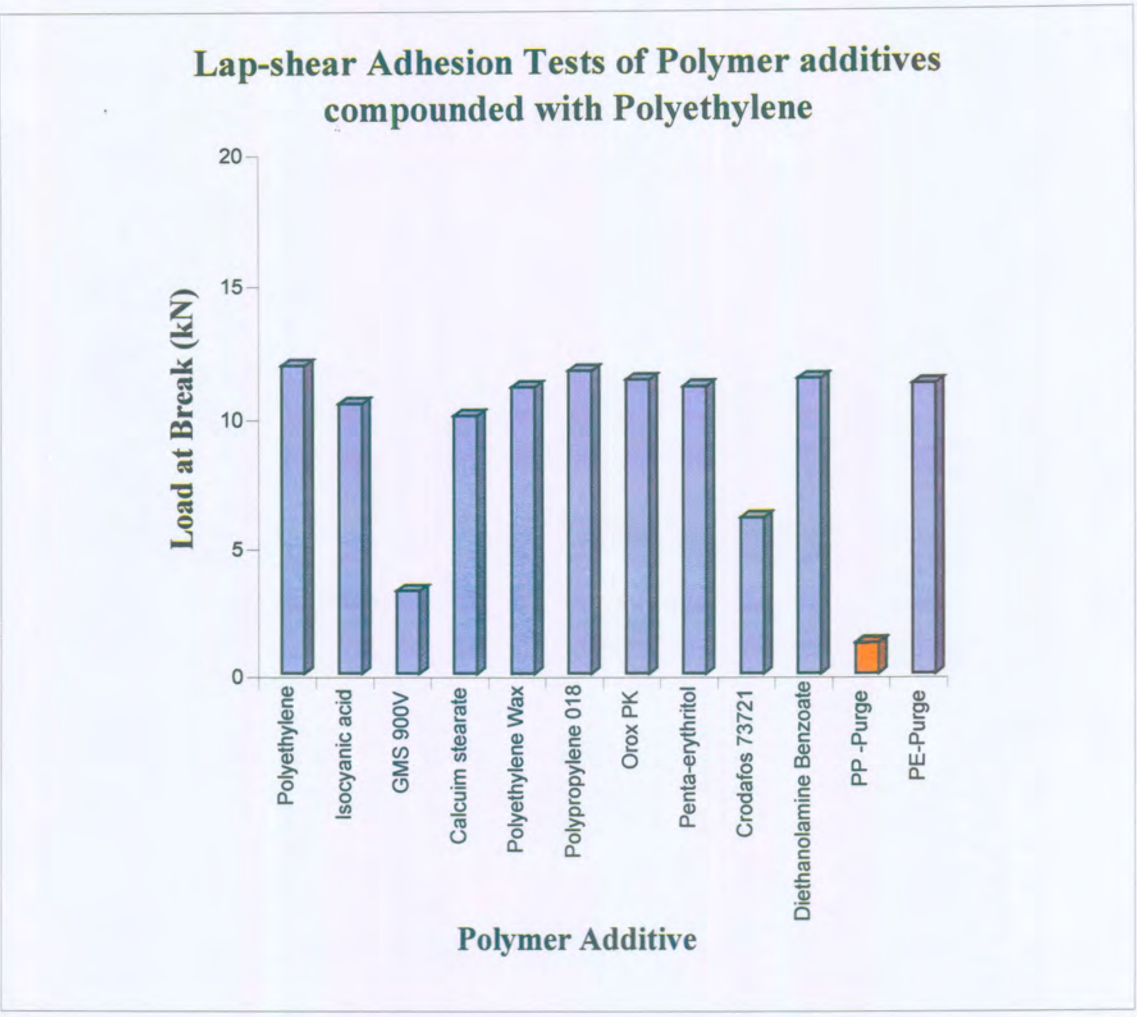

Figure 3.2: Lap-shear tests of purging additives (10%) compounded with polyethylene (old formulation) and the new final product with polypropylene as the base polymer (red)

3.2 Results of MFI Testing

3.2.1 MFI Analysis of Polypropylene (PP)

3.2.1.1 Analysis of PP at a Temperature of 190°C

The effect of various different slip additives on the melt flow index (MFI) of polypropylene (PP) was evaluated at 190°C using a weight of 2.16 kg. The MFI tests were also conducted at 210°C and 230°C with a constant mass of 2.16 kg. The MFI of the polypropylene was first evaluated without any slip additives at 190°C / 2.16 kg and was found to be 5.06 g/10min. The complete analysis of PP without additives can be found in Appendix A. Dow Chemicals was the supplier of the PP used in this study (Table 2.1).

The MFI data obtained for polypropylene with no additives was used to determine the effectiveness of the various slip additives on polypropylene. A series of additives were tested under set experimental conditions and the results evaluated. The effectiveness of each slip additive was determined from the MFI results obtained when incorporated at a 5% level into polypropylene. Figure 3.3 presents the MFI results for all the additives tested as well as the MFI of polypropylene at 190°C / 2.16 kg.

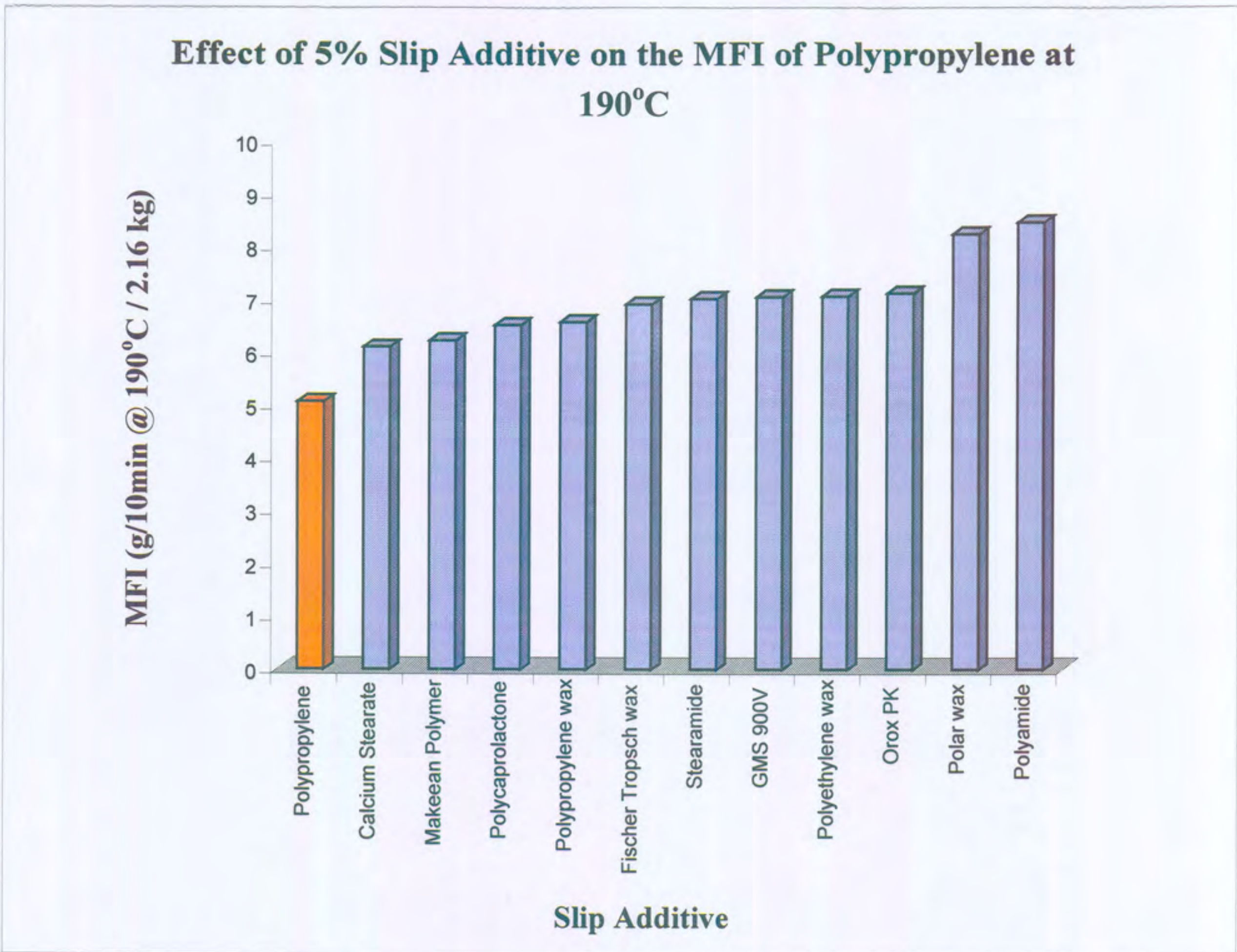

Figure 3.3: MFI results of various slip additives at a level of 5 % in PP at 190°C / 2.16 kg

Figure 3.3 illustrates the effect of each slip additive on the MFI of PP at 190°C / 2.16 kg. The experimental data for all additives as well as polypropylene is reported in Appendix A. Each slip additive does show an increase in the MFI of PP. The most significant increase is observed for the additives, polar wax and polyamide. The reason could be attributed to the size of these molecules. Both these molecules are relatively large molecules when compared to, for example, calcium stearate, which did not show a significant increase in the MFI of PP. The smaller molecules are not as effective as the larger molecules because they tend to be more soluble in the main polymer melt, rather than form a layer between the extruder wall and polymer layer. However, smaller molecules can increase the ease of flow due to their polarity but this is not the case in calcium stearate.

The MFI is a measure of the fluidity of the polymer melt expressed in terms of mass flow per unit time. It is inversely proportional to the apparent zero shear viscosity of the polymer melt at the temperature of measurement. The additives polyamide and polar wax show an increase in MFI values when compared to polypropylene (no additives) and the rest of the slip additives. The observed improvement in fluidity is attributed to two different mechanisms, these are:

- Lubricants that are soluble in the polymer melt reduce the effective viscosity by acting as internal plasticizers (Gachter, 1990).
- Immiscible lubricants act through the formation of a thin slip-layer on the channel wall that “lubricates” the main polymer flow.

The polyamide and polar wax, which exhibit the highest MFI values, perform as external rather than internal lubricants. This is due to the incompatibility between the main polymer flow and the slip additive. The external lubricants investigated in this study appear to have a more significant influence on the MFI than the internal lubricants. For example, the polypropylene wax does not show a significant improvement in the MFI.

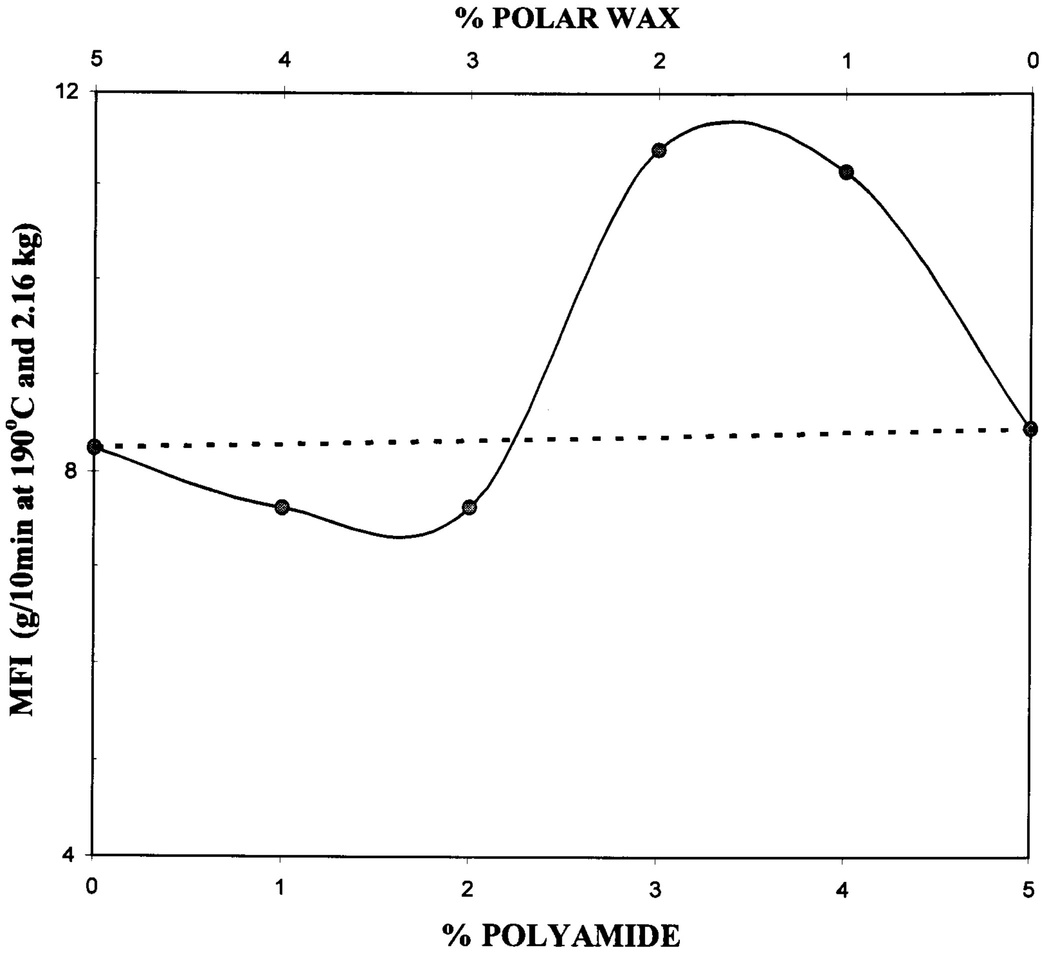

Figure 3.4: Combined synergy-antagonism between the slip additives polyamide and polar wax in polypropylene

The two additives exhibiting a significant increase in the MFI results of polypropylene resin at 190°C viz. polyamide and the polar wax where then further evaluated. The concentration of each additive in combination was varied to give a total slip-additive concentration of 5%. The temperature and mass was kept constant at 190°C and 2.16 kg respectively. Figure 3.4 shows the effect of these slip additives in combination on the MFI of PP.

It is clear from Figure 3.4, that depending on the relative concentrations, either antagonism or synergy is evident in the polar wax-polyamide additive combination in polypropylene. Antagonism can be rationalised by assuming that the combination of additives at that concentration has enhanced solubility in the main polymer melt. The result of this enhanced solubility is poor lubrication, hence a decrease in MFI. Such an effect is observed in the combination containing 1% and 2% polyamide (Figure 3.4). However, for and increase in the amount of polyamide in the combination, a synergistic effect is observed. This is a result of an increasing amount of polyamide that tends to dominate the combination resulting in separation from the main polymer flow and hence lubrication.

3.2.1.2 Analysis of (PP) at a Temperature of 210°C

The MFI for PP as the base polymer was evaluated at a temperature of 210°C. The MFI tests were carried under the same conditions as the analysis of PP at 190°C i.e., mass of piston and weight was 2.16 kg but the temperature was set at 210°C. The MFI of PP (no additives) at this temperature was found to be 10.6g/10 min (Appendix A). This is a higher MFI value than that determined for PP at 190°C, which was found to be 5.06 g/10 min. A series of slip additives were analysed for their effectiveness in improving the MFI of PP at 210°C / 2.16 kg. The results of this analysis are presented in Figure 3.5. The complete experimental data for each additive is reported in Appendix A.

At the temperature of 210°C, the most effective slip additives were polycaprolactone and the polar wax (Figure 3.5). When comparing the MFI results obtained at 190°C with these obtained at 210°C, polyamide is not as effective as the polar wax at this temperature.

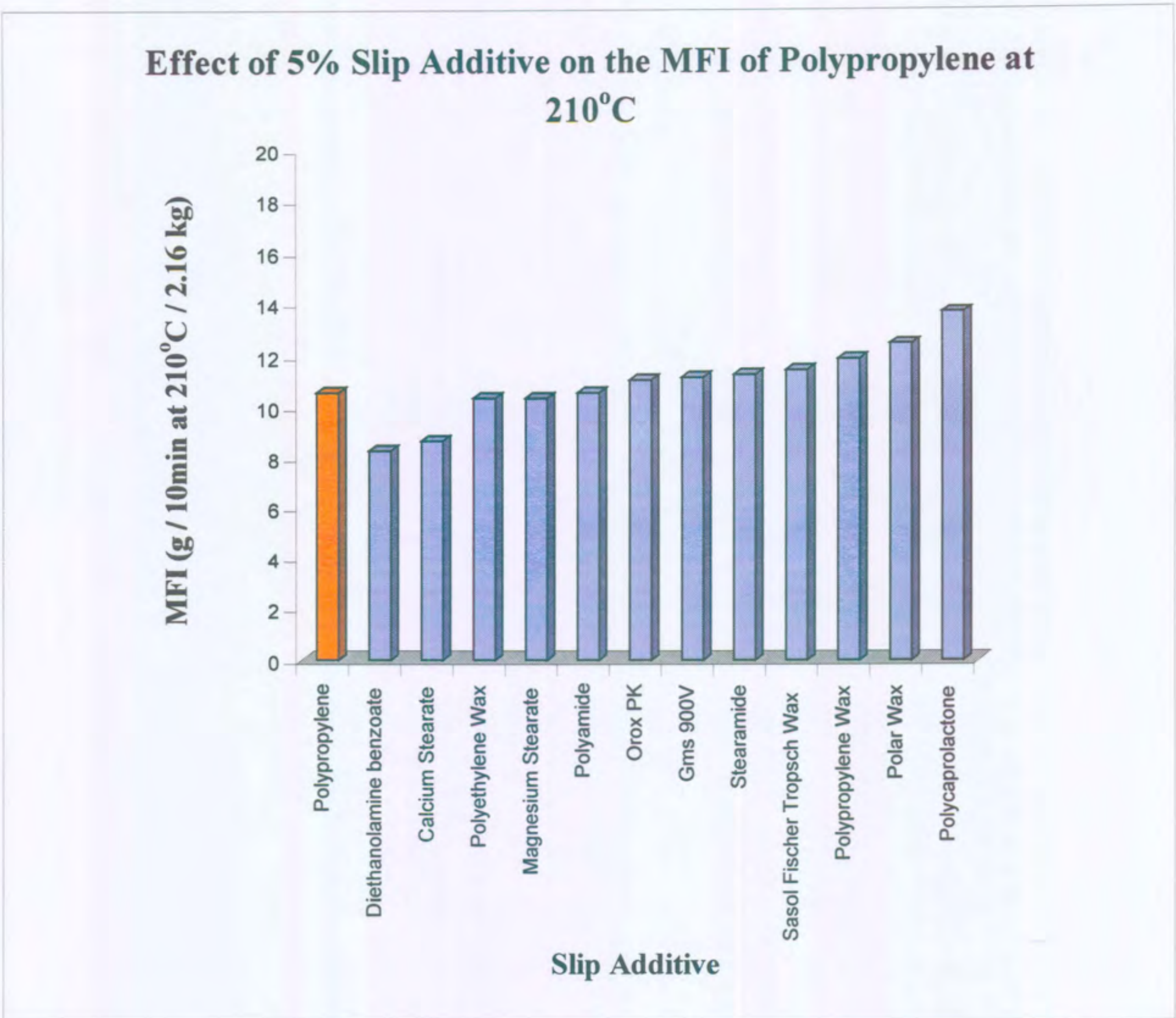

Figure 3.5: MFI results of various slip additives at a level of 5 % in PP at 210°C / 2.16 kg

3.2.1.3 Analysis of PP at a Temperature of 230°C

The effect of slip additives on the MFI of polypropylene at 230°C using a weight of 2.16 kg was also evaluated. In this experiment, apart from the change in temperature, all other experimental conditions were maintained as in previous analyses.

MFI measurements at this temperature became increasingly difficult mainly due to increased rate of flow as well as the degradation of both polymer and some additives. The MFI of polypropylene at 230°C / 2.16 kg was found to be 14.7 g/10 min (Appendix A).

The standard deviation for this analysis was 1.4 (Appendix A). Although, this is below the 2% set as the norm for this study, the analysis of the slip additives in Table 3.2 presents the inconsistencies experienced. Only the two additives presented in Table 3.2 were tested at 230°C used a weight of 2.16 kg. This was due to the degradation and inconsistent results obtained for those slip additives that were tested. It would be possible to obtain MFI values at 230°C using just the piston and no weight but for comparative reasons it was decided to keep all experimental conditions the same.

Table 3.2: MFI results for PP containing 5% slip additive at 230°C / 2.16 kg

Polyamide				
Time(s)	**Mass (g)**	**MFI (g/10min)**	**Mean**	**SD**
60.12	1.639	16.35	**19.0**	**3.2**
59.78	1.769	17.75		
59.91	1.504	15.06		
59.36	2.081	21.03		
59.79	2.041	20.48		
59.92	2.354	23.57		
Polar Wax				
Time(s)	**Mass (g)**	**MFI (g/10min)**	**Mean**	**SD**
59.89	1.676	16.79	**16.0**	**2.3**
60.03	1.414	14.13		
60.1	1.678	16.75		
60.03	1.353	13.52		
59.46	1.950	19.68		
59.5	1.471	14.83		

Table 3.2 presents the analysis of two slip additives viz., polyamide and polar wax at a temperature of 230°C using a weight of 2.16 kg. The difficulty in obtaining consistent results can be seen from the high standard deviation of the analysis. It is clear from Table 3.2 that these results have a standard deviation greater than 2%, the norm used for all experimentation in this study.

3.2.2 MFI Analysis of Acrylonitrile Butadiene Styrene (ABS)

3.2.2.1 Analysis of ABS at a Temperature of 210°C

ABS was evaluated only at 210°C as compared to PP. The ABS used in this study was obtained from Affirm Marketing as a fine powder, which made the blending with the slip additive much easier. The total weight of the piston and the dead mass used for the analysis of ABS was 5 kg as suggested by ASTM method D1238. The MFI of ABS (no additives) at 210°C / 5 kg was analysed to be 3.1 g/10min. The complete set of experimental data including the standard deviation is reported in Appendix B.

The analysis of various slip additives on the effect of the MFI of ABS was evaluated at 210°C and using a weight of 5 kg. The MFI testing was carried out with a blend of ABS and 5% slip additive. Figure 3.6 and 3.7 illustrate the effect of various slip additives on the MFI of ABS. It is clear from Figure 3.6, that all slip additives increase the MFI of ABS at 210°C / 5 kg. The most significant of these improvements can be observed for ABS containing polypropylene wax, polyamide and polar wax. Figure 3.7 shows the increase in MFI of ABS at 210°C / 5 kg at different levels of slip additive. The complete analysis of each additive can be found in Appendix B.

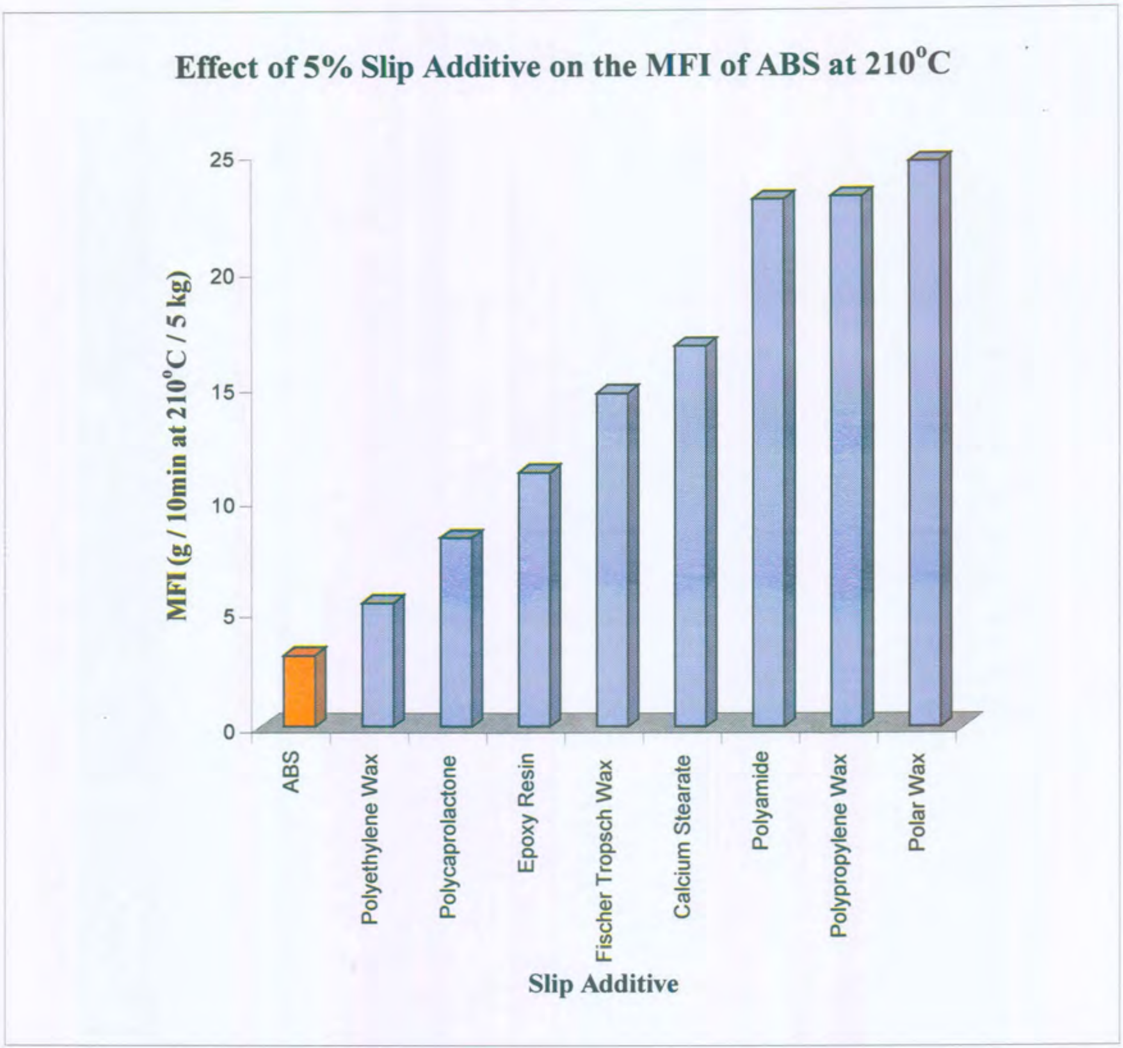

Figure 3.6: MFI results of various slip additives at a level of 5 % in ABS at 210°C / 5 kg

The increase in the MFI can be attributed to the incompatibility between the polymer and slip additive (Ricco *et al*, 2002). These additives are incompatible with the polymer and as a result act as an external lubricant through the formation of a thin slip-layer on the channel wall that "lubricates" the main polymer flow.

Two of the slip additives, polyamide and polypropylene wax, which showed a significant improvement in the MFI of ABS were evaluated further. The effect of these two slip additives in combination was investigated. MFI values were obtained at 210°C /

5 kg for combinations of the two additives making up a total additive concentration of 5 %. Figure 3.8 is an illustration of the effect these slip additive, in combination, have on the MFI of ABS. The experimental data of the additives in combination is presented in Appendix B. These results show that irrespective of the concentration of each additive, a synergistic effect can be observed (Figure 3.8). This effect is most notable for the combination consisting of 4% polypropylene wax and 1% polyamide. A physical explanation for the observed synergy is not available.

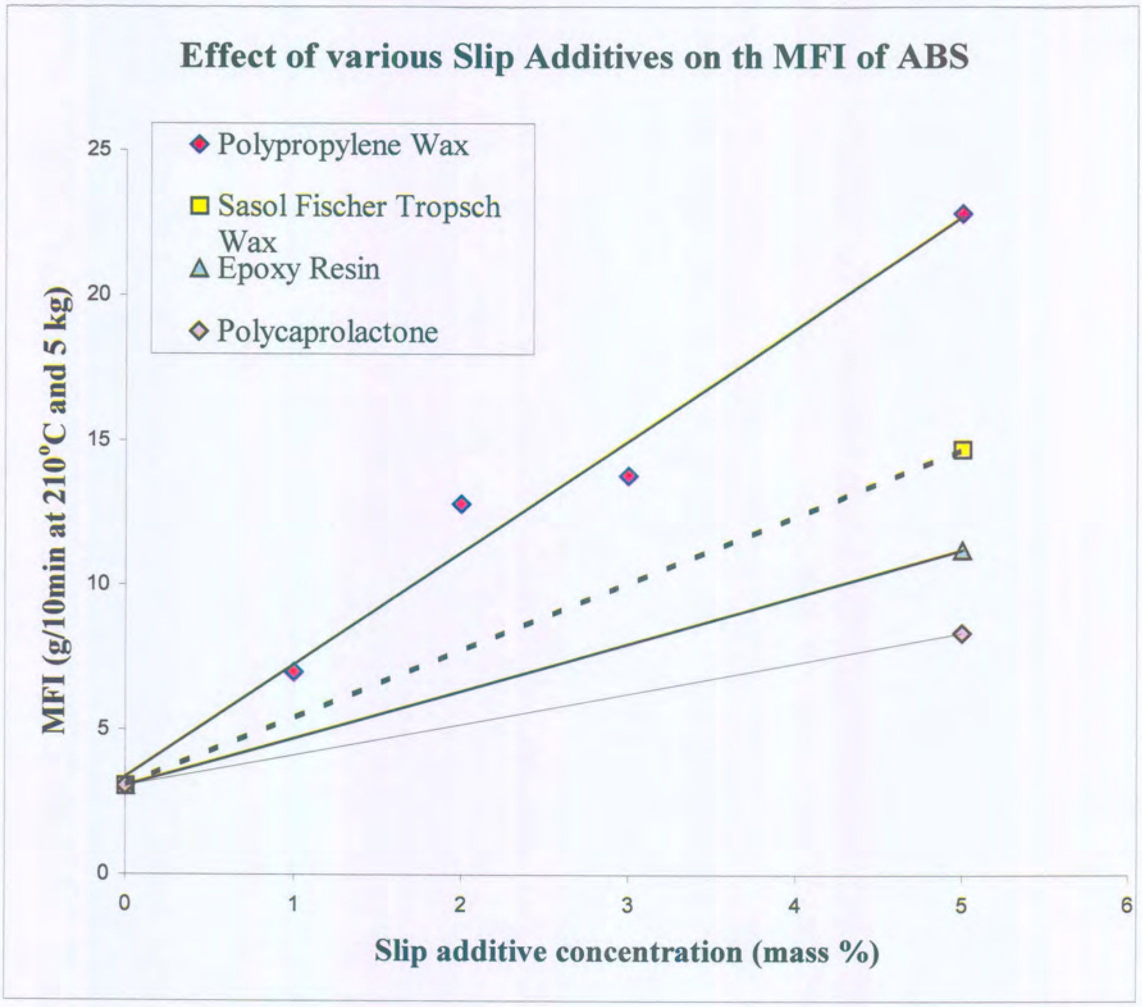

Figure 3.7: Effect of slip additives on the MFI of ABS at 210°C / 5 kg

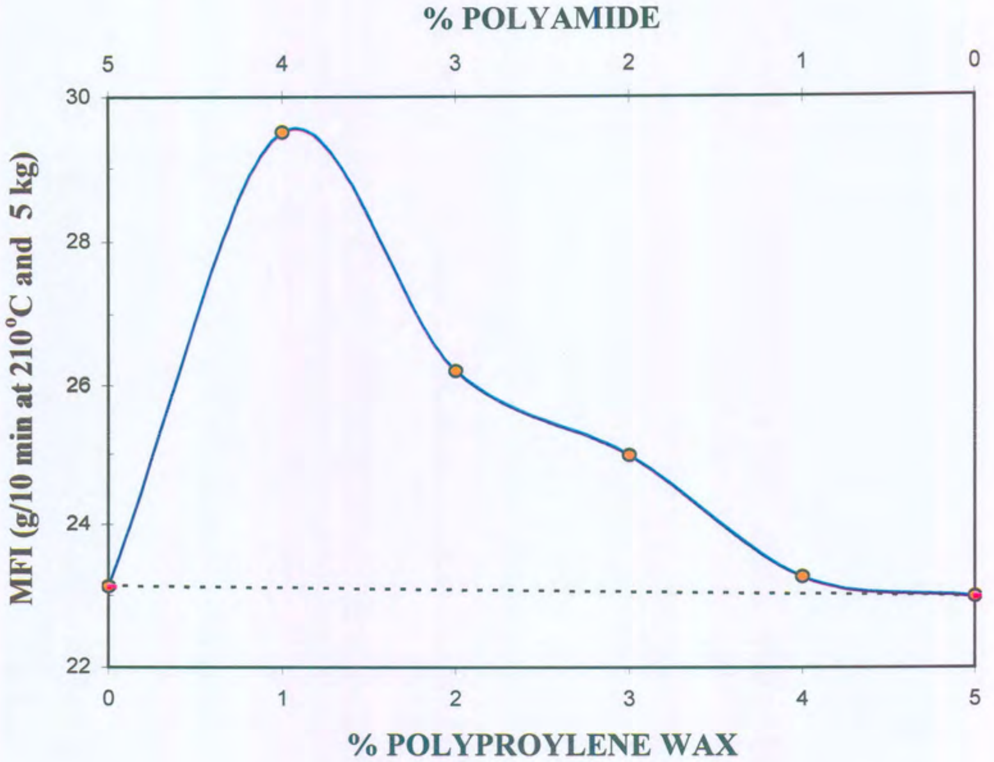

Figure 3.8: Synergy between the slip additives, polypropylene wax and polyamide in ABS at 210°C / 5 kg

3.2.3 MFI Analysis of Linear Low Density Polyethylene (LLDPE)

3.2.3.1 Analysis of LLDPE at a Temperature of 190°C

The analysis on the effect of slip additives in LLDPE was conducted with the aim of using the most effective slip additives in a series of purging experiments. The purging experiments included various commercially available purges together with the most effective slip additives.

The MFI testing was performed at 190°C and a weight of 2.16 kg. The MFI of LLDPE containing no slip additives was found to be 4.70 g/10 min and the complete analysis of which can be found in Appendix C. The slip additives tested in PP and ABS where also tested to investigate the improvement in the MFI of LLDPE. The MFI experiments of LLDPE blends containing 5% of each slip additive were performed at 190°C using a weight of 2.16 kg. The effectiveness of each slip additive in improving the MFI of LLDPE is illustrated in Figure 3.9. The analysis of each additive can be found in Appendix C.

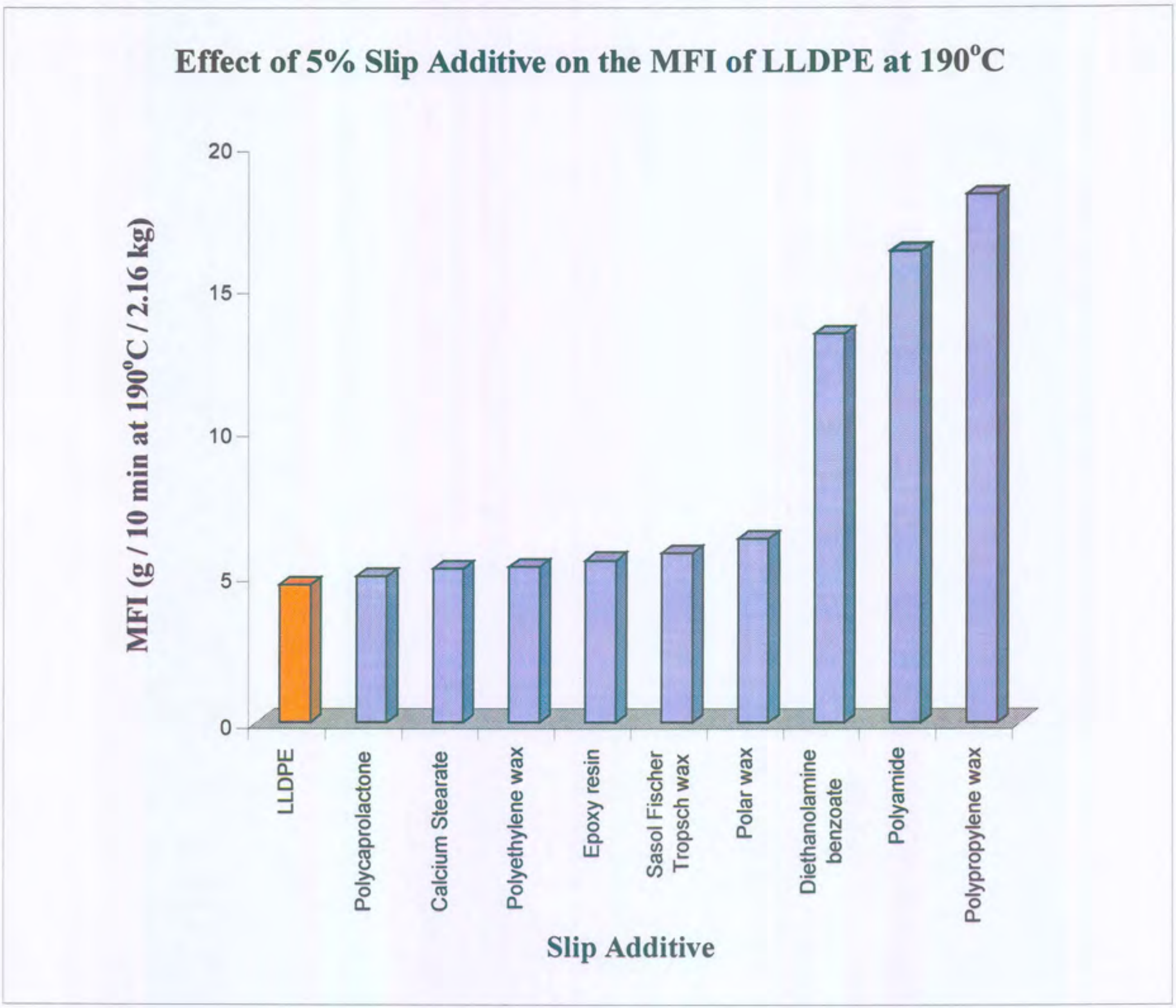

Figure 3.9: MFI results of slip additives at a level of 5% in LLDPE at 190°C / 2.16 kg

Figure 3.9 and 3.10 show the improvement in the MFI of LLDPE. Three additives viz., polypropylene wax, polyamide and diethanolamine benzoate increase the MFI of LLDPE significantly, as shown in Figure 3.9. The other additives show very little improvement in the MFI of LLDPE. The observed improvement in fluidity is attributed to two different mechanisms: Lubricants that are soluble in the polymer reduce the melt viscosity by acting as internal plasticizers (Gachter *et al.*, 1990). Immiscible lubricants act through the formation of a thin slip-layer on the channel wall that "lubricates" the main polymer flow (Ricco *et al.*, 2002; Govender *et al.*, 2002).

The observed increase in the MFI of LLDPE by those above-mentioned additives can be attributed to one of these mechanisms. However, those additives that do not show a significant increase in the MFI, for example, polyethylene wax and epoxy resin may not be as effective via either of these mechanisms. Those slip additives showing an improvement in the MFI of LLDPE were investigated further. An experiment was conducted to investigate the effect of varying the concentration of the slip additives. The additives used in this experiment were those showing a significant increase in the MFI of LLDPE at 190°C / 2.16 kg viz., polyamide, polypropylene wax, diethanolamine benzoate (Figure 3.9). The Sasol Fischer Tropsch wax, which did not exhibit a significant increase in the MFI of LLDPE (Figure 3.9), was also included in this experiment. The amount of the slip additive used in the LLDPE-slip additive blend was varied from one to five percent. Figure 3.10 illustrates an increase in the resultant MFI of LLDPE with an increasing amount of slip additive. The MFI was measured at 190°C / 2.16 kg as shown in Figure 3.10.

From Figure 3.10, an increase in the concentration of each additive does show a proportional improvement in the MFI of LLDPE. However, this improvement with increasing concentration of the Sasol Fischer Tropsch wax, is not substantial and as a result the MFI of LLDPE containing 5% slip additive is minimal, as shown in Figure 3.9 and 3.10.

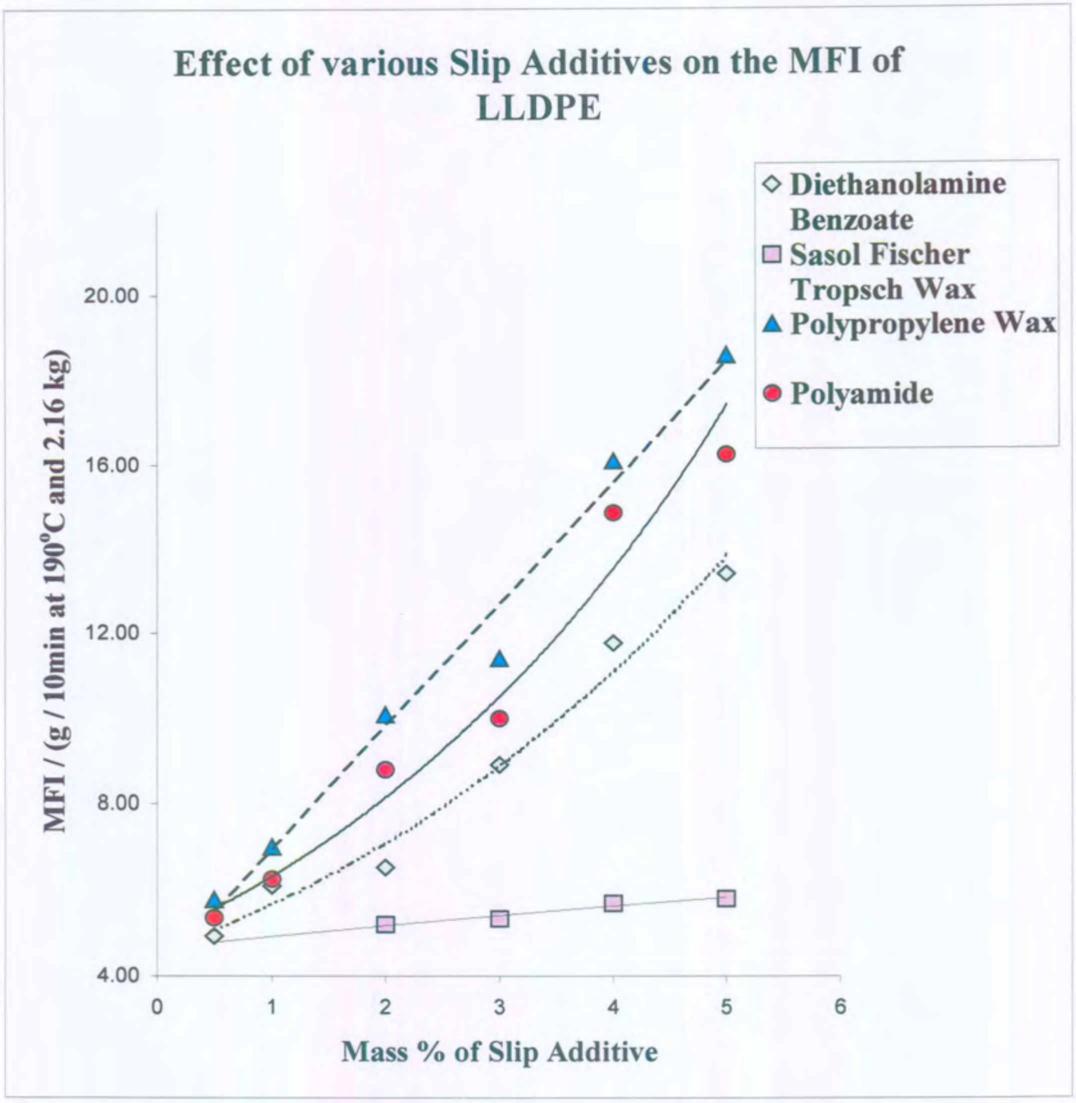

Figure 3.10: The effect of varying concentrations of slip additives on the MFI of LLDPE at 190°C / 2.16 kg

The increase in the MFI of LLDPE with increasing amounts of slip additives as shown in Figure 3.10, resulted in a further investigation into effect of the additives in combination. The use of slip additives in combination can have a synergistic or/and an antagonistic effect on the MFI has seen with polyamide and polar wax in PP (Figure 3.4). An experiment was conducted with two of the slip additives that improved the MFI of LLDPE at 190°C / 2.16 kg viz., polypropylene wax and polyamide. The concentration of each slip additives in the combination was varied to give a total additive concentration of 5%. The result of this analysis is illustrated in Figure 3.11.

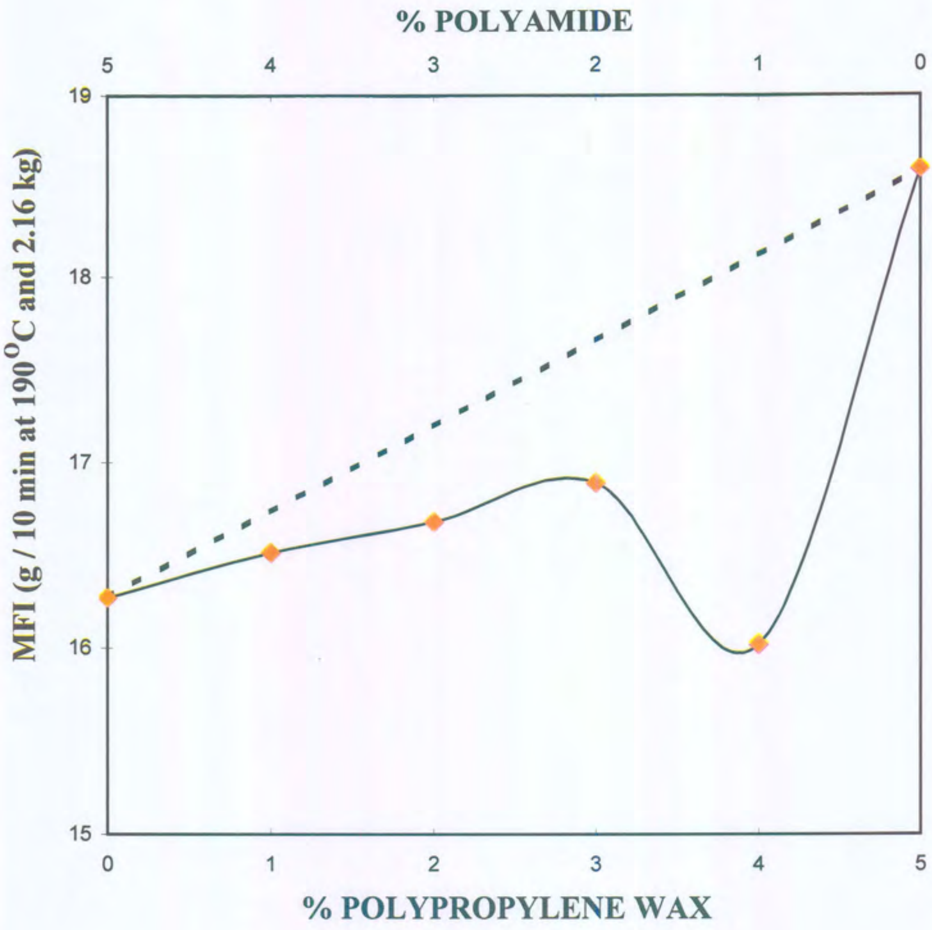

Figure 3.11: Antagonism between slip additives polyamide and polypropylene wax in LLDPE at 190°C / 2.16 kg

The additives in combination resulted in an antagonistic effect on the MFI of LLDPE (Figure 3.11). The antagonism can be rationalised by assuming that the combination has enhanced solubility. This combination of slip additives has a detrimental effect on the MFI, however, the right combination of additives can have the desired effect as was observed with the following experiment: A combination of various additives totalling 20% was mixed with LLDPE in a high-speed mixer and the effect on the MFI of LLDPE at 190°C using a weight of 2.16 kg was almost five fold. Table 3.3 and Table 3.4 show the amounts of the various additives used and the effect on the MFI of LLDPE at 190°C / 2.16 kg respectively.

Table 3.3: A combination of various additives and the quantity of each additive used in the study

Additive	Amount (g)
Calcium Stearate	0.50
Polypropylene wax	3.00
Orox PK	0.50
Super Special ($CaSO_4$)	3.00
Sasol Fischer Tropsch Wax	2.00
Wollasonite	1.00
LLDPE	40.00

Table 3.4: Effect on the MFI of LLDPE by a combination of additives (Table 3.3) at 190°C and weight of 2.16 kg

Time (s)	Mass (g)	MFI (g/10min)	Mean	SD
59.82	2.14	21.50	20.81	0.61
60.55	2.12	21.02		
60.15	2.09	20.83		
60.21	2.02	20.10		
60.10	2.01	20.07		
60.34	2.15	21.34		

3.3 Purging Trials

3.3.1 Results of Purge Trials Using a Blue EVA Master-batch

The initial trials used the slip additives, polyamide, polycaprolactone and polar wax. The slip additives where chosen due to their effectiveness in improving the MFI of LLDPE at 190°C / 2.16 kg (Figure 3.9). The data are plotted with respect to extruder volumes passed. This corresponds to, or is at least proportional to the dimensionless residence time. The blue colour of the films was imparted by use of a 70% blue EVA master-batch. The result obtained from this analysis is shown in Figure 3.12. The standard (blank) presented in Figure 3.12 contains no slip additives. It is clear from Figure 3.12 that the standard as well as the slip additives overlapped considerably.

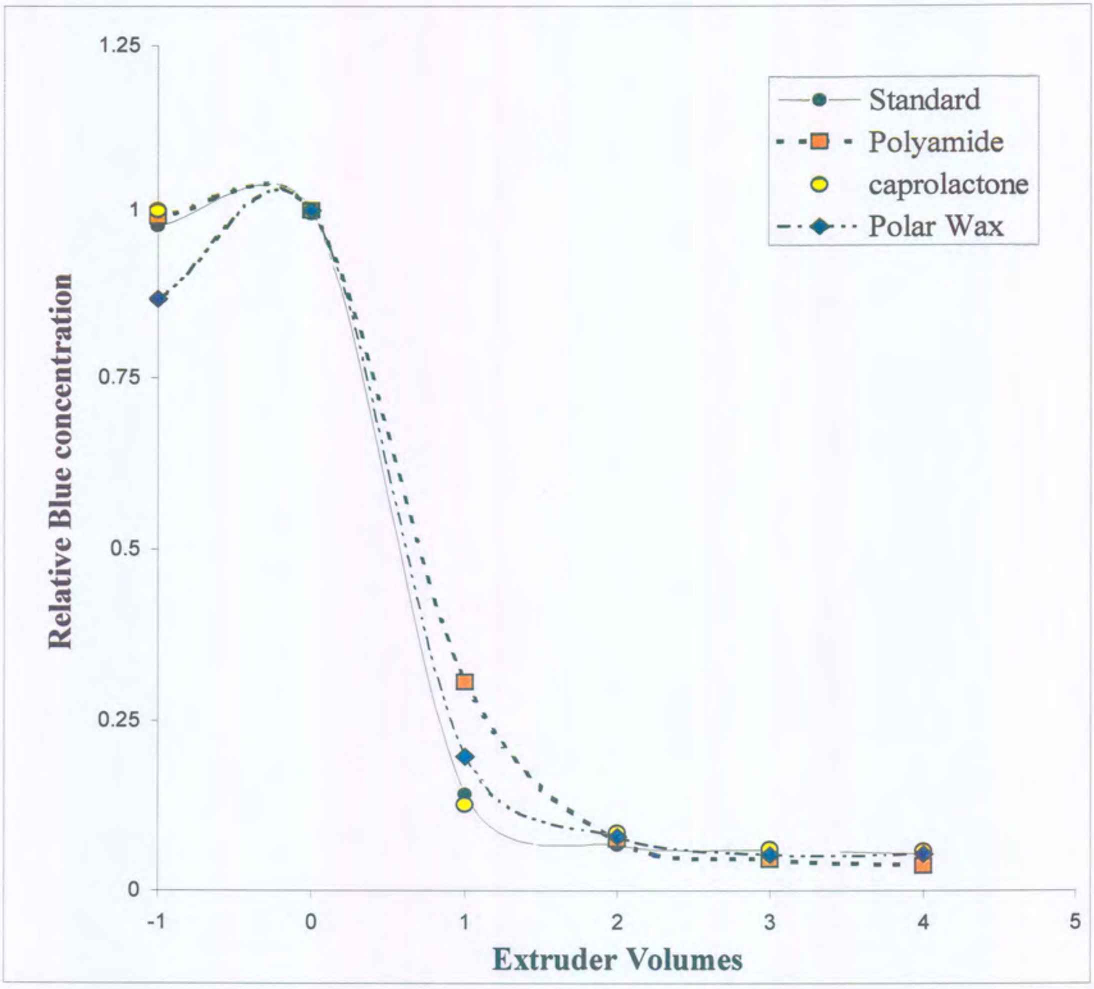

Figure 3.12: Resultant concentration curves of the standard and purges at 635 nm

From Figure 3.12, extruder volume *0* represents the end of the fifth volume of blue EVA pellets. Five extruder volumes of blue were used in order to obtain a consistent blue concentration value before the addition of any additives or the clear LDPE for the standard. Figure 3.12 shows an inconsistency in the blue concentration, visible at the end of extruder volume *–1* and *0*. This could be due to the ease at which the blue master-batch is removed or the variation in film thickness. The set of experimental data is reported in Appendix D1.

From Beer's Law, the absorbance is equal to the product of the concentration (c), path length (l) and the molar absorptivity constant (ε), i.e., from equation 1.17

$$A = \varepsilon c l$$

Which results in equation 2.1,

$$c = \frac{A}{\varepsilon l}$$

From equation 2.1, the concentration is inversely proportional to the path length. Therefore any variation in film thickness has an effect on the concentration. In the analysis shown in Figure 3.12, the path length was taken to be one. However this is not the case, in this study, the path length equates to the thickness of the polymer film being analysed. Due to the nature of the process as well as the constituents and chemical nature of the additives tested, it was difficult to maintain a film of even thickness throughout the length of the processed film.

To compensate for the variation in film thickness, a micrometer was used to determine the thickness of each polymer film analysed for absorbance. This value was then used as the path length to calculate the concentration of blue in each film. In the next set of experiments the thickness of each polymer film was taken into consideration during the calculation of the pigment concentration. Figure 3.13 is a representation of this analysis, taking into account the thickness of the polymer films. The concentration at the different extruder volumes as shown in Figure 3.13 as well as the calculations can be found in the Appendix D2.

Figure 3.13 shows a sharp decrease in the concentration between extruder volume *0* and *1*. Extruder volume *1* represents the volume containing the slip additive (5%) and clear LDPE pellets. The slip additives tested in this experiment were polyamide, polar wax, polycaprolactone and atactic polypropylene. The concentration after the end extruder volume *2* for each additive as well as the standard shows a plateau. This plateau after only extruder volume *2*, shows that the blue master-batch is easily removed.

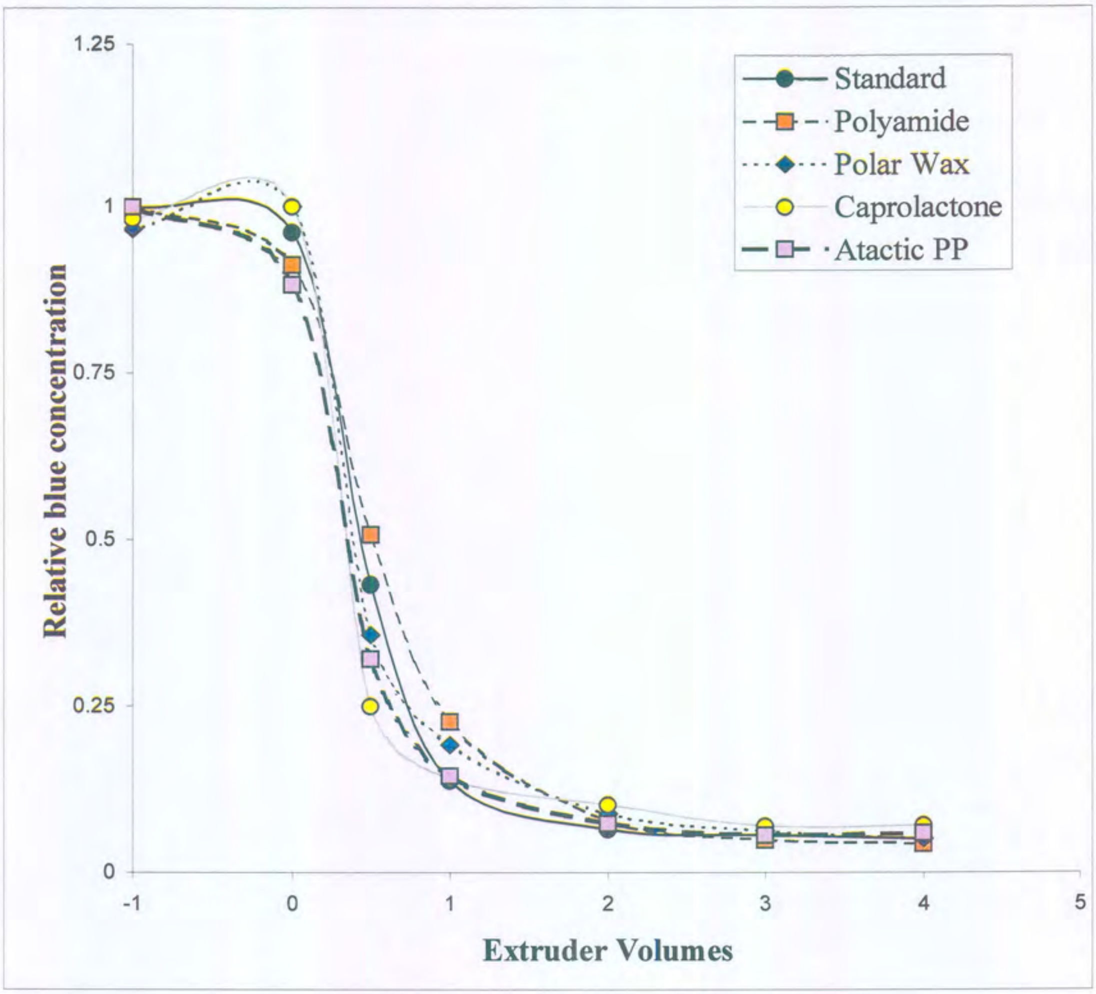

Figure 3.13: Resultant concentration curves of the standard and purges at 635 nm. The concentration presented accommodates for the variation in film thickness.

The next set of experiments made use of just two slip additives, viz., polycaprolactone and the polar wax. The results of which are shown in Figure 3.14. In this particular analysis, concentration values were also obtained at each quarter between extruder volumes *0* and *1* since the largest drop in concentration is observed between these extruder volumes. This experiment also takes into account the observed concentration of the clear polymer film. The concentrations shown in Figure 3.14 are calculated by subtracting the average clear concentration from the absorbance. This value is then divided by the difference between the maximum blue and minimum clear obtained for this set of experiments. After the first quarter, the polar wax shows a significantly lower concentration of pigment, when compared to the standard and the other slip additive, polycaprolactone as shown in Figure 3.14. However, for the rest of the volumes, the overlap of the concentrations makes it difficult to determine the efficiency of the slip additives. The complete analysis can be found in Appendix D3.

3.3.2 Results of Purge Trials Using a Phthalocyanine Blue Pigment

Before conducting any further purging trials, the amount of pigment to be used had to be determined. The results of the trials containing varying amounts blue pigment are presented in Figure 3.15 to 3.19. The data are plotted with respect to extruder volumes passed. This corresponds to, or is at least proportional to the dimensionless residence time. There is a decrease in the pigment concentration with increasing extruder volumes as shown in Figures 3.15 to 3.19. The aim of varying the pigment concentration was to obtain the ideal pigment concentration that shows significant separation between the purge and the standard. The purging compound presented in Figures 3.15 to 3.19 is a purge based on a corrosion inhibitor and the standard contains no purge compound.

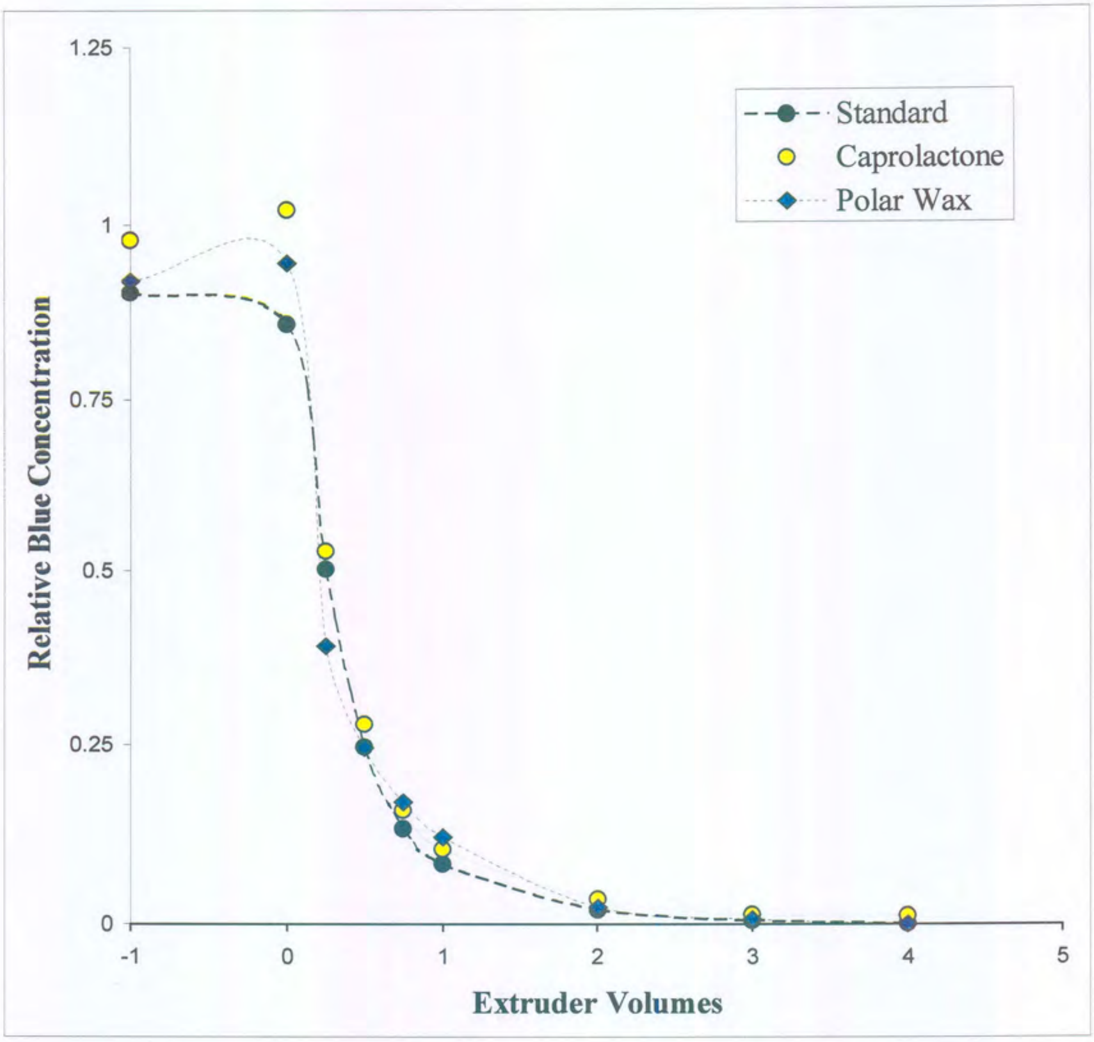

Figure 3.14: Resultant concentration curves of the standard and purges at 635 nm

Figures 3.15 and 3.16 are the purge trials containing 10% and 20% blue pigment respectively. The difference in concentration from one extruder volume to the next is more pronounced in the 20% blue pigment addition at the higher extruder volumes as shown in Figure 3.16. An increase in the amount of pigment in the extruder may require a longer time period for any difference to be observed as shown in Figures 3.17 and 3.18, containing 30% and 40% pigment, respectively. Too much of pigment in the analysis results in the rupturing of the polymer film making analysis of the initial extruder volumes not possible as shown in Figures 3.18 and 3.19 i.e., no data available for the initial extruder volumes. Figure 3.19 is the analyses of the purge trail incorporating 40% LDPE powder instead of LDPE pellets.

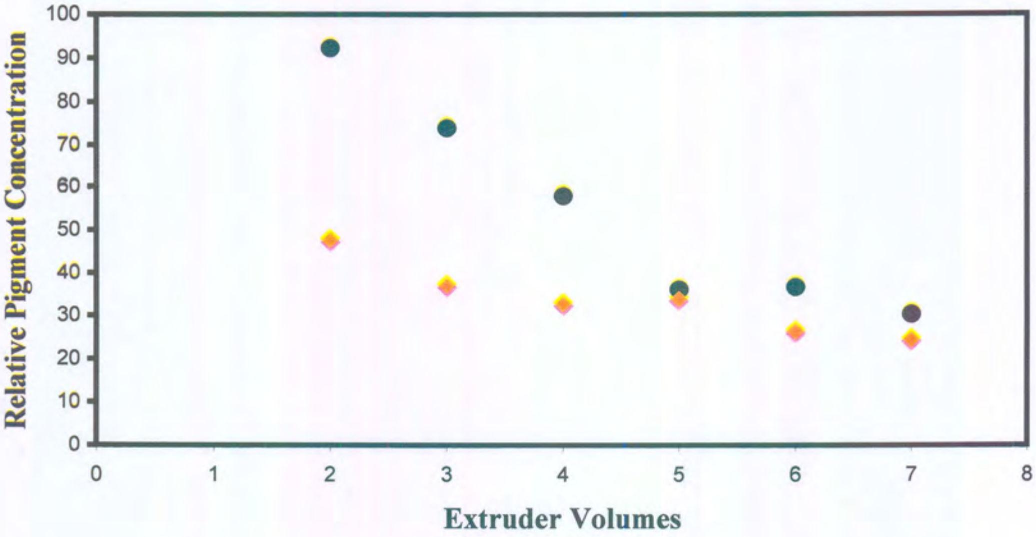

Figure 3.15: Purging trials incorporating a mixture of 10% blue pigment and 90% LDPE pellets. Standard (●) and Purge (◆)

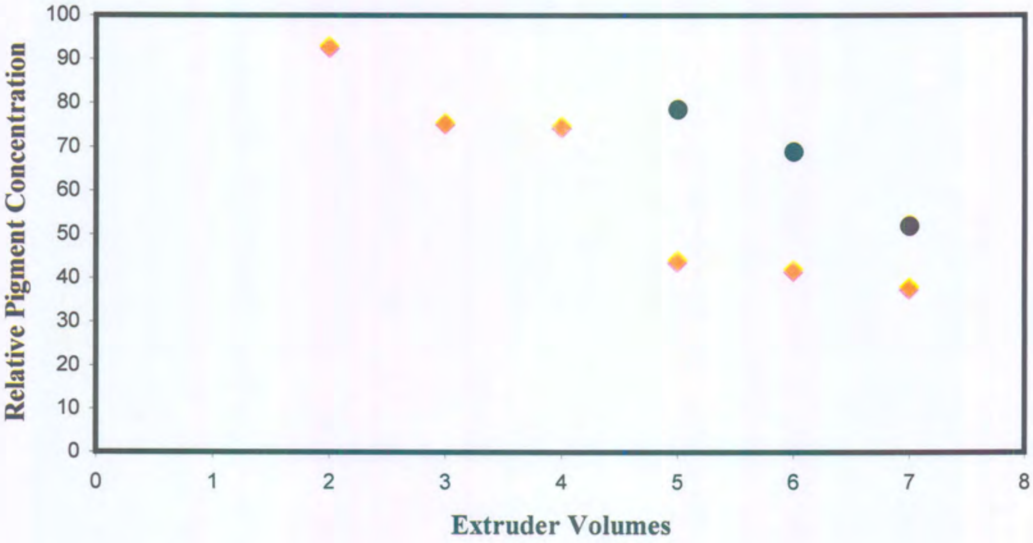

Figure 3.16: Purging trials incorporating a mixture of 20% blue pigment and 80% LDPE pellets. Standard (●) and Purge (◆)

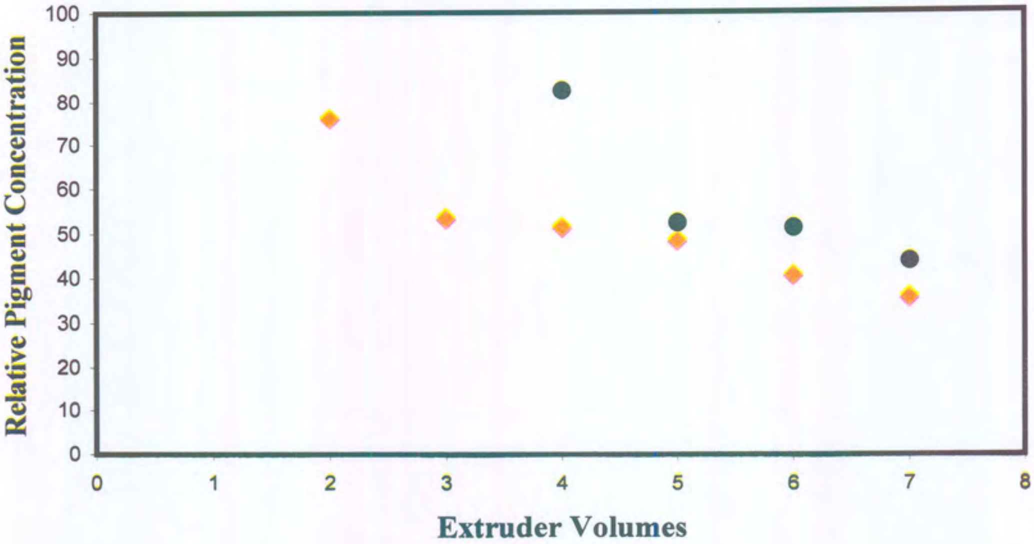

Figure 3.17: Purging trials incorporating a mixture of 30% blue pigment in 70% LDPE pellets. Standard (●) and Purge (◆)

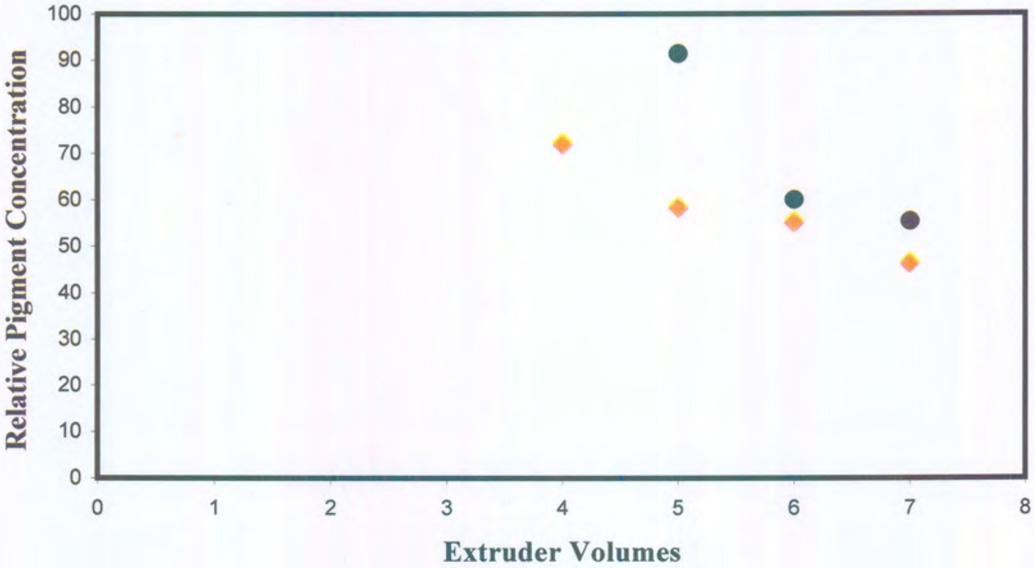

Figure 3.18: Purging trials incorporating 40% blue pigment in 60% LDPE pellets. Standard (●) and Purge (◆)

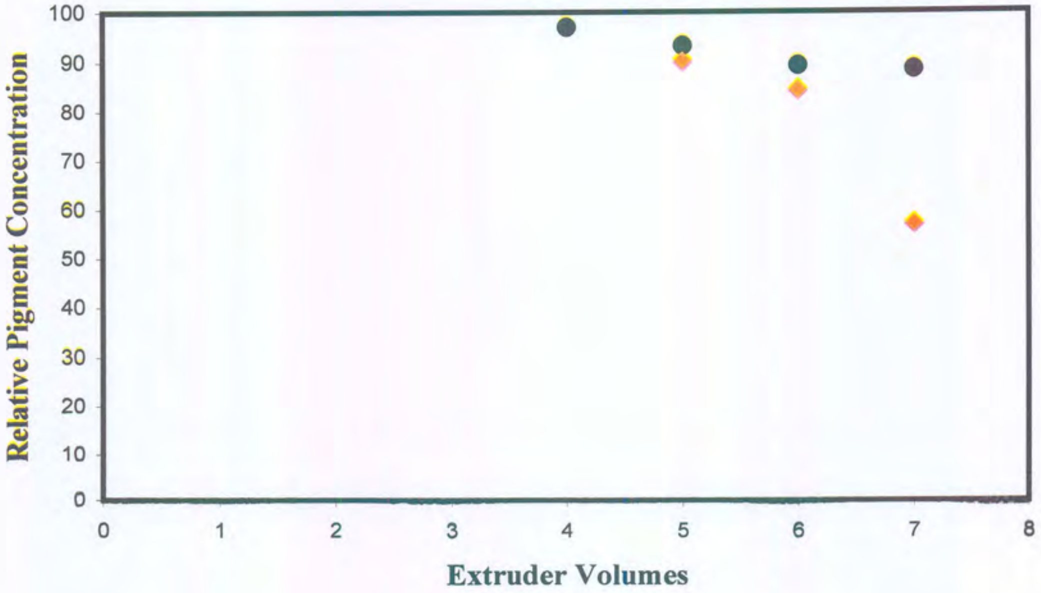

Figure 3.19: Purging trials incorporating a mixture of 40% blue pigment LDPE powder. Standard (●) and Purge (◆)

The purging trials of the commercial purges are presented in Figure 3.20. It is clear from Figure 3.20 that all the commercial purge compounds tested in this study improved the purging times with respect to the standard where no purge was used. The most effective of the purge compounds, purge D, is based on a filled compound using a scuffing or abrasive action. Concentration data for purge D was only obtained for extruder volumes *6* and *7*, as shown in Figure 3.20, due to the rupturing of the polymer film.

Figure 3.21 shows the purging results for 5% the addition of slip additive. The slip additives appear to have a significant purging effect as well. The slip additives used in the purging trail are polyamide and polypropylene wax. The concentrations at the respective extruder volumes for each purging trial can be obtained in Appendix D4.

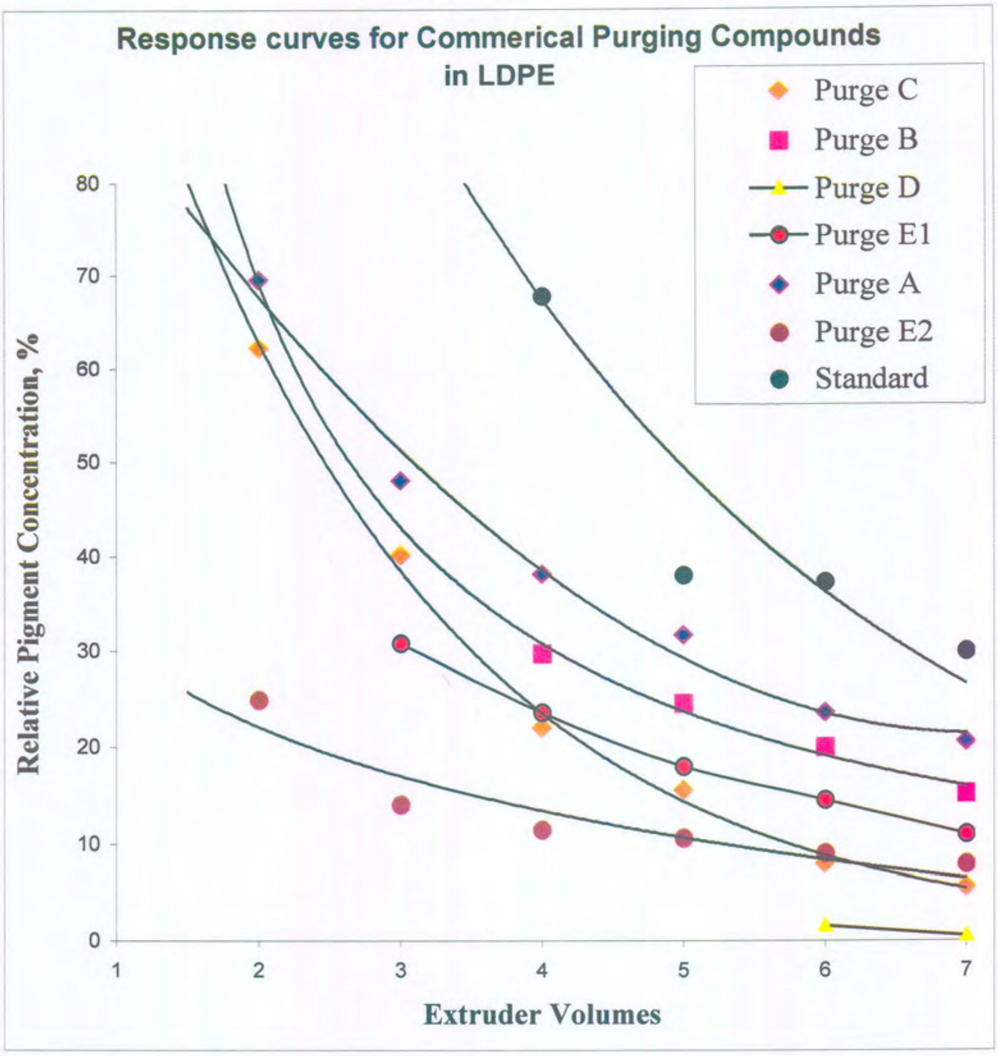

Figure 3.20: The response curves for the different commercial purging compounds

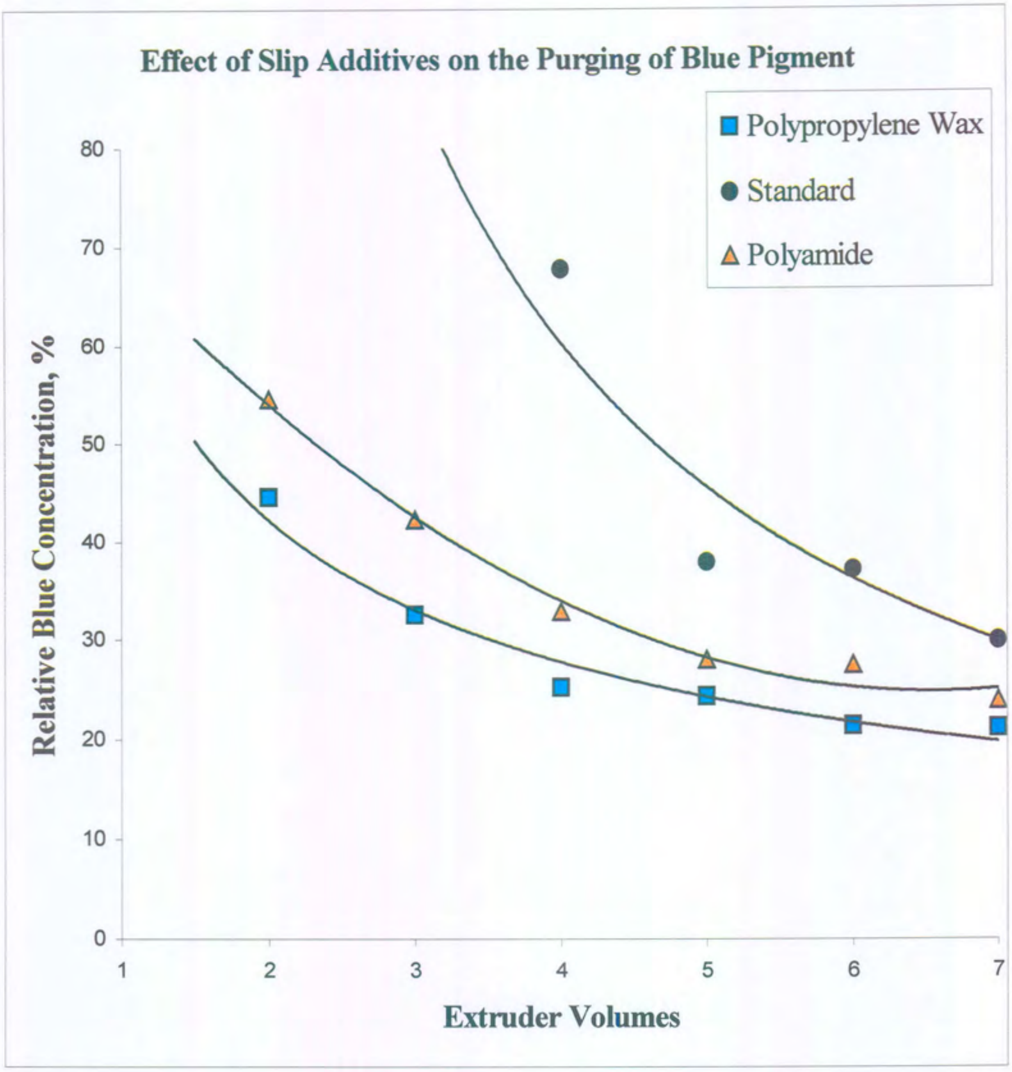

Figure 3.21: The effect of slip additives on the purging of blue pigment

CHAPTER 4

CONCLUSION

The melt flow index (MFI) is a direct measure of the fluidity of the polymer melt expressed in terms of the mass flow per unit time. The flow condition in the MFI tester is that of pure pressure flow through a circular capillary tube. This represents an idealisation of the flow pattern in the die-head of the extruder. Some of the various slip additives tested in this study do show an improvement in the MFI of polyethylene (linear-low density), polypropylene and ABS. The observed improvement in the fluidity is attributed to two different mechanisms: Lubricants that are soluble in the polymer melt reduce the effective viscosity by acting as internal plasticisers. Immiscible lubricants act through the formation of a thin slip-layer on the channel wall that "lubricates" the main polymer flow. One such example is polypropylene wax, which is incompatible with molten polyethylene and acts as an external lubricant.

The external lubricants investigated in this study appear to have a more significant influence on the MFI than the internal lubricants. Polypropylene wax was found to be an excellent lubricant for both polyethylene and ABS. The polyamide resin is a good lubricant for all three polymers, whereas polycaprolactone appears to be compatible with all of them. Interestingly, low molar mass polymeric additives performed better than those based on small molecules such as stearamide. This suggests that optimal lubrication requires a certain minimum viscosity for the slip additive.

Application of purge compounds allows rapid colour and material changes in plastics converting machines. They have both a cleaning and a purging action. In this study it was postulated that slip flow patterns could contribute to the purging action. This implies that the cleaning and purging functions can have conflicting requirements with respect to the wall shear stress. However, the slip additives tested in this study showed only limited purging efficacy.

Commercial purge products function according to additional methods including filler abrasion, solvent dissolution and the dislodging of deposits with the aid of surfactants. Several different commercial purge compounds were tested for their colour change efficiency using polyethylene and switching from blue to clear in a laboratory film blower. All commercial purge compounds tested improved purging times with respect to the standard run where no purge was used. The products based on a scrubbing or scuffing mechanism in combination with surfactants clearly outperformed the other types, i.e. they were more effective at removing a blue colour from the film blowing extruder.

The aim of the adhesion experiments was to identify the constituents of the CSIR purging compound that cause it to adhere to hot metal surfaces in extruders. It was found that many of the constituents on their own, as well as the base polymer, polyethylene, adhere significantly to hot mild steel plates. Furthermore, when the additives were compounded at 10% (by mass) in the polyethylene as carrier, adhesion was enhanced. Lap-shear adhesion test results showed that the metal adhesion could be reduced significantly by substituting the polyethylene carrier with polypropylene.

References:

1. Ashok, B. K. and G. A. Campbell; "Viscoelastic Model for a Two-Phase Simulation of Tubular Film Blowing," *Intern. Polym. Proc.*, **7**, 240-245, 1992
2. Ast, W.; "Theory and Experimental of Film Blowing," PhD Thesis, IKT Stuttgart, 1976
3. Bailey, F. W.; "Process for Cleaning Polymer Processing Equipment," US Patent No. 4,838,948, 1989.
4. Botros, M. G.; "Purging Compound for Polyamides and Ethylene vinyl Alcohol Copolymers," *J. Plastic Film Sheet.,* **12**, 212-224, 1996
5. Cain, J. J. and M. M. Denn; "Deformation and Temperature Profiles for a Newtonian, an Upper Upper Convected Maxwell and a Marruci Fluid," *Polym. Eng. Sci.*, **28**, 1527-1531, 1988.
6. Cao, B. and G. A. Campbell; "A Plastic Elastic Transition for Kinetic and Rheological Boundaries," *J. AIChE.*, **36**, 420-425, 1990.
7. Cao, B., P. Sweeney and G. A. Campbell; "Infra-red radiation Technique for Measurement of Bulk Temperatures," *J. Plastic Film Sheet.*, **6**, 117-122, 1990.
8. Choi, K. J., J. L. White and J. E. Spruiell; "OrientationDevelopment in Tubular Film Extrusion of Polystyrene," *J. Appl. Polym. Sci.*, **20**, 2777-2782, 1980.
9. Choi, K. J., J. L. White and J. E. Spruiell; *J. Appl. Polym. Sci.*, **25**, 27-33, 1982.
10. Christian, G. D; "Analytical Chemistry," John Wiley & Sons, New York, 3rd edition, 369-388, 1980.
11. Cohen, E. and E. Gutoff; "Modern Coating and Drying Technology," VCH Weinheim, 54-61, 1992.
12. Fenner, R. T.; "Principles of Polymer Processing," Processing Properties of Polymers, Chemical Publishers, New York, 16-23, 1985.

13. Fisher, E.; "Model of Film Blowing and Products," PhD Thesis, IFT Stuttgart, 1983.
14. Fujii, H., H. Takamichi, I. Haruhiko and I. Nobusuke; "Thermoplastic Resin Composition for Cleaning," US Patent No. 4,838,945, 1989.
15. Gachter, R. and H. Muller; "Lubricants and Related Auxiliaries for Thermoplastic Materials," Plastics Additives Handbook, Hanser Publishers, New York, 302-303, 1990.
16. Galli, E.; "Purging Compounds," *Plastics Compounding*, **10**, 15-16, 18, 20, 1987.
17. Gogos, C. G., D. M. Kaylon, P. Hold and J. A. Beisenberger; "Polymer Processing: An Overview," *Chem. Eng. Prog.*, **33**, 33-58, 1987.
18. Govender, M., W. W. Focke, A. T. Tolmay and D. Graeffe; "Evaluation of Commercial Plastics Purging Compounds on a Laboratory Film Blower," *South African Journal of Chemical Eng.*, **14 (1)**, 16-27, 2002.
19. Gupta, R. K.; "A New Non-isothermal Rheological Constitutive Equation and its Application to Industrial Film Blowing Processes," PhD Thesis, University of Delaware, 1980.
20. Han, C. D. and J. Y. Park; *J. Appl. Polym. Sci.*, **19,** 3277-3280, 1975a.
21. Han, C. D. and J. Y. Park; *J. Appl. Polym. Sci.*, **19**, 3257-3260, 1975b.
22. Ives, G. C.; "Handbook of Plastics Test Methods," Butterworth Group, London, 88-95, 1971.
23. Kanai T., J. L. White; "Thermodynamic Aspects in Extrusion of Wall-Slipping Materials," *Polym. Eng. Sci.*, **5**, 135-136, 1985.
24. Kanai T., J. L. White; *Polym. Eng. Sci.*, **24,** 1185-1190, 1988.
25. Kemblowski, Z. and J. Sek; "Residence Time Distribution in a Real Single Screw Extruder," *Polym. Eng. Sci.*, **21**, 1194-1202, 1981.

26. Kmiec, C. J.; "Cleaning Composition for Resin Processing Equipment," US Patent No. 5,139,694, 1992.

27. Knowles, S. and C. Burgess; "Practical Absorption Spectroscopy," Chapman and Hall, London, 1- 6, 1984.

28. Leung, P. S., P. E. Ramdatt and R. E. King; "Purging Compound for Cleaning Thermoplastic Processing Equipment," US Patent No. 5,236,514, 1993.

29. Luo, X. L. and R. I. Tanner; *Polym. Eng. Sci.*, **25**, 620-625, 1985.

30. Miller, D. N.; "Composition Comprising a Mixture of Thermoplastic Polymers for Internal Cleaning of Extruders," US Patent No. 3,869,525, 1975.

31. Obama, K., H. Takasu, S. Arase and H. Fujii; "Cleaning Resin Compositions," US Patent No. 5,087,653, 1992.

32. Oonk, J.; "Kunstoffe Magazine," **6/7**, 18-21, June/July, 1994.

33. Pearson, J. R. A. and C. J. S. Petrie; *J. Fluid Mech.*, **40**, 1-7, 1970b.

34. Pearson, J. R. A. and C. J. S. Petrie; *J. Fluid Mech.*, **42**, 609-614, 1970c.

35. Pearson, J. R. A. and C. J. S. Petrie; "Plastics and Polymers," 85, April 1970a.

36. Petrie, C. J. S.; *J. AIChE.*, **21**, 275-279, 1975.

37. Petrie, C. J. S.; *Rheol. Acta.*, **12**, 92-94, 1973.

38. Ricco, I., K. Karakatsanis, A. Arlow, M. Govender and W. W. Focke; "The effect of Polymer Lubricant Additives on Pressure and Drag induced Flows in Circular Tubes and Parallel Plate Channels," submitted for publication, 2003.

39. Ross, S. and I. D. Morrison; Colloidal System and Interfaces, Wiley, New York, 1988.

40. Scheibelhoffer, A. S., D. B. Dusek, D. L. Hammond, S. Wimolkiatisak, W. R. Meyers, R. J. Opalko and R. L. Abrams; "Abrasive and Purge Compositions," US Patent No. 5,443,768, 1995.

41. Schenkel, G.; Technology and Theory, Elsevier Publishing, New York, 57-90, 1966.

42. Simpson, D. A.; "Study of the Effects of Processing Parameters on the Morphologies and Mechanical Properties of Polyethylene blown Films," PhD Thesis, University of Pennsylvania State, 1993.

43. Thomas, M. J. K.; "Ultraviolet and Visible Spectroscopy," John Wiley & Sons, Chichester, 2nd edition, 35-66, 1996.

44. Wagner, M. H.; *Rheol. Acta.*, **15**, 40-43, 1976.

45. Wake, W. C.; *Polymer,* 19, 291, 1978.

46. Walsh, W. C., T. A. Hazenstab and M. W. Waldrop; "Substituted Pyrolidone Plasticized Thermoplastic Resin useful as a Plastic Processing Equipment Cleaning Compound," US Patent No. 6,001,188, 1999.

47. White J. L. and M. Cakmak; "Specification of Biaxial Deformation in Amorphous and Crystalline Polymers," *Adv. Polym. Technol.*, **8**, 27-30, 1988.

APPENDIX A
POLYPROPYLENE

Analysis of PP @ 190°C and weight of 2.16kg
Polypropylene with no additives and with 5 % of various additives

Time (s)	Mass (g)	MFI (g/10min)	Mean	SD
60.39	0.4697	4.67	**5.06**	**0.5**
59.93	0.4815	4.82		
59.91	0.5678	5.69		
59.79	0.4440	4.46		
60.00	0.5162	5.16		
59.20	0.5494	5.57		

PP + 5% PP Wax

Time (s)	Mass (g)	MFI (g/ 10 min)	Mean	SD
59.79	0.57	5.74	6.58	0.60
59.51	0.63	6.39		
59.72	0.64	6.48		
60.20	0.63	6.32		
60.14	0.73	7.28		
59.65	0.72	7.29		

PP + 5% Caprolactone

Time (s)	Mass (g)	MFI (g/ 10 min)	Mean	SD
59.87	0.68	6.76	6.52	0.31
59.85	0.69	6.89		
60.39	0.66	6.57		
59.50	0.59	6.00		
59.65	0.64	6.40		
59.87	0.65	6.50		
59.91	0.62	6.25		

PP + 5% Polyethylene Wax

Time (s)	Mass (g)	MFI (g/ 10 min)	Mean	SD
59.63	0.68	6.89	7.07	0.57
59.97	0.73	7.35		
59.82	0.65	6.57		
59.81	0.73	7.33		
60.41	0.79	7.89		
60.39	0.64	6.36		

PP + 5% Fischer Tropsch Wax

Time (s)	Mass (g)	MFI (g/ 10 min)	Mean	SD
59.31	0.69	6.97	6.91	0.36
60.36	0.64	6.37		
60.14	0.69	6.85		
59.79	0.72	7.23		
59.52	0.66	6.68		
59.83	0.73	7.36		
59.67	0.76	7.65		

PP + 5% Calcium Stearate

Time (s)	Mass (g)	MFI (g/ 10 min)	Mean	SD
59.73	0.58	5.84	6.1	0.24
60.08	0.61	6.07		
59.65	0.62	6.27		
59.61	0.63	6.35		
60.62	0.58	5.79		
59.62	0.62	6.29		

PP + 5% Orox PK

Time (s)	Mass (g)	MFI (g/ 10 min)	Mean	SD
60.08	0.67	6.71	7.13	0.64
59.56	0.66	6.68		
59.8	0.74	7.46		
60.26	0.77	7.7		
59.88	0.63	6.32		
59.37	0.78	7.88		

5% Polyamide in PP

Time (s)	Mass (g)	MFI (g/10min)	Mean	SD
59.74	0.6572	6.6	**8.47**	**1.6**
59.92	0.6544	6.55		
59.39	0.8152	8.24		
59.85	1.0029	10.05		
62.06	0.8171	7.89		
59.73	0.9488	9.53		
59.84	1.0418	10.44		

PP + 5% Stearamide

Time (s)	Mass (g)	MFI (g/ 10 min)	Mean	SD
59.9	0.66	6.62	7.02	0.62
59.62	0.73	7.38		
61.24	0.63	6.13		
59.74	0.76	7.61		
59.39	0.76	7.67		
59.62	0.67	6.71		

PP + 5% GMS 900V

Time (s)	Mass (g)	MFI (g/ 10 min)	Mean	SD
63.06	0.73	6.94	7.06	0.36
59.46	0.72	7.26		
60.13	0.76	7.61		
58.76	0.7	7.1		
59.68	0.65	6.54		
60.63	0.7	6.89		

PP + 5% Makeean Polymer

Time (s)	Mass (g)	MFI (g/ 10 min)	Mean	SD
59.78	0.61	6.11	6.22	0.24
60.31	0.64	6.38		
60.09	0.61	6.05		
59.81	0.59	5.89		
59.87	0.63	6.36		
60.19	0.65	6.51		
59.92	0.66	6.57		

5% Polar Wax in PP

Time (s)	Mass (g)	MFI (g/10min)	Mean	SD
59.99	0.7745	7.75	**8.25**	**0.7**
60.34	0.8506	8.46		
59.71	0.943	9.48		
59.67	0.7742	7.79		
60.62	0.8677	8.59		
59.58	0.7361	7.41		
59.52	0.813	8.2		

Polyamide and Polar Wax in combination (5%) in Polypropylene

4% Polyamide + 1% Polar Wax in PP				
Time (s)	**Mass (g)**	**MFI (g/ 10 min)**	**Mean**	**SD**
60.14	0.93	9.24	11.16	1.66
60.10	0.98	9.78		
59.72	1.24	12.43		
59.94	1.17	11.72		
59.70	1.05	10.28		
59.62	1.34	13.50		

3% Polyamide + 2% Polar Wax in PP				
Time (s)	**Mass (g)**	**MFI (g/ 10 min)**	**Mean**	**SD**
60.68	1.13	11.14	11.40	0.33
59.80	1.11	11.10		
60.43	1.16	11.50		
60.25	1.18	11.80		
59.61	1.17	11.76		
59.71	1.11	11.12		

2% Polyamide + 3% Polar Wax in PP				
Time (s)	**Mass (g)**	**MFI (g/ 10 min)**	**Mean**	**SD**
59.94	0.61	6.15	7.62	0.86
60.36	0.81	8.06		
60.03	0.87	8.67		
59.63	0.77	7.71		
61.02	0.80	7.90		
59.76	0.72	7.21		

1% Polyamide + 4% Polar Wax in PP				
Time (s)	**Mass (g)**	**MFI (g/ 10 min)**	**Mean**	**SD**
59.95	0.64	6.41	7.61	0.97
60.04	0.85	8.51		
59.90	0.74	7.41		
60.84	0.89	8.78		
59.71	0.66	6.64		
60.53	0.80	7.92		

Analysis of PP @ 210°C and weight of 2.16kg

Polypropylene with no additives and with 5 % of various additives

Time(s)	Mass (g)	MFI (g/10min)	Mean	SD
59.59	1.046	10.53	10.6	0.3
59.93	1.112	11.14		
59.39	1.070	10.80		
59.2	1.036	10.50		
59.89	1.054	10.56		
60.95	1.053	10.36		
PP + 5% Polypropylene Wax				
Time (s)	**Mass (g)**	**MFI (g/10min)**	**Mean**	**SD**
59.97	1.23	12.30	11.95	1.07
60.05	1.37	13.66		
60.09	1.18	11.77		
59.89	1.27	12.76		
59.64	1.10	11.08		
59.46	1.15	11.60		
59.96	1.05	10.47		
PP + 5% Caprolactone				
Time (s)	**Mass (g)**	**MFI (g/10min)**	**Mean**	**SD**
60.42	1.61	16.03	13.67	1.30
60.11	1.41	14.12		
60.15	1.23	12.31		
60.73	1.33	13.11		
59.48	1.29	13.04		
60.15	1.34	13.38		
PP + 5% Diethanolamine Benzoate				
Time (s)	**Mass (g)**	**MFI (g/10min)**	**Mean**	**SD**
59.73	0.80	8.04	8.34	0.36
60.06	0.77	7.73		
59.64	0.86	8.67		
60.05	0.84	8.39		
59.79	0.86	8.67		
61.36	0.84	8.25		
59.55	0.86	8.62		

PP + 5% Polyethylene Wax				
Time (s)	**Mass (g)**	**MFI (g/10min)**	**Mean**	**SD**
59.56	0.96	9.65	10.35	0.67
59.58	0.98	9.82		
59.72	0.97	9.78		
60.19	1.11	11.03		
59.79	1.10	11.08		
59.69	1.07	10.74		
PP + 5% Polyamide				
Time (s)	**Mass (g)**	**MFI (g/10min)**	**Mean**	**SD**
59.25	1.09	11.02	10.61	0.30
60.04	1.04	10.43		
59.17	1.04	10.57		
58.85	1.02	10.41		
59.47	1.08	10.94		
60.06	1.03	10.28		
PP + 5% Stearamide				
Time (s)	**Mass (g)**	**MFI (g/10min)**	**Mean**	**SD**
60.00	1.24	12.38	11.27	0.68
59.48	1.16	11.68		
59.77	1.10	11.03		
59.88	1.06	10.57		
62.67	1.11	10.66		
59.23	1.12	11.31		
PP + 5% Calcium Stearate				
Time (s)	**Mass (g)**	**MFI (g/10min)**	**Mean**	**SD**
59.48	0.95	9.59	8.67	1.07
60.14	0.93	9.27		
60.23	0.99	9.82		
59.45	0.84	8.48		
60.29	0.75	7.47		
59.66	0.73	7.37		

PP + 5% GMS 900V

Time (s)	Mass (g)	MFI (g/10min)	Mean	SD
59.47	1.08	10.94	11.25	0.60
60.01	1.06	10.63		
60.09	1.23	12.28		
60.06	1.15	11.45		
59.68	1.13	11.37		
60.64	1.09	10.81		

PP + 5% Fischer Tropsch Wax

Time (s)	Mass (g)	MFI (g/10min)	Mean	SD
59.55	1.14	11.50	11.51	0.84
60.18	1.14	11.39		
60.00	1.12	11.22		
59.52	1.13	11.34		
59.83	1.30	13.07		
60.13	1.05	10.54		

PP + 5% Orox PK

Time (s)	Mass (g)	MFI (g/10min)	Mean	SD
59.85	0.98	9.84	11.14	1.23
59.37	1.11	11.22		
60.08	1.27	12.72		
59.61	1.05	10.54		
60.17	1.01	10.03		
60.37	1.25	12.47		

PP + 5% Polar Wax

Time (s)	Mass (g)	MFI (g/10min)	Mean	SD
59.65	1.06	10.65	12.53	1.46
59.71	1.18	11.85		
60.14	1.46	14.58		
59.30	1.38	13.95		
59.46	1.22	12.33		
59.79	1.18	11.85		

PP + 5% Magnesium Stearate

Time (s)	Mass (g)	MFI (g/10min)	Mean	SD
60.17	1.02	10.17	10.35	0.56
59.64	1.01	10.11		
59.91	1.06	10.59		
60.73	0.96	9.45		
59.65	1.08	10.86		
59.61	1.09	10.93		

Analysis of PP @ 230°C and weight of 2.16kg

Polypropylene with no additives and with 5 % of various additives

Time (s)	Mass (g)	MFI (g/10 min)	Mean	SD
60.31	1.64	16.29	14.65	1.4
60.46	4.54	15.25		
60.46	1.30	12.93		
59.95	1.59	15.95		
60.70	1.43	14.17		
60.09	1.34	13.33		

PP + 5% Polyamide

Time (s)	Mass (g)	MFI (g/10 min)	Mean	SD
60.12	1.64	16.35	19.04	3.2
59.78	1.77	17.75		
59.91	1.50	15.06		
59.36	2.08	21.03		
59.79	2.04	20.48		
59.92	2.35	23.57		

PP + 5% Polar Wax

Time (s)	Mass (g)	MFI (g/10 min)	Mean	SD
59.89	1.68	16.79	15.95	2.3
60.03	1.41	14.13		
60.10	1.68	16.75		
60.03	1.35	13.52		
59.46	1.95	19.68		
59.50	1.47	14.83		

APPENDIX B
ACRYLONITRILE BUTADIENE STYRENE (ABS)

Analysis of ABS @ 210°C and weight of 5 kg

ABS (no additives) and with 5% of various additives

Time (s)	Mass (g)	MFI (g/10min)	Mean	SD
60.34	0.29	2.88	**3.1**	**0.3**
60.07	0.27	2.73		
59.97	0.33	3.29		
60.05	0.32	3.19		
60.03	0.33	3.32		
ABS + 5% PP Wax 230				
Time (s)	**Mass (g)**	**MFI (g/10 min)**	**Mean**	**SD**
59.81	2.27	22.77	23.14	0.40
59.96	2.29	22.95		
44.17	1.75	23.71		
59.97	2.31	23.13		
ABS + 5% Fisher Tropsch Sasol Wax				
Time (s)	**Mass (g)**	**MFI (g/10 min)**	**Mean**	**SD**
61.14	1.48	14.55	14.72	0.21
59.92	1.47	14.77		
60.17	1.50	15.00		
59.85	1.45	14.56		
ABS + 5% Calcium Stearate				
Time (s)	**Mass (g)**	**MFI (g/10 min)**	**Mean**	**SD**
64.36	1.70	15.88	16.73	1.36
60.23	1.53	15.27		
59.87	1.76	17.65		
59.8	1.80	18.10		
ABS + 5% Epoxy Resin				
Time (s)	**Mass (g)**	**MFI (g/10 min)**	**Mean**	**SD**
60.11	1.24	12.41	11.23	1.41
59.94	1.23	12.39		
59.07	0.94	9.55		
117.79	2.07	10.57		

ABS + 5% Polycaprolactone

Time (s)	Mass (g)	MFI (g/10 min)	Mean	SD
64.52	0.93	8.66	8.35	0.68
58.79	0.86	8.83		
60.1	0.76	7.57		

ABS + 5% Polyethylene Wax

Time (s)	Mass (g)	MFI (g/10 min)	Mean	SD
60.68	0.54	5.33	5.38	0.10
60.65	0.56	5.5		
59.86	0.53	5.31		

ABS + 5% Polyamide

Time (s)	Mass (g)	MFI (g/10 min)	Mean	SD
59.25	2.50	25.31	23.00	1.52
62.39	2.20	21.16		
59.83	2.24	22.5		
59.97	2.23	22.3		
59.97	2.24	22.41		
59.54	2.42	24.34		

ABS + 5% Polar Wax

Time (s)	Mass (g)	MFI (g/10 min)	Mean	SD
60.4	2.36	23.40	24.61	2.07
60.04	2.34	23.36		
59.64	2.75	27.69		
59.48	2.38	24.00		

ABS + varying concentrations of Polypropylene Wax

ABS + 5% Polypropylene Wax				
Time (s)	**Mass (g)**	**MFI (g/10 min)**	**Mean**	**SD**
59.99	1.98	19.78	22.83	1.72
59.81	2.27	22.77		
59.96	2.29	22.95		
59.01	2.23	22.69		
61.23	2.54	24.93		
60.75	2.41	23.83		
ABS + 3% Polypropylene Wax				
Time (s)	**Mass (g)**	**MFI (g/10 min)**	**Mean**	**SD**
59.33	1.23	12.45	13.81	1.11
60.24	1.29	12.82		
59.82	1.41	14.14		
60.19	1.51	15.02		
59.69	1.50	15.06		
59.68	1.33	13.37		
59.54	1.38	13.88		
ABS + 2% Polypropylene Wax				
Time (s)	**Mass (g)**	**MFI (g/10 min)**	**Mean**	**SD**
59.52	1.09	11.00	12.82	1.28
59.95	1.18	11.76		
60.30	1.40	13.97		
0.59	1.22	12.46		
59.09	1.39	14.10		
59.83	1.36	13.60		
58.27	0.33	13.67		
ABS + 1% Polypropylene Wax				
Time (s)	**Mass (g)**	**MFI (g/10 min)**	**Mean**	**SD**
60.24	0.76	7.56	7.02	0.28
59.68	0.69	6.94		
59.83	0.69	6.92		
60.32	0.69	6.87		
59.89	0.71	7.09		
59.62	0.67	6.76		

Polyamide and Polypropylene Wax in combination (5%) in ABS

4% PP wax + 1% Polyamide in ABS				
Time(s)	**Mass (g)**	**MFI (g/10 min)**	**Mean**	**SD**
59.74	2.42	24.31	23.28	1.02
59.68	2.22	22.28		
59.89	2.27	22.77		
59.75	2.43	24.44		
59.69	2.25	22.61		
3% PP wax + 2% Polyamide in ABS				
Time(s)	**Mass (g)**	**MFI (g/10 min)**	**Mean**	**SD**
61.29	2.62	25.69	25.01	0.81
59.60	2.42	24.34		
60.22	2.55	25.42		
59.69	2.36	23.75		
59.88	2.57	25.77		
59.74	2.49	25.05		
2% PP wax + 3% Polyamide in ABS				
Time(s)	**Mass (g)**	**MFI (g/10 min)**	**Mean**	**SD**
60.26	2.46	24.47	26.29	0.90
59.97	2.68	26.80		
59.54	2.63	26.46		
60.33	2.69	26.70		
60.55	2.69	26.66		
60.02	2.67	26.65		
1% PP wax + 4% Polyamide in ABS				
Time(s)	**Mass (g)**	**MFI (g/10 min)**	**Mean**	**SD**
59.42	3.02	30.47	29.50	0.67
60.02	2.90	28.94		
59.72	2.85	28.61		
59.76	2.94	29.50		
59.47	2.97	29.98		
59.58	2.93	29.52		

APPENDIX C
Linear Low-Density Polyethylene

Linear Low Density Polyethylene (LLDPE) with no additives and with 5% slip additives

Time(s)	Mass (g)	MFI (g/10min)	Mean	SD
59.69	0.47	4.74	4.70	0.03
59.85	0.47	4.70		
60.18	0.47	4.71		
60.20	0.47	4.66		
LLDPE + 5% Epoxy				
Time (s)	**Mass (g)**	**MFI (g / 10 min)**	**Mean**	**SD**
71.34	0.67	5.68	5.55	0.18
59.41	0.53	5.39		
59.63	0.57	5.72		
59.47	0.53	5.33		
60.13	0.57	5.65		
LLDPE + 5% Calcium Stearate				
Time (s)	**Mass (g)**	**MFI (g / 10 min)**	**Mean**	**SD**
59.94	0.56	5.61	5.26	0.41
59.88	0.49	4.87		
59.44	0.57	5.74		
60.05	0.49	4.87		
60.59	0.53	5.21		
LLDPE + 5% Polar Wax				
Time (s)	**Mass (g)**	**MFI (g / 10 min)**	**Mean**	**SD**
58.75	0.59	6.07	6.25	0.42
60.34	0.60	5.94		
60.10	0.65	6.52		
60.07	0.59	5.89		
61.51	0.70	6.85		
LLDPE + 5% Polyethylene Wax				
Time (s)	**Mass (g)**	**MFI (g / 10 min)**	**Mean**	**SD**
60.01	0.52	5.20	5.33	0.12
59.91	0.53	5.26		
61.32	0.54	5.29		
59.52	0.55	5.52		
59.81	0.53	5.36		

LLDPE + 5% Polycaprolactone

Time (s)	Mass (g)	MFI (g / 10 min)	Mean	SD
59.74	0.50	5.01	5.01	0.10
60.07	0.50	4.95		
59.81	0.49	4.95		
59.54	0.51	4.95		
59.53	0.50	5.18		

LLDPE + 5% Fischer Tropsch Wax

Time (s)	Mass (g)	MFI (g / 10 min)	Mean	SD
69.89	0.66	5.70	5.81	0.13
55.15	0.53	5.75		
55.63	0.54	5.79		
56.54	0.57	6.00		

LLDPE + 5% Diethanolamine Benzoate

Time (s)	Mass (g)	MFI (g / 10 min)	Mean	SD
66.61	1.58	14.22	13.42	0.84
69.13	1.40	12.18		
70.49	1.55	13.16		
62.56	1.48	14.17		
64.36	1.43	13.37		

LLDPE + 5% Polypropylene Wax

Time (s)	Mass (g)	MFI (g / 10 min)	Mean	SD
49.42	1.40	16.98	18.29	1.08
49.77	1.57	18.96		
41.62	1.35	19.53		
53.45	1.66	18.63		
47.50	1.37	17.36		

LLDPE + 5% Polyamide

Time (s)	Mass (g)	MFI (g / 10 min)	Mean	SD
61.74	1.64	15.98	16.31	0.64
59.79	1.65	16.54		
59.94	1.54	15.37		
59.83	1.66	16.66		
50.28	1.42	16.98		

LLDPE + Varying percentages of Fischer Tropsch Wax

LLDPE + 2% Sasol Fisher Tropsch Wax

Time (s)	Mass (g)	MFI (g / 10 min)	Mean	SD
60.43	0.52	5.18	5.19	0.01
60.45	0.52	5.19		
60.34	0.52	5.20		
60.22	0.52	5.19		

LLDPE + 3 % Sasol Fisher Tropsch Wax

Time (s)	Mass (g)	MFI (g / 10 min)	Mean	SD
60.48	0.54	5.32	5.34	0.07
58.54	0.53	5.42		
48.30	0.43	5.39		
60.97	0.54	5.33		
70.74	0.62	5.24		

LLDPE + 4 % Sasol Fisher Tropsch Wax

Time (s)	Mass (g)	MFI (g / 10 min)	Mean	SD
60.58	0.56	5.54	5.69	0.34
40.33	0.37	5.52		
60.48	0.54	5.31		
60.69	0.60	5.94		
32.13	0.33	6.15		

LLDPE + 5 % Sasol Fisher Tropsch Wax

Time (s)	Mass (g)	MFI (g / 10 min)	Mean	SD
69.44	0.66	5.70	5.81	0.13
55.15	0.53	5.75		
55.63	0.54	5.79		
56.54	0.57	6.00		

LLDPE + Varying percentages of Diethanolamine Benzoate

LLDPE + 0.5% Diethanolamine Benzoate

Time (s)	Mass (g)	MFI (g / 10 min)	Mean	SD
61.01	0.50	4.88	4.93	0.06
53.18	0.44	4.92		
60.96	0.51	4.97		
60.60	0.49	4.87		
54.71	0.46	5.00		

LLDPE + 1% Diethanolamine Benzoate				
Time (s)	**Mass (g)**	**MFI (g / 10 min)**	**Mean**	**SD**
67.23	0.66	5.89	6.09	0.33
60.55	0.60	5.99		
60.39	0.59	5.86		
56.51	0.63	6.66		
40.64	0.41	6.04		
LLDPE + 2% Diethanolamine Benzoate				
Time (s)	**Mass (g)**	**MFI (g / 10 min)**	**Mean**	**SD**
60.45	0.61	6.09	6.53	0.31
60.40	0.68	6.75		
60.43	0.68	6.76		
60.39	0.66	6.53		
LLDPE + 3% Diethanolamine Benzoate				
Time (s)	**Mass (g)**	**MFI (g / 10 min)**	**Mean**	**SD**
60.87	0.82	8.11	8.89	0.58
55.12	0.80	8.67		
60.44	0.88	8.75		
31.71	0.50	9.42		
72.00	1.14	9.52		
LLDPE + 4% Diethanolamine Benzoate				
Time (s)	**Mass (g)**	**MFI (g / 10 min)**	**Mean**	**SD**
71.86	1.43	11.96	11.78	0.31
72.81	1.48	12.16		
73.80	1.44	11.67		
72.08	1.36	11.35		
73.23	1.44	11.77		
LLDPE + 5% Diethanolamine Benzoate				
Time (s)	**Mass (g)**	**MFI (g / 10 min)**	**Mean**	**SD**
66.61	1.58	14.22	13.42	0.84
69.13	1.40	12.18		
70.49	1.55	13.16		
62.56	1.48	14.17		
64.36	1.43	13.37		

LLDPE + Varying percentages of Polypropylene (PP) Wax

LLDPE + 0.5% PP Wax				
Time (s)	**Mass (g)**	**MFI (g / 10 min)**	**Mean**	**SD**
60.46	0.60	5.95	5.77	0.22
60.92	0.60	5.89		
60.49	0.55	5.45		
60.40	0.59	5.81		
LLDPE + 1% PP Wax				
Time (s)	**Mass (g)**	**MFI (g / 10 min)**	**Mean**	**SD**
60.35	0.79	7.87	6.99	0.71
60.44	0.70	6.91		
60.48	0.65	6.31		
60.43	0.64	6.31		
60.72	0.76	7.56		
LLDPE + 2% PP Wax				
Time (s)	**Mass (g)**	**MFI (g / 10 min)**	**Mean**	**SD**
60.56	1.07	10.62	10.06	0.91
60.43	0.88	8.70		
60.39	0.98	9.72		
63.39	1.17	11.07		
60.34	1.03	10.19		
LLDPE + 3% PP wax				
Time (s)	**Mass (g)**	**MFI (g / 10 min)**	**Mean**	**SD**
60.65	1.16	11.51	11.43	1.26
76.92	1.33	10.36		
65.48	1.10	10.01		
63.05	1.29	12.29		
53.58	1.61	12.99		

LLDPE + 4% PP wax				
Time (s)	**Mass (g)**	**MFI (g / 10 min)**	**Mean**	**SD**
67.13	1.628	14.55	16.12	1.26
55.32	1.516	16.44		
52.13	1.565	18.01		
57.12	1.490	15.65		
59.82	1.589	15.94		
LLDPE + 5% PP wax				
Time (s)	**Mass (g)**	**MFI (g / 10 min)**	**Mean**	**SD**
49.42	1.40	16.98	18.29	1.08
49.77	1.57	18.96		
41.62	1.35	19.53		
53.45	1.66	18.63		
47.50	1.37	17.36		

LLDPE + Varying percentages of Polyamide

LLDPE + 0.5% Polyamide				
Time (s)	**Mass (g)**	**MFI (g / 10 min)**	**Mean**	**SD**
60.15	0.54	5.34	5.35	0.11
59.85	0.55	5.50		
60.24	0.53	5.24		
60.48	0.54	5.31		
LLDPE + 1% Polyamide				
Time (s)	**Mass (g)**	**MFI (g / 10 min)**	**Mean**	**SD**
59.77	0.62	6.24	6.25	0.07
59.98	0.62	6.17		
60.09	0.63	6.33		
60.14	0.63	6.27		

LLDPE + 2% Polyamide

Time (s)	Mass (g)	MFI (g / 10 min)	Mean	SD
61.20	0.97	9.53	8.77	1.40
60.42	0.90	8.93		
60.20	0.79	7.87		
60.43	1.11	11.06		
60.25	1.02	10.19		
60.48	0.75	7.45		
60.42	0.72	7.11		
60.44	0.81	8.04		

LLDPE + 3% Polyamide

Time (s)	Mass (g)	MFI (g / 10 min)	Mean	SD
60.55	0.95	9.37	9.99	0.84
37.46	0.55	8.85		
66.99	1.21	10.88		
60.46	1.05	10.45		
69.15	1.20	10.39		

LLDPE + 4% Polyamide

Time (s)	Mass (g)	MFI (g / 10 min)	Mean	SD
61.23	1.39	13.65	14.92	0.89
62.98	1.61	15.29		
53.14	1.39	15.71		
59.97	1.50	15.02		

LLDPE + 5% Polyamide

Time (s)	Mass (g)	MFI (g / 10 min)	Mean	SD
61.74	1.64	15.98	16.31	0.64
59.79	1.65	16.54		
59.94	1.54	15.37		
59.83	1.66	16.66		
50.28	1.42	16.98		

Polyamide and Polypropylene Wax in combination (5%) in LLDPE

1% Polyamide + 4% PP wax				
Time (s)	**Mass (g)**	**MFI (g / 10 min)**	**Mean**	**SD**
51.71	1.25	14.05	16.03	1.93
59.84	1.51	15.74		
57.44	1.60	16.72		
66.93	1.63	14.65		
43.80	1.38	18.96		
2% Polyamide + 3% PP wax				
Time (s)	**Mass (g)**	**MFI (g / 10 min)**	**Mean**	**SD**
44.49	1.22	16.46	16.89	1.90
53.02	1.61	18.18		
52.90	1.65	18.77		
50.27	1.49	17.15		
68.31	1.58	13.89		
3% Polyamide + 2% PP wax				
Time (s)	**Mass (g)**	**MFI (g / 10 min)**	**Mean**	**SD**
48.30	1.27	15.73	16.68	1.10
52.66	1.37	15.62		
45.38	1.35	17.78		
47.75	1.30	16.35		
53.23	1.59	17.91		
4% Polyamide + 1% PP wax				
Time (s)	**Mass (g)**	**MFI (g / 10 min)**	**Mean**	**SD**
62.76	1.54	14.72	16.51	1.54
58.15	1.62	16.70		
48.39	1.49	18.45		
64.48	1.74	16.20		

APPENDIX D1: Comparison between standard and slip additives

	Standard			**Polycaprolactone**			**Polyamide**			**Polar wax**		
Extruder Volume	Absorbance @ 635 nm	Average absorbance (A)	Division by highest A	Absorbance @ 635 nm	Average absorbance (A)	Division by highest A	Absorbance @ 635 nm	Average absorbance (A)	Division by highest A	Absorbance @ 635 nm	Average absorbance (A)	Division by highest A
-1.00	3.26	3.25	0.98	1.95	1.96	1.00	3.17	3.27	0.99	2.29	2.31	0.87
	3.25			1.96			3.30			2.33		
	3.23			1.97			3.40			2.31		
	3.26			1.97			3.22			2.33		
0.00	3.32	3.33	1.00	1.94	1.96	1.00	3.24	3.30	1.00	2.65	2.67	1.00
	3.32			1.96			3.33			2.67		
	3.34			1.96			3.33			2.68		
	3.33			1.96			3.31			2.68		
1.00	0.47	0.47	0.14	0.26	0.25	0.13	1.02	1.01	0.31	0.53	0.53	0.20
	0.47			0.25			1.01			0.53		
	0.46			0.24			1.00			0.52		
	0.48			0.24			1.01			0.52		
2.00	0.23	0.22	0.07	0.16	0.17	0.08	0.23	0.25	0.07	0.22	0.21	0.08
	0.22			0.17			0.27			0.21		
	0.22			0.16			0.22			0.20		
	0.22			0.17			0.27			0.22		
3.00	0.19	0.20	0.06	0.11	0.12	0.06	0.15	0.15	0.05	0.14	0.14	0.05
	0.20			0.12			0.15			0.14		
	0.20			0.13			0.15			0.14		
	0.20			0.12			0.15			0.14		
4.00	0.18	0.18	0.05	0.12	0.11	0.06	0.12	0.12	0.04	0.14	0.14	0.05
	0.18			0.11			0.12			0.14		
	0.18			0.12			0.12			0.14		
	0.18			0.11			0.12			0.14		

APPENDIX D2: Comparison between standard and slip additives taking into account the polymer film thickness

Standard								Polycaprolactone						
Extruder Volume	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L	Division by highest c	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L	Division by highest c
				(mm)	(cm)						(mm)	(cm)		
-1.00	3.26	3.25	0.10	0.11	0.011	307.99	1.00	1.95	1.96	0.05	0.06	0.006	348.84	0.98
	3.25		0.10					1.96		0.05				
	3.23		0.12					1.97		0.06				
	3.26		0.11					1.97		0.06				
0.00	3.32	3.33	0.11	0.11	0.011	295.76	0.96	1.94	1.96	0.06	0.06	0.006	355.68	1.00
	3.32		0.11					1.96		0.06				
	3.34		0.12					1.96		0.05				
	3.33		0.11					1.96		0.05				
0.50	1.06	1.06	0.10	0.08	0.008	133.77	0.43	0.48	0.47	0.07	0.05	0.005	89.19	0.25
	1.06		0.10					0.47		0.04				
	1.07		0.01					0.47		0.05				
	1.05		0.11					0.47		0.05				
1.00	0.47	0.47	0.11	0.11	0.011	42.60	0.14	0.26	0.25	0.05	0.05	0.005	49.95	0.14
	0.47		0.11					0.25		0.05				
	0.46		0.11					0.24		0.05				
	0.48		0.11					0.24		0.05				
2.00	0.23	0.22	0.10	0.11	0.011	20.34	0.07	0.16	0.17	0.05	0.05	0.005	36.48	0.10
	0.22		0.11					0.17		0.05				
	0.22		0.12					0.16		0.04				
	0.22		0.11					0.17		0.04				
3.00	0.19	0.20	0.11	0.11	0.011	17.70	0.06	0.11	0.12	0.05	0.05	0.005	24.79	0.07
	0.20		0.11					0.12		0.05				
	0.20		0.11					0.13		0.04				
	0.20		0.11					0.12		0.05				
4.00	0.18	0.18	0.11	0.12	0.012	15.65	0.05	0.12	0.11	0.05	0.04	0.004	25.62	0.07
	0.18		0.12					0.11		0.05				
	0.18		0.12					0.12		0.04				
	0.18		0.11					0.11		0.04				

Comparison between standard and slip additives taking into account the polymer film thickness, continued…

	Polyamide							Polar wax						
Extruder Volume	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L	Division by highest c	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L	Division by highest c
				(mm)	(cm)						(mm)	(cm)		
-1.00	3.17	3.27	0.10	0.10	0.010	322.24	1.00	2.29	2.31	0.07	0.08	0.008	292.91	0.97
	3.30		0.11					2.33		0.07				
	3.40		0.11					2.31		0.09				
	3.22		0.10					2.33		0.09				
0.00	3.24	3.30	0.11	0.11	0.011	293.51	0.91	2.65	2.67	0.09	0.09	0.009	303.52	1.00
	3.33		0.11					2.67		0.09				
	3.33		0.12					2.68		0.09				
	3.31		0.11					2.68		0.09				
0.50	1.21	1.17	0.09	0.07	0.007	163.51	0.51	0.93	0.93	0.08	0.09	0.009	108.66	0.36
	1.13		0.08					0.94		0.09				
	1.17		0.06					0.94		0.08				
	1.16		0.06					0.93		0.09				
1.00	1.02	1.01	0.13	0.14	0.014	72.96	0.23	0.53	0.53	0.09	0.09	0.009	58.18	0.19
	1.01		0.14					0.53		0.09				
	1.00		0.15					0.52		0.09				
	1.01		0.14					0.52		0.09				
2.00	0.23	0.25	0.10	0.10	0.010	25.11	0.08	0.22	0.21	0.07	0.08	0.008	26.88	0.09
	0.27		0.10					0.21		0.08				
	0.22		0.10					0.20		0.08				
	0.27		0.10					0.22		0.09				
3.00	0.15	0.15	0.09	0.09	0.009	15.99	0.05	0.14	0.14	0.07	0.07	0.007	19.02	0.06
	0.15		0.08					0.14		0.07				
	0.15		0.10					0.14		0.08				
	0.15		0.10					0.14		0.08				
4.00	0.12	0.12	0.08	0.09	0.009	14.08	0.04	0.14	0.14	0.09	0.09	0.009	15.55	0.05
	0.12		0.08					0.14		0.08				
	0.12		0.10					0.14		0.10				
	0.12		0.09					0.14		0.09				

continued…

Atactic Polypropylene

Extruder Volume	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L	Division by highest c
				(mm)	(cm)		
-1.00	2.35	2.43	0.08	0.07	0.007	341.02	1.00
	2.43		0.07				
	2.51		0.07				
	2.43		0.08				
0.00	2.27	2.28	0.07	0.08	0.008	300.63	0.88
	2.29		0.07				
	2.30		0.08				
	2.29		0.08				
0.50	0.93	0.94	0.08	0.09	0.009	109.59	0.32
	0.94		0.09				
	0.94		0.08				
	0.96		0.09				
1.00	0.54	0.53	0.11	0.11	0.011	49.49	0.15
	0.54		0.11				
	0.52		0.10				
	0.53		0.11				
2.00	0.24	0.23	0.09	0.09	0.009	25.44	0.07
	0.23		0.09				
	0.22		0.09				
	0.23		0.09				
3.00	0.19	0.19	0.10	0.10	0.010	19.50	0.06
	0.19		0.11				
	0.20		0.10				
	0.19		0.10				
4.00	0.14	0.14	0.07	0.07	0.007	20.11	0.06
	0.14		0.07				
	0.13		0.07				
	0.14		0.06				

APPENDIX D3: Standard against slip additives with corrected concentrations for each quarter between volumes 0 and 1

Absorbance @ 635 nm

	Standard					Polycaprolactone							
Extruder Volume	Experiment 1	Experiment 2	Experiment 3	Average absorbance (A)	Corrected concentration	Experiment 1	Experiment 2	Experiment 3	Average absorbance (A)	Corrected concentration	Avg.max. blue (B)	Avg. mini. clear (C)	B - C
-1.00	**366.27**	**327.29**	278.93	324.17	0.90	239.72	**462.63**	348.84	350.40	0.98	357.57	14.80	342.78
0.00	318.06	312.76	**295.08**	308.63	0.86	**381.15**	357.45	**355.68**	364.76	1.02			
0.25	194.57	189.40	177.08	187.02	0.50	330.42	128.72	128.72	195.95	0.53			
0.50	104.25	104.58	91.10	99.98	0.25	166.93	77.01	89.19	111.04	0.28			
0.75	61.74	58.28	60.91	60.31	0.13	99.04	53.96	55.90	69.63	0.16			
1.00	45.71	44.16	41.99	43.95	0.09	53.82	47.76	49.95	50.51	0.10			
2.00	21.92	22.00	21.57	21.83	0.02	20.71	24.21	36.48	27.13	0.04			
3.00	16.06	16.92	17.38	16.79	0.01	15.28	18.24	24.79	19.44	0.01			
4.00	15.33	15.37	15.66	15.45	0.00	15.36	15.33	25.62	18.77	0.01			

Polar wax

Extruder Volume	Experiment 1	Experiment 2	Experiment 3	Average absorbance (A)	Corrected concentration
-1.00	**348.56**	349.33	292.91	330.27	0.92
0.00	336.12	**377.99**	**303.52**	339.21	0.95
0.25	141.65	156.78	149.81	149.41	0.39
0.50	85.14	104.05	108.66	99.29	0.25
0.75	61.37	83.86	74.75	73.33	0.17
1.00	55.08	55.06	58.18	56.11	0.12
2.00	21.32	19.44	26.88	22.54	0.02
3.00	18.19	14.15	19.02	17.12	0.01
4.00	15.39	13.60	15.55	14.84	0.00

APPENDIX D4: Comparison between Standard and Commercial Purge a using 10% pigment + 90% LDPE pellets

Standard

Extruder Volume	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L
				(mm)	(cm)	
2.00	0.52	0.39	0.06	0.04	0.004	92.45
	0.48		0.05			
	0.50		0.06			
	0.49		0.06			
	0.27		0.04			
	0.27		0.03			
	0.28		0.02			
	0.29		0.02			
3.00	0.20	0.27	0.04	0.04	0.004	74.14
	0.18		0.04			
	0.17		0.04			
	0.20		0.03			
	0.37		0.04			
	0.35		0.04			
	0.35		0.03			
	0.34		0.04			
4.00	0.17	0.23	0.05	0.04	0.004	57.92
	0.17		0.04			
	0.17		0.04			
	0.20		0.04			
	0.28		0.04			
	0.26		0.04			
	0.27		0.03			
	0.28		0.03			
5.00	0.14	0.14	0.05	0.04	0.004	36.16
	0.13		0.04			
	0.13		0.04			
	0.13		0.03			
	0.14		0.04			
	0.15		0.04			
	0.14		0.04			
	0.14		0.04			
6.00	0.15	0.14	0.03	0.04	0.004	36.73
	0.14		0.03			
	0.15		0.04			
	0.14		0.04			
	0.15		0.05			
	0.14		0.04			
	0.14		0.04			
	0.12		0.04			
7.00	0.11	0.13	0.05	0.04	0.004	30.40
	0.11		0.07			
	0.11		0.04			
	0.11		0.03			
	0.13		0.04			
	0.14		0.04			
	0.16		0.03			
	0.13		0.04			

Commercial Purge A

Extruder Volume	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L
				(mm)	(cm)	
2.00	0.25	0.29	0.05	0.06	0.006	47.46
	0.25		0.07			
	0.25		0.07			
	0.23		0.07			
	0.38		0.05			
	0.34		0.05			
	0.32		0.07			
	0.31		0.06			
3.00	0.20	0.21	0.08	0.06	0.006	36.84
	0.12		0.06			
	0.19		0.06			
	0.19		0.06			
	0.26		0.05			
	0.26		0.05			
	0.24		0.06			
	0.25		0.05			
4.00	0.20	0.19	0.06	0.06	0.006	32.41
	0.19		0.05			
	0.17		0.05			
	0.15		0.06			
	0.20		0.06			
	0.21		0.06			
	0.21		0.06			
	0.21		0.07			
5.00	0.15	0.16	0.04	0.05	0.005	33.67
	0.16		0.04			
	0.16		0.06			
	0.15		0.06			
	0.17		0.05			
	0.18		0.06			
	0.16		0.05			
	0.17		0.04			
6.00	0.13	0.14	0.05	0.05	0.005	26.18
	0.14		0.05			
	0.15		0.05			
	0.14		0.05			
	0.14		0.05			
	0.14		0.06			
	0.14		0.06			
	0.14		0.05			
7.00	0.11	0.12	0.05	0.05	0.005	24.33
	0.10		0.05			
	0.10		0.04			
	0.11		0.05			
	0.13		0.06			
	0.14		0.05			
	0.14		0.05			
	0.13		0.05			

Comparison between Standard and Commercial Purge a using 20% pigment + 80% LDPE pellets

Standard								Commercial Purge A						
Extruder Volume	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L		Extruder Volume	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L
				(mm)	(cm)							(mm)	(cm)	
2.00	1.08	1.21	0.05	0.05	0.005	221.83		2.00	0.56	0.52	0.06	0.06	0.006	92.79
	1.12		0.05						0.64		0.07			
	1.19		0.05						0.61		0.08			
	1.27		0.04						0.62		0.06			
	1.38		0.06						0.42		0.05			
	1.28		0.05						0.45		0.05			
	1.23		0.04						0.43		0.05			
	1.16		0.09						0.48		0.05			
3.00	0.62	0.73	0.05	0.05	0.005	154.72		3.00	0.29	0.34	0.06	0.05	0.005	75.34
	0.72		0.07						0.25		0.06			
	0.69		0.04						0.26		0.04			
	0.73		0.04						0.25		0.04			
	0.88		0.05						0.43		0.04			
	0.80		0.05						0.42		0.04			
	0.72		0.04						0.45		0.04			
	0.68		0.05						0.40		0.04			
4.00	0.60	0.52	0.04	0.05	0.005	104.86		4.00	0.36	0.34	0.04	0.05	0.005	74.61
	0.59		0.04						0.37		0.05			
	0.60		0.04						0.37		0.06			
	0.55		0.05						0.36		0.05			
	0.43		0.08						0.34		0.06			
	0.46		0.07						0.32		0.05			
	0.46		0.04						0.33		0.04			
	0.45		0.04						0.32		0.03			
5.00	0.45	0.39	0.05	0.05	0.005	78.56		5.00	0.25	0.22	0.05	0.05	0.005	43.99
	0.45		0.06						0.25		0.05			
	0.42		0.04						0.26		0.05			
	0.44		0.06						0.26		0.05			
	0.35		0.04						0.18		0.06			
	0.35		0.04						0.16		0.08			
	0.34		0.05						0.22		0.05			
	0.36		0.07						0.17		0.03			
6.00	0.44	0.37	0.07	0.05	0.005	68.95		6.00	0.21	0.20	0.07	0.05	0.005	41.78
	0.42		0.05						0.21		0.07			
	0.43		0.05						0.19		0.05			
	0.41		0.05						0.17		0.04			
	0.31		0.05						0.21		0.04			
	0.31		0.07						0.20		0.05			
	0.33		0.04						0.21		0.04			
	0.32		0.06						0.20		0.04			
7.00	0.26	0.22	0.04	0.04	0.004	51.98		7.00	0.23	0.19	0.05	0.05	0.005	37.67
	0.25		0.04						0.22		0.05			
	0.25		0.04						0.20		0.06			
	0.27		0.04						0.18		0.05			
	0.18		0.04						0.18		0.05			
	0.18		0.06						0.17		0.05			
	0.18		0.05						0.17		0.06			
	0.18		0.04						0.19		0.05			

Comparison between Standard and Commercial Purge a using 30% pigment + 70% LDPE pellets

Standard

Extruder Volume	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L
				(mm)	(cm)	
2.00	0.94	0.93	0.04	0.05	0.005	186.30
	0.91		0.06			
	0.96		0.05			
	1.06		0.04			
	0.82		0.06			
	0.84		0.06			
	0.93		0.05			
	1.01		0.05			
3.00	0.76	0.64	0.04	0.05	0.005	134.87
	0.77		0.04			
	0.78		0.04			
	0.80		0.05			
	0.59		0.05			
	0.58		0.06			
	0.46		0.06			
	0.41		0.05			
4.00	0.40	0.42	0.05	0.05	0.005	82.70
	0.40		0.05			
	0.40		0.05			
	0.47		0.04			
	0.42		0.06			
	0.42		0.05			
	0.41		0.06			
	0.41		0.06			
5.00	0.27	0.23	0.05	0.04	0.004	52.64
	0.27		0.05			
	0.28		0.05			
	0.28		0.06			
	0.19		0.04			
	0.18		0.04			
	0.18		0.04			
	0.19		0.04			
6.00	0.17	0.21	0.03	0.04	0.004	51.57
	0.16		0.04			
	0.16		0.03			
	0.26		0.03			
	0.25		0.04			
	0.25		0.06			
	0.23		0.04			
	0.19		0.05			
7.00	0.14	0.17	0.03	0.04	0.004	44.10
	0.14		0.03			
	0.15		0.04			
	0.14		0.04			
	0.19		0.05			
	0.20		0.04			
	0.21		0.04			
	0.22		0.05			

Commercial Purge A

Extruder Volume	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L
				(mm)	(cm)	
2.00	0.31	0.38	0.04	0.05	0.005	76.04
	0.28		0.04			
	0.27		0.06			
	0.55		0.04			
	0.51		0.07			
	0.45		0.06			
	0.40		0.04			
	0.31		0.05			
3.00	0.33	0.25	0.05	0.05	0.005	53.46
	0.04		0.05			
	0.36		0.04			
	0.32		0.04			
	0.25		0.04			
	0.23		0.04			
	0.23		0.05			
	0.23		0.06			
4.00	0.25	0.24	0.06	0.05	0.005	51.38
	0.26		0.05			
	0.27		0.04			
	0.26		0.04			
	0.23		0.04			
	0.22		0.04			
	0.20		0.06			
	0.21		0.04			
5.00	0.18	0.19	0.05	0.04	0.004	48.46
	0.19		0.05			
	0.17		0.03			
	0.18		0.04			
	0.19		0.03			
	0.19		0.04			
	0.19		0.03			
	0.19		0.04			
6.00	0.17	0.16	0.05	0.04	0.004	40.53
	0.17		0.05			
	0.16		0.04			
	0.18		0.04			
	0.16		0.03			
	0.16		0.03			
	0.15		0.04			
	0.17		0.04			
7.00	0.17	0.15	0.05	0.04	0.004	35.75
	0.18		0.05			
	0.17		0.05			
	0.17		0.04			
	0.12		0.04			
	0.12		0.03			
	0.14		0.04			
	0.13		0.04			

Comparison between Standard and Commercial Purge a using 40% pigment + 60% LDPE pellets

Standard

Extruder Volume	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L
				(mm)	(cm)	
2.00	1.02	1.03	0.06	0.06	0.006	169.23
	0.99		0.06			
	0.81		0.09			
	0.72		0.07			
	0.14		0.06			
	1.57		0.07			
	1.61		0.05			
	1.42		0.04			
3.00	0.71	0.78	0.05	0.05	0.005	165.08
	0.78		0.07			
	0.82		0.07			
	0.78		0.04			
	0.80		0.04			
	0.80		0.04			
	0.76		0.03			
	0.82		0.03			
4.00	0.47	0.45	0.04	0.05	0.005	97.13
	0.42		0.06			
	0.43		0.07			
	0.43		0.04			
	0.49		0.05			
	0.47		0.05			
	0.48		0.04			
	0.43		0.04			
5.00	0.34	0.38	0.04	0.04	0.004	93.32
	0.33		0.04			
	0.34		0.04			
	0.35		0.05			
	0.29		0.03			
	0.82		0.04			
	0.29		0.04			
	0.31		0.05			
6.00	0.50	0.41	0.06	0.05	0.005	89.45
	0.48		0.06			
	0.48		0.09			
	0.47		0.04			
	0.36		0.04			
	0.35		0.03			
	0.34		0.03			
	0.30		0.03			
7.00	0.33	0.32	0.04	0.04	0.004	88.66
	0.34		0.04			
	0.32		0.03			
	0.36		0.03			
	0.32		0.04			
	0.30		0.03			
	0.30		0.04			
	0.31		0.04			

Commercial Purge A

Extruder Volume	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L
				(mm)	(cm)	
2.00	0.80	0.87	0.05	0.06	0.006	151.39
	0.80		0.04			
	0.90		0.06			
	0.83		0.06			
	0.83		0.10			
	0.94		0.05			
	0.90		0.05			
	0.96		0.04			
3.00	0.59	0.59	0.08	0.05	0.005	116.37
	0.58		0.06			
	0.60		0.07			
	0.59		0.03			
	0.55		0.03			
	0.54		0.04			
	0.60		0.05			
	0.67		0.06			
4.00	0.53	0.57	0.07	0.06	0.006	95.83
	0.52		0.08			
	0.54		0.07			
	0.55		0.06			
	0.58		0.04			
	0.58		0.07			
	0.60		0.05			
	0.62		0.06			
5.00	0.40	0.44	0.07	0.05	0.005	90.23
	0.39		0.06			
	0.42		0.03			
	0.39		0.08			
	0.48		0.04			
	0.49		0.05			
	0.47		0.04			
	0.49		0.03			
6.00	0.40	0.40	0.04	0.05	0.005	84.34
	0.39		0.05			
	0.41		0.05			
	0.41		0.05			
	0.41		0.05			
	0.40		0.06			
	0.40		0.05			
	0.40		0.05			
7.00	0.35	0.32	0.03	0.06	0.006	57.19
	0.34		0.04			
	0.33		0.05			
	0.31		0.04			
	0.33		0.08			
	0.31		0.04			
	0.32		0.09			
	0.30		0.08			

Comparison between Standard and Commercial Purge a using 40% pigment + 60% LDPE powder

Standard

Extruder Volume	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L
				(mm)	(cm)	
2.00	0.15	1.51	0.04	0.05	0.005	301.97
	1.46		0.04			
	1.44		0.05			
	1.51		0.06			
	1.81		0.05			
	1.84		0.05			
	1.87		0.05			
	2.00		0.06			
3.00	0.45	0.46	0.02	0.03	0.003	183.13
	0.43		0.02			
	0.44		0.03			
	0.50		0.03			
	0.45		0.02			
	0.51		0.03			
	0.46		0.03			
	0.44		0.02			
4.00	0.27	0.23	0.02	0.02	0.002	123.92
	0.26		0.02			
	0.25		0.02			
	0.22		0.02			
	0.23		0.02			
	0.21		0.02			
	0.20		0.02			
	0.20		0.03			
5.00	0.22	0.18	0.02	0.02	0.002	91.50
	0.21		0.01			
	0.20		0.02			
	0.20		0.03			
	0.15		0.02			
	0.14		0.02			
	0.15		0.02			
	0.14		0.02			
6.00	0.16	0.17	0.03	0.03	0.003	60.14
	0.14		0.03			
	0.14		0.02			
	0.14		0.03			
	0.19		0.04			
	0.19		0.03			
	0.18		0.02			
	0.19		0.03			
7.00	0.12	0.12	0.04	0.02	0.002	55.60
	0.12		0.03			
	0.12		0.01			
	0.12		0.02			
	0.11		0.02			
	0.11		0.02			
	0.11		0.02			
	0.11		0.02			

Commercial Purge A

Extruder Volume	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L
				(mm)	(cm)	
2.00	0.61	0.55	0.03	0.03	0.003	186.27
	0.62		0.03			
	0.63		0.03			
	0.63		0.03			
	0.48		0.03			
	0.47		0.04			
	0.47		0.03			
	0.48		0.02			
3.00	0.28	0.25	0.02	0.02	0.002	115.35
	0.27		0.02			
	0.24		0.02			
	0.24		0.03			
	0.23		0.02			
	0.23		0.02			
	0.24		0.02			
	0.26		0.02			
4.00	0.25	0.22	0.03	0.03	0.003	72.18
	0.24		0.03			
	0.25		0.03			
	0.23		0.03			
	0.20		0.03			
	0.21		0.03			
	0.22		0.03			
	0.21		0.03			
5.00	0.13	0.13	0.02	0.02	0.002	58.47
	0.12		0.02			
	0.12		0.02			
	0.12		0.02			
	0.13		0.02			
	0.14		0.02			
	0.14		0.03			
	0.14		0.03			
6.00	0.13	0.13	0.02	0.02	0.002	55.25
	0.14		0.02			
	0.13		0.02			
	0.14		0.02			
	0.11		0.03			
	0.12		0.02			
	0.12		0.02			
	0.12		0.02			
7.00	0.09	0.10	0.02	0.02	0.002	46.40
	0.09		0.02			
	0.10		0.04			
	0.09		0.03			
	0.11		0.02			
	0.11		0.02			
	0.11		0.02			
	0.10		0.02			

APPENDIX D5: STANDARD AGAINST COMMERCIAL PURGES AND SLIP ADDITIVES

Standard							
Extruder Volume	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L	Corrected concentration
				(mm)	(cm)		
2.00	0.83	0.79	0.05	0.05	0.01	146.34	130.17
	0.91		0.06				
	0.82		0.05				
	0.71		0.04				
	0.82		0.07				
	0.69		0.08				
	0.80		0.05				
	0.75		0.05				
3.00	0.70	0.58	0.04	0.05	0.00	116.92	100.74
	0.60		0.04				
	0.66		0.05				
	0.66		0.05				
	0.59		0.05				
	0.58		0.06				
	0.46		0.06				
	0.41		0.06				
4.00	0.40	0.42	0.05	0.05	0.01	84.07	67.89
	0.40		0.05				
	0.41		0.05				
	0.47		0.04				
	0.43		0.06				
	0.42		0.05				
	0.41		0.06				
	0.45		0.06				
5.00	0.29	0.24	0.05	0.04	0.00	54.27	38.09
	0.28		0.05				
	0.28		0.05				
	0.29		0.06				
	0.19		0.04				
	0.19		0.04				
	0.19		0.04				
	0.19		0.04				
6.00	0.17	0.22	0.03	0.04	0.00	53.42	37.25
	0.16		0.04				
	0.16		0.03				
	0.26		0.03				
	0.25		0.04				
	0.25		0.05				
	0.24		0.04				
	0.24		0.05				
7.00	0.14	0.18	0.03	0.04	0.00	46.19	30.01
	0.16		0.03				
	0.17		0.04				
	0.17		0.04				
	0.19		0.05				
	0.20		0.04				
	0.21		0.04				
	0.22		0.05				

Clear Polymer Film					
Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L
			(mm)	(cm)	
0.07	0.06	0.02	0.04	0.00	16.18
0.07		0.02			
0.08		0.03			
0.07		0.03			
0.05		0.05			
0.05		0.05			
0.06		0.06			
0.05		0.06			

Commercial Purge A

Extruder Volume	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L	Corrected concentration
				(mm)	(cm)		
2.00	0.44	0.49	0.05	0.06	0.006	84.90	69.64
	0.36		0.07				
	0.44		0.07				
	0.36		0.09				
	0.55		0.06				
	0.61		0.02				
	0.57		0.05				
	0.57		0.04				
3.00	0.26	0.31	0.01	0.05	0.005	63.34	48.08
	0.25		0.02				
	0.27		0.03				
	0.24		0.04				
	0.36		0.07				
	0.33		0.09				
	0.36		0.07				
	0.43		0.07				
4.00	0.21	0.24	0.04	0.05	0.005	53.43	38.17
	0.22		0.04				
	0.19		0.02				
	0.18		0.02				
	0.30		0.06				
	0.30		0.07				
	0.30		0.07				
	0.25		0.06				
5.00	0.19	0.22	0.07	0.05	0.005	47.03	31.77
	0.19		0.07				
	0.19		0.06				
	0.18		0.07				
	0.26		0.02				
	0.25		0.02				
	0.25		0.04				
	0.26		0.04				
6.00	0.15	0.16	0.02	0.04	0.004	38.96	23.71
	0.14		0.02				
	0.12		0.03				
	0.10		0.03				
	0.21		0.06				
	0.20		0.06				
	0.20		0.06				
	0.20		0.07				
7.00	0.20	0.15	0.04	0.04	0.004	35.95	20.69
	0.19		0.04				
	0.17		0.06				
	0.14		0.06				
	0.12		0.04				
	0.12		0.03				
	0.11		0.03				
	0.11		0.03				

Clear Polymer Film

Absorbance @ 635 nm	Average absorbance	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L
			(mm)	(cm)	
0.07	0.06	0.02	0.04	0.004	15.26
0.07		0.02			
0.07		0.03			
0.07		0.03			
0.05		0.05			
0.05		0.05			
0.05		0.06			
0.05		0.06			

Commercial Purge B

Extruder Volume	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L	Corrected concentration
				(mm)	(cm)		
4.00	0.23	0.17	0.02	0.04	0.004	47.22	29.80
	0.23		0.01				
	0.24		0.04				
	0.23		0.04				
	0.12		0.05				
	0.13		0.05				
	0.10		0.05				
	0.11		0.04				
5.00	0.20	0.15	0.02	0.04	0.004	42.02	24.60
	0.21		0.02				
	0.20		0.02				
	0.20		0.02				
	0.09		0.05				
	0.12		0.06				
	0.12		0.05				
	0.09		0.05				
6.00	0.07	0.12	0.07	0.03	0.003	37.51	20.09
	0.07		0.05				
	0.08		0.04				
	0.08		0.04				
	0.18		0.01				
	0.17		0.02				
	0.18		0.01				
	0.17		0.02				
7.00	0.15	0.11	0.02	0.03	0.003	32.71	15.29
	0.14		0.01				
	0.16		0.02				
	0.16		0.02				
	0.07		0.06				
	0.06		0.06				
	0.06		0.04				
	0.06		0.04				

Clear Polymer Film

Absorbance @ 635 nm	Average absorbance	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L
			(mm)	(cm)	
0.08	0.07	0.04	0.04	0.004	17.42
0.09		0.03			
0.09		0.01			
0.08		0.01			
0.05		0.05			
0.05		0.04			
0.06		0.07			
0.06		0.06			

Commercial Purge C

Extruder Volume	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L	Corrected concentration
				(mm)	(cm)		
2.00	0.60	0.45	0.10	0.06	0.006	81.87	62.29
	0.59		0.10				
	0.57		0.08				
	0.56		0.08				
	0.30		0.00				
	0.36		0.01				
	0.32		0.04				
	0.35		0.04				
3.00	0.34	0.25	0.07	0.04	0.004	59.79	40.21
	0.37		0.08				
	0.35		0.05				
	0.35		0.05				
	0.17		0.02				
	0.14		0.02				
	0.13		0.02				
	0.15		0.03				
4.00	0.29	0.22	0.03	0.05	0.005	41.71	22.14
	0.31		0.02				
	0.29		0.03				
	0.30		0.04				
	0.16		0.10				
	0.14		0.07				
	0.14		0.07				
	0.13		0.07				
5.00	0.21	0.17	0.03	0.05	0.005	35.21	15.63
	0.21		0.04				
	0.21		0.02				
	0.20		0.02				
	0.14		0.08				
	0.12		0.07				
	0.13		0.06				
	0.12		0.06				
6.00	0.20	0.15	0.04	0.05	0.005	27.59	8.01
	0.21		0.03				
	0.20		0.03				
	0.21		0.08				
	0.10		0.08				
	0.10		0.06				
	0.10		0.06				
	0.09		0.06				
7.00	0.07	0.14	0.09	0.06	0.006	25.25	5.67
	0.07		0.08				
	0.07		0.07				
	0.08		0.08				
	0.20		0.05				
	0.20		0.04				
	0.21		0.02				
	0.22		0.02				

Clear Polymer Film

Absorbance @ 635 nm	Average absorbance	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L
			(mm)	(cm)	
0.06	0.08	0.02	0.04	0.004	19.58
0.06		0.03			
0.06		0.02			
0.06		0.02			
0.09		0.05			
0.09		0.05			
0.10		0.06			
0.10		0.06			

Commercial Purge D

Extruder Volume	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L	Corrected concentration
				(mm)	(cm)		
6.00	0.14	0.11	0.09	0.06	0.006	19.34	1.60
	0.17		0.08				
	0.13		0.07				
	0.09		0.06				
	0.09		0.06				
	0.08		0.05				
	0.08		0.02				
	0.14		0.03				
7.00	0.08	0.11	0.07	0.06	0.006	18.25	0.51
	0.12		0.07				
	0.10		0.07				
	0.10		0.09				
	0.12		0.05				
	0.13		0.04				
	0.11		0.05				
	0.11		0.05				

Clear Polymer Film

Absorbance @ 635 nm	Average absorbance	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L
			(mm)	(cm)	
0.06	0.07	0.01	0.04	0.004	17.73
0.05		0.02			
0.06		0.03			
0.06		0.04			
0.08		0.04			
0.08		0.05			
0.08		0.07			
0.08		0.06			

Commercial Purge E1

Extruder Volume	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L	Corrected concentration
				(mm)	(cm)		
3.00	0.29	0.23	0.07	0.05	0.005	45.53	30.87
	0.25		0.06				
	0.24		0.07				
	0.24		0.05				
	0.19		0.08				
	0.23		0.05				
	0.21		0.02				
	0.23		0.02				
4.00	0.21	0.20	0.04	0.05	0.005	38.28	23.61
	0.25		0.04				
	0.26		0.02				
	0.19		0.03				
	0.14		0.06				
	0.17		0.13				
	0.17		0.04				
	0.19		0.06				
5.00	0.19	0.13	0.07	0.04	0.004	32.74	18.08
	0.19		0.08				
	0.18		0.05				
	0.19		0.08				
	0.06		0.02				
	0.08		0.01				
	0.09		0.01				
	0.10		0.01				
6.00	0.10	0.16	0.07	0.06	0.006	29.25	14.59
	0.09		0.09				
	0.10		0.08				
	0.10		0.12				
	0.23		0.03				
	0.20		0.03				
	0.22		0.01				
	0.25		0.01				
7.00	0.08	0.13	0.07	0.05	0.005	25.69	11.02
	0.08		0.08				
	0.09		0.06				
	0.09		0.07				
	0.18		0.05				
	0.17		0.04				
	0.18		0.02				
	0.17		0.02				

Clear Polymer Film

Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L
			(mm)	(cm)	
0.06	0.06	0.04	0.04	0.004	14.67
0.05		0.04			
0.05		0.03			
0.05		0.03			
0.06		0.04			
0.09		0.05			
0.06		0.05			
0.07		0.05			

Commercial Purge E2

Extruder Volume	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L	Corrected concentration
				(mm)	(cm)		
2.00	0.31	0.25	0.04	0.06	0.006	39.67	24.92
	0.34		0.06				
	0.33		0.02				
	0.39		0.01				
	0.13		0.10				
	0.17		0.10				
	0.17		0.09				
	0.18		0.09				
3.00	0.24	0.18	0.03	0.06	0.006	28.89	14.14
	0.26		0.03				
	0.24		0.06				
	0.25		0.04				
	0.13		0.09				
	0.10		0.09				
	0.10		0.08				
	0.11		0.08				
4.00	0.10	0.16	0.08	0.06	0.006	26.22	11.47
	0.12		0.07				
	0.11		0.08				
	0.09		0.09				
	0.21		0.05				
	0.21		0.03				
	0.22		0.05				
	0.24		0.06				
5.00	0.11	0.15	0.08	0.06	0.006	25.36	10.61
	0.11		0.08				
	0.11		0.08				
	0.11		0.08				
	0.20		0.05				
	0.20		0.04				
	0.19		0.04				
	0.20		0.03				
6.00	0.08	0.11	0.07	0.05	0.005	23.82	9.07
	0.09		0.07				
	0.08		0.05				
	0.09		0.06				
	0.14		0.02				
	0.13		0.02				
	0.13		0.04				
	0.13		0.04				
7.00	0.18	0.14	0.04	0.06	0.006	22.71	7.96
	0.17		0.05				
	0.17		0.05				
	0.17		0.05				
	0.10		0.07				
	0.11		0.08				
	0.11		0.08				
	0.09		0.07				

Clear Polymer Film

Absorbance @ 635 nm	Average absorbance	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L
			(mm)	(cm)	
0.08	0.08	0.04	0.05	0.005	14.75
0.09		0.04			
0.09		0.04			
0.08		0.05			
0.07		0.06			
0.07		0.05			
0.08		0.07			
0.07		0.06			

Slip additive Polypropylene Wax

Extruder Volume	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L	Corrected concentration
				(mm)	(cm)		
2.00	0.47	0.44	0.08	0.08	0.008	58.54	44.61
	0.45		0.06				
	0.48		0.07				
	0.49		0.08				
	0.38		0.05				
	0.42		0.09				
	0.43		0.09				
	0.41		0.09				
3.00	0.31	0.32	0.09	0.07	0.007	46.52	32.59
	0.32		0.08				
	0.33		0.05				
	0.34		0.06				
	0.34		0.08				
	0.32		0.06				
	0.33		0.06				
	0.30		0.08				
4.00	0.24	0.26	0.08	0.07	0.007	39.12	25.20
	0.25		0.08				
	0.26		0.08				
	0.26		0.06				
	0.27		0.06				
	0.26		0.07				
	0.27		0.06				
	0.29		0.05				
5.00	0.25	0.25	0.06	0.07	0.007	38.28	24.36
	0.24		0.06				
	0.26		0.08				
	0.26		0.07				
	0.22		0.07				
	0.24		0.08				
	0.28		0.06				
	0.29		0.06				
6.00	0.23	0.22	0.07	0.06	0.006	35.33	21.40
	0.26		0.05				
	0.24		0.05				
	0.25		0.06				
	0.18		0.08				
	0.19		0.07				
	0.19		0.06				
	0.21		0.06				
7.00	0.17	0.20	0.08	0.06	0.006	35.11	21.19
	0.20		0.07				
	0.19		0.05				
	0.19		0.05				
	0.25		0.06				
	0.21		0.05				
	0.21		0.05				
	0.19		0.05				

Clear Polymer Film

Absorbance @ 635 nm	Average absorbance	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L
			(mm)	(cm)	
0.07	0.07	0.05	0.05	0.005	13.92
0.07		0.06			
0.08		0.05			
0.07		0.05			
0.07		0.06			
0.07		0.05			
0.07		0.05			
0.07		0.04			

Slip additive Polyamide

Extruder Volume	Absorbance @ 635 nm	Average absorbance (A)	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L	Corrected concentration
				(mm)	(cm)		
2.00	0.35	0.36	0.05	0.05	0.005	69.32	54.58
	0.32		0.08				
	0.31		0.04				
	0.33		0.04				
	0.40		0.05				
	0.40		0.06				
	0.39		0.04				
	0.38		0.06				
3.00	0.25	0.28	0.04	0.05	0.005	57.09	42.34
	0.25		0.06				
	0.26		0.05				
	0.28		0.05				
	0.27		0.05				
	0.29		0.05				
	0.34		0.05				
	0.33		0.06				
4.00	0.26	0.25	0.04	0.05	0.005	47.67	32.92
	0.29		0.04				
	0.25		0.05				
	0.26		0.06				
	0.22		0.04				
	0.23		0.05				
	0.24		0.06				
	0.26		0.08				
5.00	0.16	0.21	0.06	0.05	0.005	42.74	28.00
	0.16		0.05				
	0.17		0.04				
	0.20		0.05				
	0.25		0.05				
	0.27		0.06				
	0.24		0.04				
	0.24		0.05				
6.00	0.24	0.22	0.05	0.05	0.005	42.25	27.51
	0.24		0.05				
	0.24		0.09				
	0.24		0.01				
	0.22		0.05				
	0.21		0.05				
	0.18		0.06				
	0.17		0.07				
7.00	0.20	0.21	0.06	0.05	0.005	38.63	23.89
	0.21		0.06				
	0.21		0.05				
	0.22		0.06				
	0.21		0.05				
	0.22		0.06				
	0.22		0.06				
	0.21		0.06				

Clear Polymer Film

Absorbance @ 635 nm	Average absorbance	Film Thickness	Average Thickness (L)		Concentration (c) c = A / L
			(mm)	(cm)	
0.06	0.07	0.05	0.04	0.004	14.75
0.07		0.05			
0.06		0.04			
0.07		0.04			
0.07		0.05			
0.06		0.05			
0.07		0.04			
0.06		0.04			