



Effects of Processing Parameters on Mechanical Properties of Polymer

SA Amadi, CP Ukpaka

Department of Chemical/Petrochemical Engineering Rivers State University of Science and Technology Nkpolu, PMR. 5080, Port Harcourt, Nigeria.

Abstract This work utilized the theory of polymerization of unsaturated hydrocarbon compounds into polymer resins which were transformed into simple Engineering product (film). Films of various thicknesses were produced by extrusion using Italwork Tubular Film Line equipment. The films were tested first by Dart Drop test using ASTM D1709 method and secondly by polyethylene Geomembranes test using ASTM D5323 method. The results were plotted in graphs and it was observed that the films produced were of poor quality, with the exception of those produced at take-up speed of 1rpm and 2rpm with corresponding thicknesses of 0.21mm and 0.13mm respectively. These were found through tests to be of good quality that could be compared with existing ones in market, it was then recommended to film only when it is produced at F6A could be used for production of good quality films only when it is produced at take-up speed of 1rpm or 2rpm with corresponding thickness of 0.21mm and 0.13mm respectively, using Italwork tubular Film Line equipment.

Keywords Effect, Parameters Processing, Mechanical, Polymer, Properties.

Introduction

A polymer is a chemical compound with large molecules made of simple molecules of the same kind. The joining of the simple molecules (units) to produce a large one is known as polymerization. Through this process, polymers such as polyethylene, polystyrene, polyvinyl chloride (PVC) and many others were made. Polymers are made from resins. There are natural as well as synthetic resins. Synthetic resins are made chemically. Resins are either in crystalline form or in powdered form. They melt when subjected to heat [1 - 41].

Substances have varying melting temperatures, as they melt, liquid or semi-liquid and sometimes thick paste-like substance known as melt results. The different melts flow differently, some fast like air and water, some flow slowly like oil and others flow very slowly and yet others resist flow, they remain stationary except a force (stress) is applied on them. This type of forceful flow is described as rheology, which is defined as the science of deformation and flow of material. Melt rheology depends greatly on temperature. The force on a fluid acting between the surface of the fluid and the plane on which the fluid is flowing encounters a resisting force, and the force is more pronounced in some substances than in others. This resistance to flow is called viscosity [34 - 41].

Viscosity is dependent on temperature. Increase in temperature reduces viscosity while the reverse is the case. Low temperatures have adverse effects on polymers because the activities of bacteria are generally higher at such temperature.

It is not appropriate to fix a common processing temperature because some polymers decompose while others do not become molten at such temperatures. A temperature at which most commercial polymers are processed lies between 150-300 °C. The temperature 200 °C above the glass transition temperature, T_g, is a temperature, which lies within



the processing range of many commercial polymers and one at which the molecules may be considered to experience a common state of excitation [7-16].

Proper study of temperature effects on viscosity of polymer melts will lead to understanding of processing conditions of polymers. The mastery of the equipment-extruder and the various molds and their conditions of usage will lead to proper processing of polymers. Polymers are used in production of plastic materials.

The importance of polymer and its application is seen every where. The application of polymer covers almost all areas in life. Some areas are cited below. The application of polymeric materials is most in the industry. The industry is sub-divided into major and minor consumers of polymeric materials. In the major industries, packaging, constructions, electronics and furniture take the greater proportion while the household goods, adhesives, paints and automobile industries take lesser proportion [10-20].

The role played by polymeric materials in the improvement of agriculture, horticulture and erosion checking is tremendous. The application of polymeric materials in agriculture is known as plasticulture. It is primarily concerned with:

- (i) Improvement of water handling (irrigation), and
- (ii) Agriculture machinery.

The prevalent use of disposable plastic syringes is both cheap and neat. In packaging of drugs, polymers materials are widely used. Optical glasses, frames, and cases form other extensive areas of application of polymer materials. The making of upholstery chairs, plastic chairs and tablets, drinking cups, plates, jugs, trays and spoons are very glaring. Polymeric materials are also applied in the making of ladies handbags, babies' wears and toys. The foams on our chairs and beds, in our homes, are made of polymeric materials

Here we see another variety of application materials lumped together. This ranges into the making of computers, air-crafts, ship-building and several others. This work is no doubt of great value [17-25].

Polymers can be classified as natural or synthetic according to their origin. Those isolated from natural materials are called natural polymers. Examples are cotton, silk, wool and rubber. Cellophane, cellulose, rayon, leather are chemical modifications of natural polymers. Polymers synthesized from low molecular weight compounds are called synthetic polymers. Examples include polyethylene, polyvinyl chloride (PVC), Nylon and Terylene. A polymer whose backbone chain is essentially made of carbon atoms is termed an organic polymer. The atoms attached to the side valences of the backbone carbon atoms are usually those of hydrogen, oxygen, and nitrogen. The majority of synthetic polymers are organic; they are large in number and variety. The molecules of inorganic polymers on the other hand generally contain no carbon atom in their chain backbone. Glass and silicone rubber are examples of inorganic polymers [26-34].

Some polymers soften on heating and can be converted into any shape that they can retain on cooling. The process of heating, reshaping and retaining the shape on cooling can be repeated several times. Such polymers that soften on heating and stiffen on cooling are termed thermoplastics. Examples include; polyethylene, PVC, polypropylene, polystyrene, nylon and sealing wax [34-40].

Some polymers, on the other hand, undergo some chemical change on heating and convert themselves into an infusible mass. They set into a mass on heating and once they are set, cannot be reshaped. Such polymers are called thermosetting polymers. Examples include; epoxy, melamine-formaldehyde, urea-formaldehyde. When a polymer is shaped into hard and tough utility articles by the application of heat and pressure, it is used as a plastic. Examples include; polystyrene, PVC, polymethyl-methacrylate. When vulcanized into rubber products exhibiting good strength and elongation, polymers are used as elastomers. Examples include; natural rubber, synthetic rubber, and silicone rubber. If drawn into long filament-like materials, whose length is at least 100 times its diameter, polymers are said to have been converted into fibers, examples include nylon, terylene etc. Polymers used as adhesives, potting compounds, sealants in a liquid form are described as liquid resins. Examples are epoxy adhesives and polysulphide sealants. The vast majority of polymers used today as plastics, rubbers, adhesives and paints are synthetic and are made from chemicals derived from oil.



Materials and Methods

Theoretical Principles and Mathematical Models Formulation

Based on the relation between shear rate and shear stress two types of fluid can be distinguished, that is, Newtonian and non-Newtonian fluids. The viscosity of a Newtonian fluid completely describes the flow characteristics of the fluid, since it is constant at all shear rates. The stress in a fluid is a function of the rate of agitation, the rate of deformation, and the shear rate. Fluids with a non-linear relationship between shear stress and shear rate are non-Newtonian.

Fluid Flow Models

A fluid flow model describes the flow behaviour of a fluid by expressing the relationships between shear stress (pressure) and shear rate (flow rate). For Newtonian fluids, however, shear rate is more complex. A generalized relationship for all non-Newtonian fluids has not been found. Instead various models have been proposed to describe the behaviour of several ideal non-Newtonian fluids. Two non-Newtonian models shall be discussed, namely, the Bingham Plastic Model and the Power Law Model. The Newtonian fluid model is defined by the relationship,

$$\tau = \mu \dot{\gamma} \quad (1)$$

At constant temperature and pressure, the shear stress and the shear rate are directly proportional; the constant of proportionality, μ is the absolute viscosity.

The Bingham Plastic Model

The Bingham plastic fluid model shown in figure below is defined by the relationship,

$$\tau = \tau_o + \mu \dot{\gamma} \quad (2)$$

The Bingham fluid most notably from a Newtonian fluid by the presence of a yield stress, commonly called “yield point”. The yield stress is a measure of electrical attractive forces, in the fluid under flowing conditions which collapses at τ_o before flow begins. No bulk movement of the fluid occurs until the applied stress exceeds the yield stress.

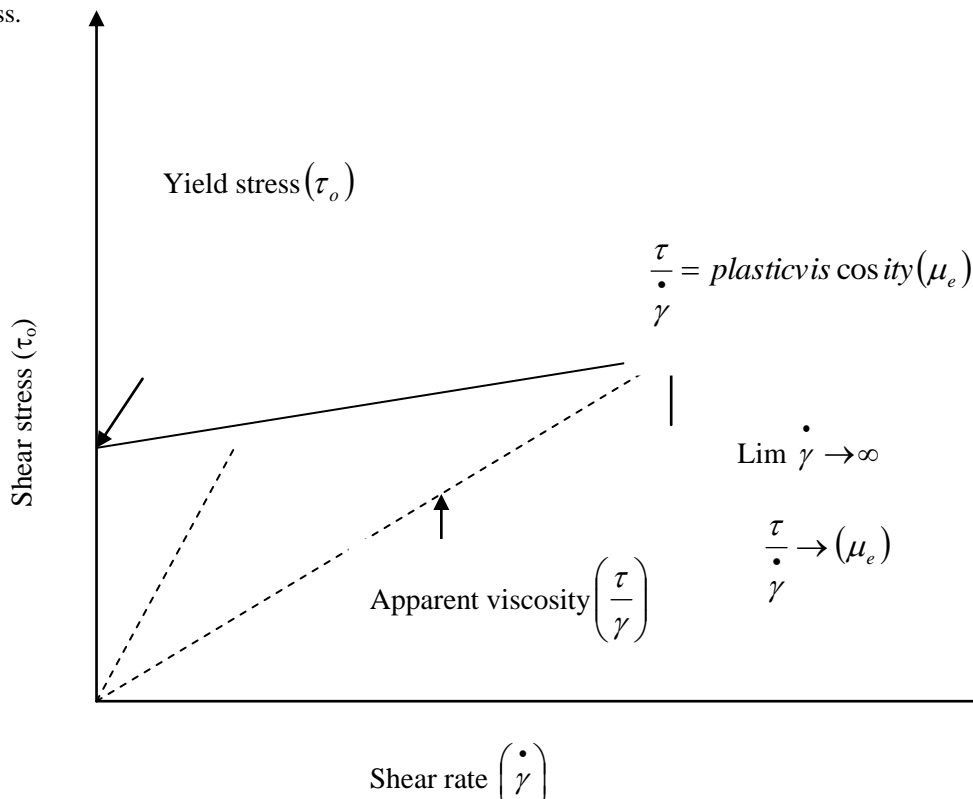


Figure 1: Flow curve for Bingham Plastic fluid



The apparent viscosity or effective viscosity is defined as the shear stress divided by the shear rate, and varies with shear rate for non-Newtonian fluids. The slopes of the dashed lines in figure 3.1, represent apparent viscosities at various shear rates. The apparent viscosity decreases with increasing shear rate. This phenomenon is called “shear thinning”. As the shear rate approaches infinity, the apparent viscosity reaches a limit called the plastic viscosity. The plastic viscosity is the slope of the Bingham plastic line.

The Power Law Fluid Flow Model

“The power law fluid model” (or Ostwald-de Waele-Nutting) model is defined by the relationship.

$$\tau = K \dot{\gamma}^n \quad (3)$$

Where n is the power index. For the special case of $n=1$, the special Newtonian case is recovered from the more general power law. Ling and Sandford, used equation to relate zero-shear viscosity, μ_0 to weight average molecular weight.

$$\mu = KM_w^{3.4} \quad (4)$$

Where μ_0 is zero shear viscosity and M_w is weight average molecular weight. Equation (4) clearly establishes that the zero-shear viscosity μ_0 , is related to the weight average molecular weight. This correlation was found to be universally obeyed for linear polymers based on both theoretical and experimental considerations.

Generally, the consistency factor, K , describes the thickness of the fluid and it is somewhat analogous to the apparent viscosity. As K increases, the fluid becomes thicker. The flow behaviour index, n , indicates the degree of non-Newtonian behaviour, where $n=1$, the power law equation is identical to the Newtonian fluid equation. If n is greater than 1, the fluid is classified as dilatant (thickened); the apparent viscosity increases if the shear rate increases. If n is between zero and 1, the fluid is classified as pseudoplastic. Pseudoplastic fluid exhibits shear thinning.

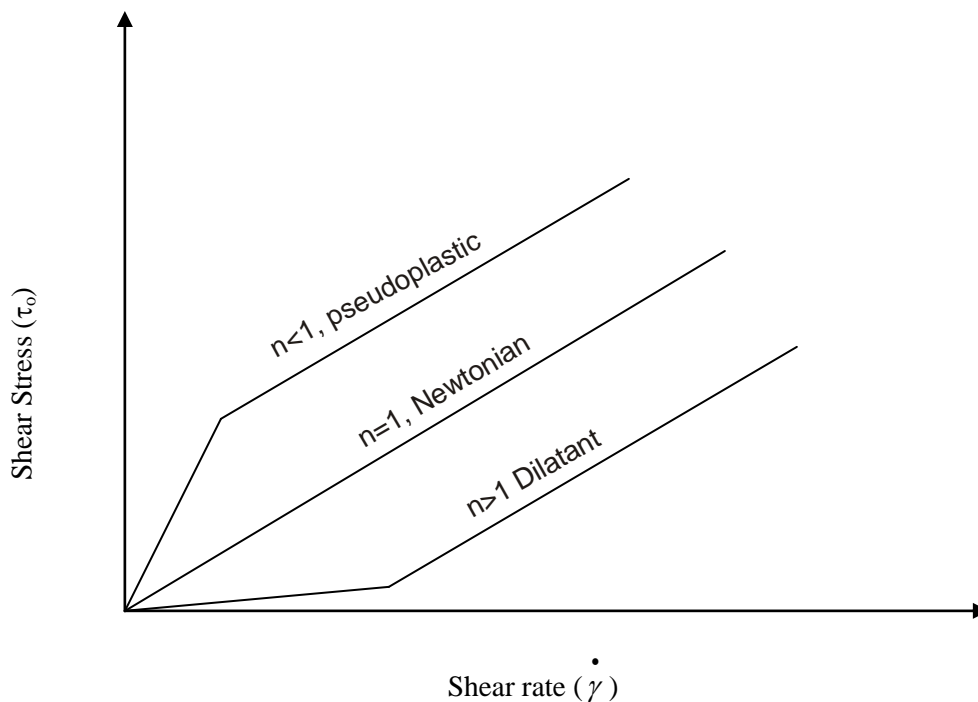


Figure 2: Flow curve for power Law fluids



Experimental Procedure

Materials and Equipment

The chemicals (polymer resin) which was used for this experiment were linear high-density polyethylene (LHDPE)-Butene-1 co-monomer and an additive) which acted as a colour agent. Both were prepared and supplied by Eleme Petrochemicals Company Limited (EPCL), Eleme, Port Harcourt.

The equipment used for the experiment is Italwork Tubular Film Line. It is used for extruding polymer films which are usually used for general packaging materials. An extruder machine is shown in appendix 1B.

The films produced were tested. The test was done in the company's laboratory in the Standardization and Testing Section.

The experiments and tests were conducted in the Products Application Section and the Laboratory of the Standardization and Testing Section of Eleme Petrochemicals Company Limited (EPCL), Eleme, Port Harcourt.

All the facilities used were provided by the (PTDC) of the company. However some tests could not be done in their laboratory because of non-functionality of PTDC 'Instron 4482' which would have been used to determine mechanical properties of elongation modulus, tear strength, toughness and puncture strength. These parameters were analysed at Michelin laboratory.

Experimentation

The experimenter is titled 'Production of Tubular Films using Italwork Tubular Film Line'. The experiment was carried out to observe the influence of feed rate (screw speed) on orientation of tubular film, that is, how does the feed rate affect the arrangement of molecules in the film at constant take-up speed of 3 rpm. Temperature and pressure were kept constant throughout the experiment. Pressure was internally applied.

Procedure

- (i) The extruder, Ital work tubular film line was started and 1/3 of the content of a 250kg bag of high-density polyethylene-butene-1 co-monomer resin, and 20g of additive were put in the hopper of the extruder (the resin and additive were in crystal form). A force provided by the rotation of the screw moved the molten polymer through various zones to the die. An amount of air was let in through a valve. The amount of air let in controlled the width of the film. It also has effect on the thickness of the film produced. The pressure built up in the metering zone enabled the polymer melt to enter the die and emerge out of it with the desired profiles. The extruded material of the required profile emerging from the die is quite hot (usually 125 - 350 °C) but in this particular work the temperature of the die was 175 °C. The hot material was cooled rapidly to avoid deshaping. The extrudate (film) was cooled by cold air blast. The product (film) formed passed through many rolls and was cut to desired lengths, which were taken to the laboratory for required measurement an test.
- (ii) The second experiment was aimed at observing the influence of take-up speed (rollers speed) on orientation of tubular films. In other words, what is the influence of take-up speed on orientation of tubular film at constant feed rate (screw speed).

In this experiment, the first process was repeated with varying take-up speed at a fixed feed rate. The extrudate (film) was also cut to desired lengths, which were taken to the laboratory for measurement and test.

Tests and Measurements

These are done in the Standardization and Testing Section. Thickness of the film was measured with a micrometer screw gauge while dart impact strength test was performed using ASTM D1709 method. The test helps to assess the quality of the films.

In performing the test, the films were cut into small squares measuring 160mmx160mm and were slipped one after the other across a circular hole in a dart impact tester equipment when it was opened. After slipping the piece of film, a knob was pressed which tightened the film across the hole in the equipment. A weight known as the tub or falling dart which is usually cylindrical with rounded nose that contacts the specimen (film) was released from a height to fall on the tensed film. This was done five to ten times and the number of failures and passes recorded.



When this had been done again five to ten times, from the record percentage failures were calculated and from the sum of percentage failures impact failure were calculated.

Results and Discussion

The results obtained from the experiment were tabulated as follows:

Table 1: Shows variation in thickness of film at constant take-up speed of 3rpm.

Feed Rate (Screw Speed) rpm	Thickness (mm)
4	0.03
6	0.07
8	0.08
10	0.10
12	0.11

Table 2: Shows Variation in thickness of film at constant feed rate of 10rpm

Take-up Speed (rpm)	Thickness (mm)
1	0.21
2	0.13
3	0.09
4	0.07
5	0.05
6	0.04
7	0.03
8	0.03
9	0.03
10	0.03
11	0.03
12	0.02
13	0.02
14	0.02
15	0.02
16	0.02
17	0.02
18	0.02
19	0.02
20	0.02

Table 3: Dart Prop Test Result showing 100 percent failure

Weight (g)	No. of Failures	No. of passes	Percentage Failure
1530	5	0	100
45	5	0	100
60	5	0	100
75	5	0	100
90	5	0	100

Sample HDFE-BU-1 FILM 1
 Number of Specimens: 5
 Temperature: 25
 Humidity: 38
 Speed 1: 50.00 mm/min



Table 4: Showing result of HDPE-BU-1 Film 1

S/N	Modulus (secant 2%) (MPa)	Tensile Strength (MPa)	Yield Elongation (%)	Break Elongation (%)	Modulus of Elasticity (MPa)	Specimen Info
1	516.262	33.796	2.886	1441.504	493.646	0.21 thick
2	473.364	30.402	3.141	1359.651	490.880	0.21 thick
3	494.899	29.731	2.624	1078.961	498.309	0.21 thick
4	506.532	33.521	2.616	1522.305	502.088	0.21 thick
5	504.011	32.737	2.532	1330.259	504.784	0.21 thick
Mean	499.014	32.037	2.760	1346.536	496.622	0.00
S.D	16.231	1.856	0.251	167.292	21.220	0.00
Minimum	473.364	29.731	2.532	1078.961	490.880	0.00
Maximum	516.262	33.796	3.141	1522.305	504.784	0.00
Range	42.898	4.065	0.609	443.344	13.904	0.00

Sample HDPE-BU-1 Film 2
 Number of Specimens: 5
 Temperature: 25
 Humidity: 38
 Speed 1: 50.00 mm/min

Table 5: Showing result of HDPE-BU-1 Film 2

S/N	Modulus (secant 2%) (MPa)	Tensile Strength (MPa)	Yield Elongation (%)	Break Elongation (%)	Modulus of Elasticity (MPa)	Specimen Info
1	621.627	46.720	2.486	1082.626	628.911	0.13 thick
2	548.825	40.701	2.912	1072.319	628.402	0. 13 thick
3	628.064	40.773	2.496	916.257	634.298	0. 13 thick
4	639.303	42.545	2.512	1009.460	630.999	0. 13 thick
5	549.441	38.855	2.939	1096.502	622.598	0. 13 thick
Mean	597.452	42.719	2.669	1035.433	629.042	0.00
S.D	44.561	3.110	0.234	74.489	47.207	0.00
Minimum	548.825	38.855	2.486	916.257	622.598	0.00
Maximum	639.303	46.720	2.939	1096.502	634.298	0.00
Range	90.478	7.865	0.453	180.245	11.700	0.00

Sample PLASTIC FILM COMMERCIAL
 Number of Specimens: 5
 Temperature: 25
 Humidity: 38
 Speed 1: 50.00 mm/min

Table 6: Showing Result of Commercial Film

S/N	Modulus (Secant 2%) (MPa)	Tensile Strength (MPa)	Yield Elongation (%)	Break Elongation (%)	Modulus of Elasticity (MPa)	Specimen Info
1	409.353	25.166	3.534	567.453	409.421	0.06 thick
2	460.421	24.778	4.069	538.277	410.011	0.06 thick
3	557.016	24.802	3.701	569.808	402.820	0.06 thick



4	599.956	28.173	3.624	619.505	399.910	0.06 thick
5	356.108	24.068	4.059	633.739	391.846	0.06 thick
Mean	476.571	25.379	3.905	485.76	402.805	0.00
S.D	101.225	1.602	1.022	236.954	85.538	0.00
Minimum	356.108	24.068	3.534	67.453	391.846	0.00
Maximum	599.956	28.173	4.069	633.739	410.011	0.00
Range	243.848	4.105	0.535	566.286	18.165	0.00

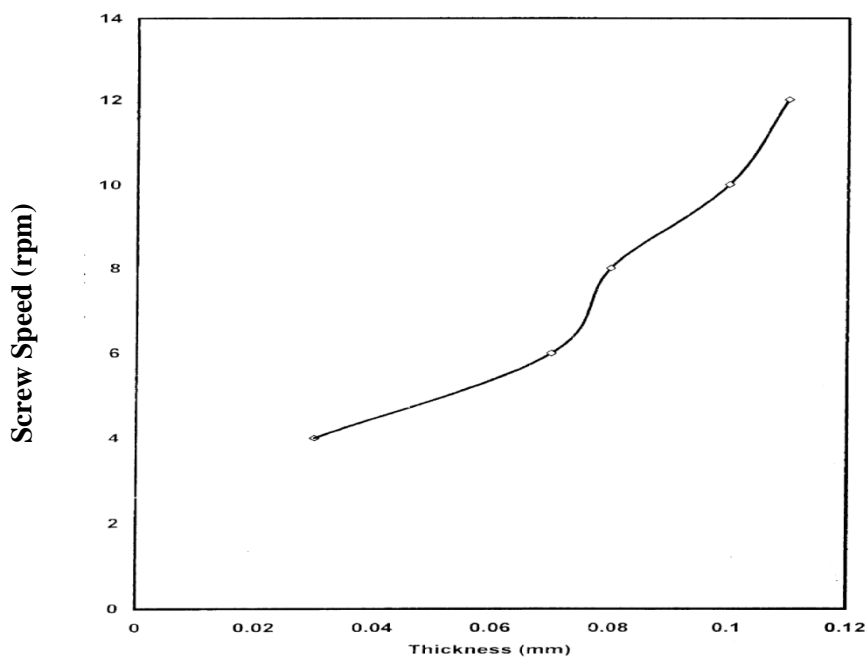


Figure 3: Trend of feed Rate (Screw Speed) vs. Thickness

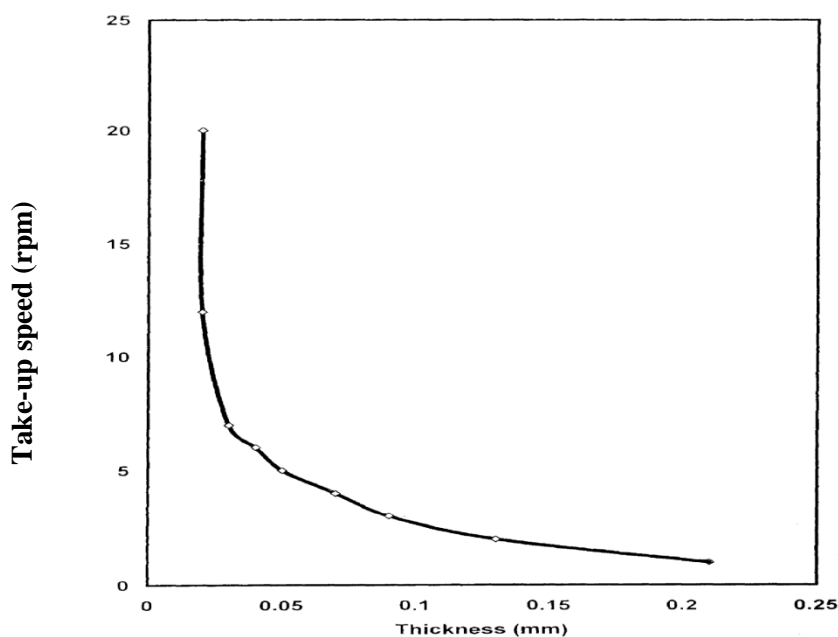


Figure 4: Trend of Take-up Speed vs. Thickness



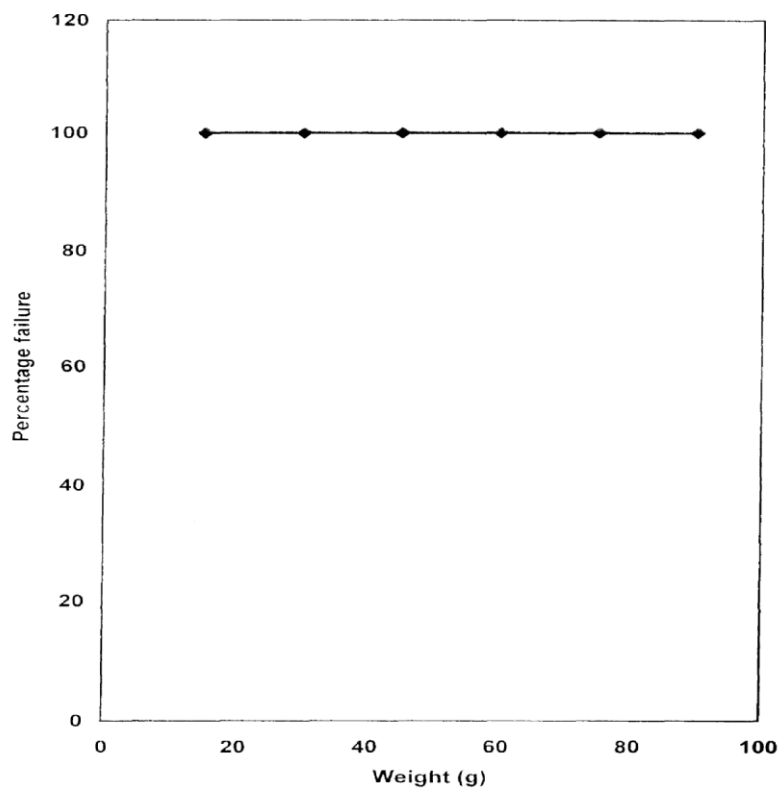


Figure 4a: Trend of weight (g) vs. percentage failure

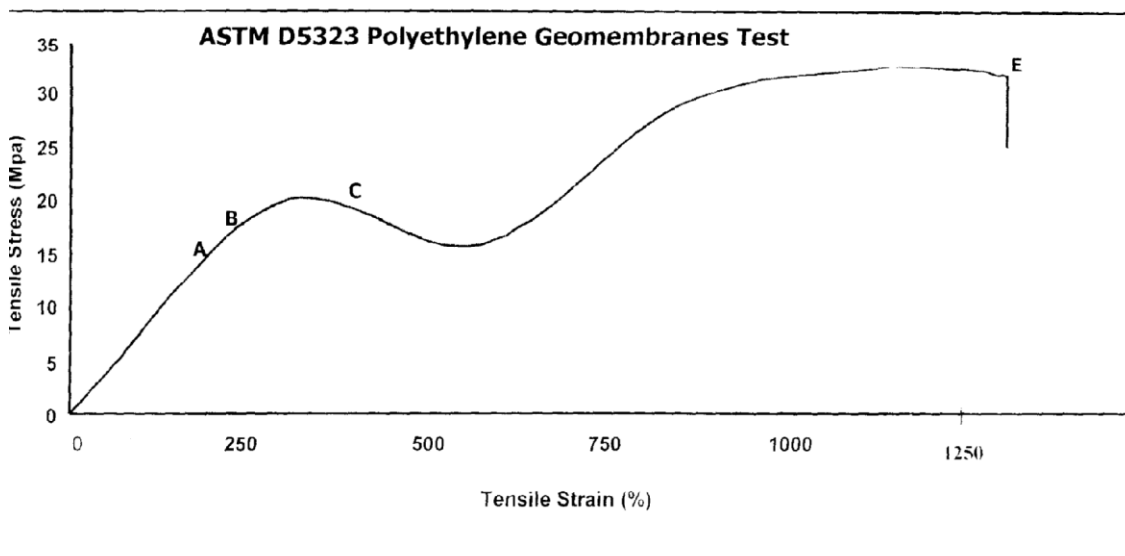


Figure 5: Tensile stress – strain diagram for HDPE-BU-1 Film 1



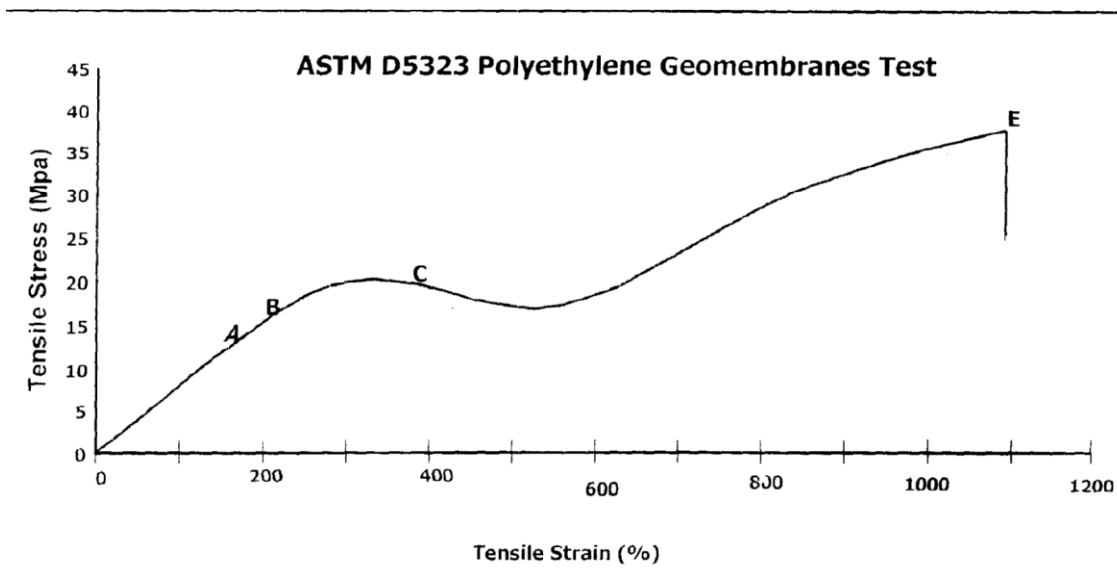


Figure 6: Tensile Stress – Strain diagram for HDPE-BU-2

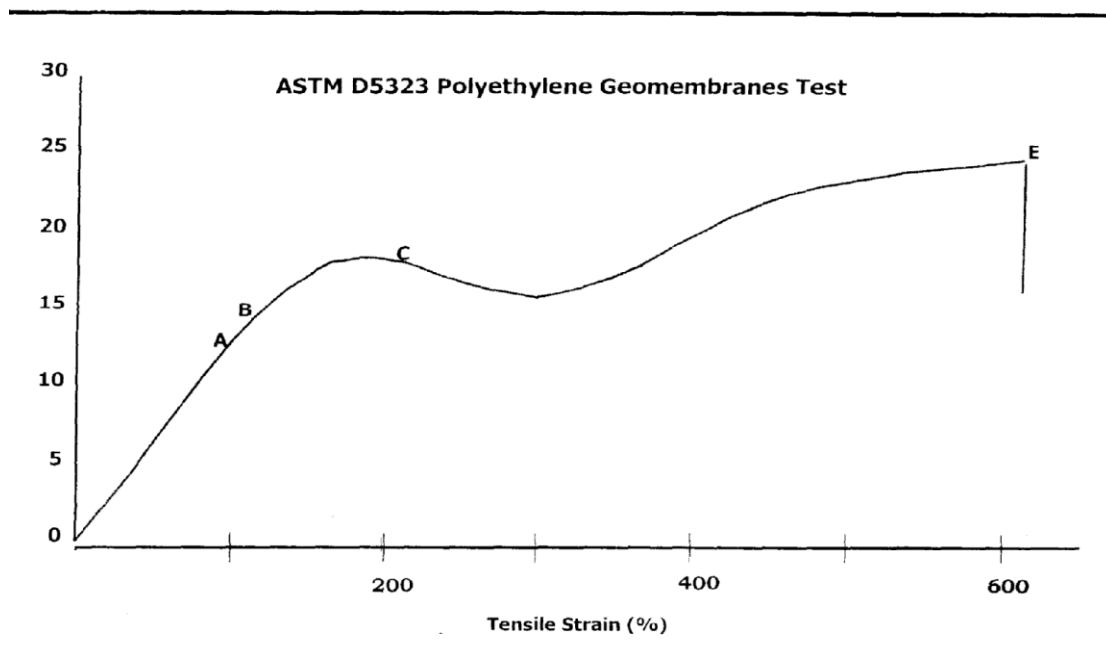


Figure 7: Tensile Stress – Strain diagram of commercial film

In Table 1, increase in feed rate (Screw Speed) at constant orientation speed (take-up speed) of 3rpm produced corresponding increases in thickness of set of films. This is because increase in feed rate increases the volume of melt that move to the die. Though the die opening is fixed it could allow a small range of thickness because of the high degree of hotness of the film and its attachment to series of rolls. Plotting trend of feed rate against thickness showed some element of relationship and some degree of linearity is observed from one point to the other. On the other hand (table 2), increasing take-up speed at constant feed rate of 10rpm gave corresponding decrease in thickness of set of films. The trend also showed the corresponding decrease in thickness.



The Feed

There were three elements seen resulting from feed rate. The pressure built up latter at the meeting zone was manifestation of feed rate. In molten polymer, the force applied was proportional to the rate of flow of the melt. This explained why the higher the feed rate (screw speed), the more the thickness of film, the force was applied as the screw rotated. That is, the screw rotation resulted in movement of the polymer melt from compression zone to the die.

Take-Up Speed

This parameter showed great effect on the film produced. As the take-up speed increased, molecular orientation increased while thickness of the film decreased.

Elastic Property of Film

In Figure 3, 4, and 5 the initial portion of the stress-strain diagram (OA) is a straight line passing through the origin. This is true of the polymer films up to the point A. the relationship between stress and strain in this region of the diagram is linear and the slope at any point on this straight line is the ratio between the stress and strain. Thus:

$$\frac{\tau}{\gamma} = E \quad (5)$$

$$\tau = E\gamma \quad (6)$$

Where, τ is the stress and γ is the corresponding strain. The constant of proportionality E is called Young's Modulus (or Modulus of Elasticity) – see column 6 of table 3, 4, and 5. Hence the films produced and the commercial one obey Hook's law. When subjected to equal load, they will sustain it provided the elastic limit is not exceeded. The films therefore exhibit elastic property (see Figures 4, 5, and 6).

Tensile Strength

Looking at Tables 3, 4 (experimental) and 5 (commercial), it is seen that the tensile strength of the experimental is slightly higher than that of the commercial showing that the experimental material is of a better quality than the commercial because it can sustain a higher load than the commercial (see column 3 of Tables 4, 5, and 6).

In Figures 4, 5, and 6, the behaviour of a ductile material such as the films produced is observed. Beyond the elastic limit, point A, the material (film) undergoes plastic deformation and yield elongation occurs.

Force Applied

The force was applied took source from the rotation.

This is force per unit area as the polymer melt moved towards the die.

Fa Shear(γ) The force applied was directly proportional to the rate of flow of polymer melt. Thus, have

$$\tau = k\gamma \quad (7)$$

As the force was applied, the manifestation was seen in the thickness of the film produced (see Tables 1 and 2). As the polymer melt moved towards the die, velocity of molecules became maximum at the center of the barrel of the extruder. At the walls of the barrel, velocity was zero and resistance to flow (viscosity) was at maximum.

Temperature as a Processing Parameter

Without heat there would be no mobility of molecules and the molecules could only be mobile when the external heat energy supplied by the heaters is higher than the intra-molecular (Van der waals) forces of attraction holding the molecules together in solid state. The heat manifested through the heaters and was shown as profile from feed zone to die. At feed zone where the energy level was lowest, the resin takes in heat and the heat intake increased gradually to compression zone. At compression zone, the molecules become mobile. More heat was needed in the transition zone. Here any resin in the solid state was transformed into liquid. At the metering zone, the molecules



should be at the same energy level, that is, between the feed zone and metering zone, all the molecules would have attended the same energy level. But if enough heat was not applied, there would be inhomogeneous melt which gives rise to variety in thickness.

Conclusion

Resin sample F6A, which is a co-monomer of polyethylene and butane-1 which was used for this experiment was found through tests to be of low quality polymer for production commercial films. However, the films produced to take-up speed of 1rpm and 2rpm with corresponding thicknesses of 0.21mm and 0.13mm respectively were of good quality could be compared with commercial ones in market.

It is therefore concluded that using sample F6A, good quality films could be obtained using Italwork Tubular Film Line equipment, only at take-up speed of 1rpm and 2rpm respectively, keeping feed rate constant at 10rpm.

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APPENDIX 1A

Calculation of Failures

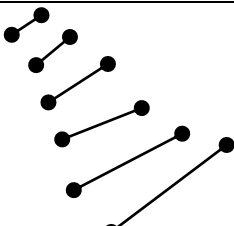
$$\% \text{ Failure} = \frac{\text{Failure}}{\text{No. of Experiments}} \times 100$$

Calculation of Impact Failure, Weight (g)

$$W_F = W_L - \left[D_W \left(\frac{S}{100} - \frac{1}{2} \right) \right]$$

Where W_F = Impact failure, Wt(g)
 W_L = Lowest missile, (Wt(g) at which 100% failure occurred.
 S = Sum of missile failure.
 D_W = Missile increment.

Molecular arrangement and thickness as take-up speed increases.

Take-up speed (rpm)	Molecular (thickness)	Orientation	Film (increases)	thickness
1				6μ
2				4.8μ
3				3.9μ
4				2.8μ
5				1.6μ
6				0.7μ
Rheology	→	Crystallization	→	Finished products

APPENDIX 1B

POLYMER PROCESSING EQUIPMENT

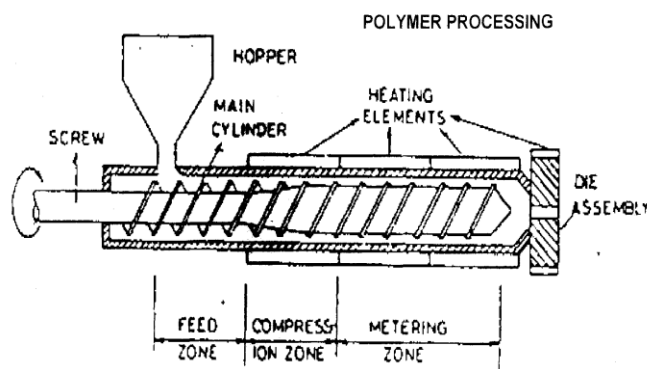


Figure 1a: Schematic diagram of a simple extrusion machine

The extruder is made up of the following parts; hopper, main cylinder, heating elements, screw and the die. Within the extruder, it is divided into four parts of differing temperature degrees. This range of temperature is called zones. Thus, we have feed zone, compression zone, transition zone and the metering zone. The heat supply varies from 160 °C at the feed zone to about 200 °C at the die. Feed zone has temperature range of 160-175 °C, compression zone has between 175-180 °C, transition zone has between 180-190 °C and the metering zone has between 190-195 °C. The die temperature is either at 175 °C or 200 °C depending on the polymer being treated.



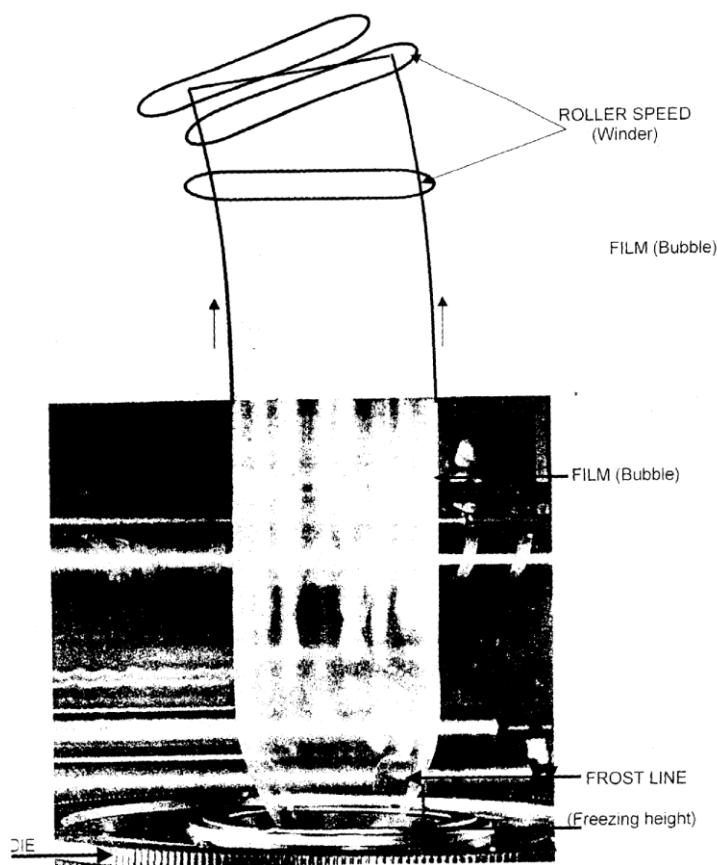


Figure 1b: Showing extruded film (bubble) coming out of die

Appendix 2

Representative Properties of some Important Commercial Polymers

1. Physical and Thermal Properties ^a

Polymer	$P^b \text{ g cm}^{-3}$	$T_g^0 \text{ } ^\circ\text{C}$	$T_m^{b0} \text{ } ^\circ\text{C}$
Cellulose acetate	1.27-1.34	49	-
Nylon-6	1.08-1.23	46-60	223
Nylon-6,6	1.07-1.24	45-57	265
Polycarbonate	1.20-1.31	141-150	227
Polyethylene (all grade)	0.91-1.00	-120	98-135
Polyethylene terephthalate	1.33-1.48	69-77	267
Polymethy metacrylate	1.17-1.23	105-126	160
Polypropylene	0.9-0.95	-10 to - 18	177
Polystyrene	1.05-1.13	100	240
Polyvinyl acetate	1.19-1.34	28-31	-
Polyvinyl chloride	1.39-1.52	81	273
Silicon rubber	1.07	-123	-43

^a Numbers typically indicate a range of reported values for samples with different crystallinity, water content, molecular weight and thermal histories. Uncertain or controversial values are given within parentheses.



^b In most cases, values indicate the range of densities between that of the glassy amorphous state to that of the fully crystalline polymer as calculated from X-ray data of crystalline domains.

2. Mechanical Properties

Polymer	E ² GPa	$\gamma b(\gamma_r)^b$ MPa	$\epsilon b(\epsilon_r)^c$ %	Izod impact strength J/m ^d
Cellulose acetate	2	30(60)	30(6)	6-133
Nylon -6	1.9	75(50)	300(30)	(25)
Nylon-6,6	2.0	80(57)	200(25)	110
Polycarbonate	2.5	60(65)	125(30)	800
Polyethylene (all grade)	0.2-1	10-30	600-800	130-700
Polyethylene terephthalate	3.0	54	275(6)	70
Polymethy metacrylate	3.2	65	10	27
Polypropylene	1.4	33(32)	400(12)	80
Polystyrene	3.4	50	2.5	28
Polyvinyl acetate	0.6	29-49	10-20	160
Polyvinyl chloride	2.6	50(48)	30(3)	43
Silicon rubber	-	4.8-7.0	100-400	-

Tensile modulus; to convert GPa to Psi, multiply by 1.45×10^5 .

Stress at break (yield); to convert MPa to Psi, multiply by 145.

Elongation at break (yield); to convert Im^{-1} to ft-ibf in^{-1} divide by 53.38.

Appendix 3 Major ASTMs* Standards for Plastics and Rubber, plastics (vols. 8.01, 8.02 and 8.03)

ASTM	STANDARD
D256	Impact resistance of plastics and electrical insulating materials.
D412	Rubber properties intension.
D543	Resistance of plastics to chemical reagents.
D569	Measuring the flow properties of thermoplastic molding materials.
D570	Water absorption of plastics.
D621	Deformation of plastics under load.
D638	Tensile properties of plastics.
D695	Compressive properties of rigid plastics.
D792	Specific gravity and density of plastics by displacement.
D1745	Transparency of plastic sheeting.
D1898	Sampling of plastics.
D1925	Yellowness index of plastics.
D1929	Ignition properties of plastics.
D2240	Rubber property-durometer hardness.
D2288	Weight loss o plasticizers on heating.
D2582	Puncture-propagation tear resistance of plastic film and thin sheeting.
D2684	Determining permeability of thermoplastic containers.
D2734	Void content of reinforce plastics.
D2857	Dilute solution viscosity of polymers.
D3029	Impact resistance of rigid plastic sheeting or parts by means of a tube (falling weight).
D3420	Test method for dynamic ball burst (pendulum) impact resistance of plastic films.



D3593	Test method for molecular weight averages and molecular weight distribution of certain polymers by liquid size-exclusion chromatography (gel permeation chromatography, GPC) using universal calibration.
D4272	Test method for impact resistance of plastic film by instrumented dart drop.
D4440	Practice for rheological measurement of polymer melts using dynamic mechanical procedures.

Rubber (Vols. 9.01 and 9.02)

ASTM	STANDARD
D297	Methods for rubber products – chemical analysis.
D395	Test method for rubber property – compression set.
D412	Test methods for rubber properties in tension.
D471	Test methods for rubber property effect of liquids.
D624	Test methods for rubber property – tear resistance.
D797	Test methods for rubber property – Young’s modulus at normal and subnormal temperatures.
D814	Test methods for rubber property – vapour transmission of volatile liquids.
D1349	Recommended practice for rubber – standard temperatures and atmospheres for testing and conditioning.
D1630	Test method for rubber property – abrasion resistance (NBS abrader).
D2084	Test method for rubber property – vulcanization characteristics using oscillating disk cure meter.

Appendix 4

SI Units^a and Physical constants

Units and Symbols

Quality	Name	Symbols	CGS Equivalent
Capacity	Liter	L	10^{-3}m^3
Electric current	Ampere	A	Ampere
Electric capacitance	Farad	F	ASV^{-1}
Energy, work, heat	Joule	J	Nm
Force	Newton	N	MkgS^{-2}
Frequency	Hertz	Hz	S^{-1}
Mass	Kilopgram	Kg	Kg
Plane angle	Radian	rad	rad
Power	Watt	W	JS^{-1}
Pressure, stress	Pascal	Pa	Nm^{-2}
Viscosity (dynamic)	Pascal second	Pas	NSm^{-2}

Conversion Factors

Energy: 1J	=	0.2387 cal
Force: 1N	=	10^5 dynes = 0.102kg _T = 0.2248ib _f
Pressure, Stress: 1Pa	=	10 dyne cm ⁻² = 7.5×10^{-3} mm Hg = 10^5 bar = 1.02×10^{-5} kgcm ⁻² = 1.45×10^{-4} psi
Viscosity: 1Pas	=	10 poise
Density: 1gcm ⁻³	=	0.0361 ib in ⁻³
Temperature: ⁰ R	=	(5/9)K ⁰ C = (5/9) (⁰ F-32) = K+273.15

International System of Units (ISU)

SI Prefixes

Prefix	Symbol	Equivalent
Pico	P	10^{-12}
Nano	N	10^{-9}
Micro	μ	10^{-6}
Milli	m	10^{-3}
Centi	c	10^{-2}
Deci	d	10^{-1}
Kilo	K	10^3
Mega	M	10^6
Giga	G	10^9

Physical Constants

	Symbol	Unit	Value
Avogadro constant	N_A	Mol^{-1}	6.0222E+23
Boltzman constant R/N_A	K	JK^{-1}	1.3807E-23
Gas constant	R	$\text{J}(\text{mol K})^{-1}$	8.3143
		$\text{Bar cm}^3 (\text{mol. K})^{-1}$	83.144
		$\text{Psia ft}^2 (\text{ib mol}^0 \text{R})$	10.732
		$\text{Atm cm}^3 (\text{mol K})^{-1}$	82.057
Gravitational acceleration	g_0	Ms^{-2}	9.80665
Plank constant	H	J _s	6.6262E-34
Permeability of vacuum	μ_0	Na^{-2}	12.566e-7
Permittivity of vacuum $1/\mu_0 c^2$	ϵ_0	Fm^{-1}	8.85419E-12

