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VISUALISATION STUDIES OF FLOW OF RUBBER IN AN INTERNAL MIXER

by

MOHAMAD BIN HAMZAH
BSc, ANCRT

A Master's Thesis
submitted in partial fulfilment of the requirements
for the award of
Master of Philosophy
of the
Loughborough University of Technology

January 1984

Acting Head: Dr D E Marshall
Supervisor: Mr P K Freakley FPRI

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Dedicated to my parents, my wife Hasaniah and my children.
I certify that I am responsible for the work submitted in this thesis, that the original work is my own except as specified in the acknowledgements, and that neither the thesis, nor the original work contained therein has been submitted to this or any other institution for a higher degree.
ACKNOWLEDGEMENTS

In the name of Allah the most Magnificent and most Merciful. All praise be to Allah the Lord of the whole Universe. I am grateful that with the blessing of Allah, I have completed this work.

I would like to express by gratitude to Mr P.K. Freakley for the supervision, guidance and encouragement throughout this work.

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To all my friends, I would like to convey my sincerity for their kind discussions and help in one way or another during my years in Loughborough. My special word of thanks goes to Encik Kamarul Bahrain bin Basir for taking my silicone rubber to the Avon Rubber Company for characterisation testing and to Andrew of the Avon Rubber Company for carrying out the tests. Also to Encik Mohd Sallah Sahimi of Computer Studies for his invaluable advice on computer programming.

My thanks also go to Mrs Janet Smith for her patience in typing this thesis.
Finally, to my wife and others in the family, my feelings of obligation and appreciation goes to them for their sacrifice and tolerance throughout the years of my study.
ABSTRACT

The visualisation study of the dynamics of flow in an internal mixer was undertaken by using a laboratory-scale Banbury mixer with a transparent plastic chamber. The elastomer used was a silicone rubber (ICI grade SE 33) which provided a satisfactory rubbery behaviour and enabled cinematography to be used. The detailed characteristics of flow patterns in the mixing chamber were determined by the movement of coloured non-dispersible markers.

For the purpose of analysis four regions inside the mixing chamber were identified. The region in front of the rotor wings, the void region, the S-shaped region and the bridge region. The movement of material in each of these regions has been determined separately for a range of rotor speeds and fill factors, followed by the interaction between the regions.

The distribution of the voids in the mixing chamber was studied by sketching the shapes and sizes of the voids at various locations around the mixing chamber for a series of relative rotor positions at different fill factors and rotor speeds. By this method the fracture phenomena of the rubber passing under the flight tip could be visualised.

In addition to flow visualisation, pressure measurement inside the mixing chamber was also carried out. This was done by means of a Dynisco pressure transducer located at four positions on the mixing chamber.
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CHAPTER 1
INTRODUCTION

1.1 Investigation Method

Flow visualisation is one of the many tools available in experimental fluid mechanics. It differs from other experimental methods in that it renders certain properties of the flow field directly accessible to visual perception. Throughout history a great number of scientists have been able to develop ideas of elucidating physical phenomena from visual observation. Among the earliest examples of using flow visualisation methods was the experiment carried out by O. Reynold in 1879\(^1\) in which the transition from a laminar flow to turbulent flow has been shown to take place in a horizontal circular pipe by visualising the behaviour of the dye injected into a water flow. Since then a variety of experiments have been established not only in fluid mechanics but also in other fields.

Nowadays the flow visualisation method is becoming more sophisticated and a number of new equipments have been invented. With the development of these new equipments, complicated and delicate flow patterns can be visualised and studied. Two of the examples of employing flow visualisation techniques in carrying out the experiments are the smoke tunnel in studying the drag wind behind car bodies and the tracer method where tracer elements are introduced into the flowing fluid. The tracer elements can either be dye, smoke or particle droplets. Optical and electrical methods are also being used.
In the field of polymers, flow visualisation techniques have also been employed. Anatas et al.\(^{(2)}\) used flow visualisation methods to study the dynamics of polymer extrusion. They used a 25 mm diameter and 2 L/D ratio single screw extruder with a transparent barrel. The extrudate was composed of blue and red coloured frozen pellets of a 40\% solution of polystyrene in diethylphthalate plasticizer. The reason for using this type of extrudate was to reduce its viscosity so that it could be extruded using the transparent plastic barrel. Maddock\(^{(3)}\) used visual observation to study the profile of the melting mechanism in extrusion by means of stopping the extrusion, cooling, removing the screw and polymer by force and unravelling the latter. By this method he was able to postulate the melting mechanism of polymers while the extruder was running. A somewhat similar method was used independently by Street\(^{(4)}\) for roughly the same experiment. Barboza\(^{(5)}\) et al visualised the flow pattern of dilute and concentrated aqueous solution of polyacrylanide flowing through porous media. They also performed the same experiment with a Newtonian liquid and found that the flow pattern was identical with the viscoelastic solution when the Reynolds number of the Newtonian solution was a factor of 3-4 times smaller than the non-Newtonian one. Fruman et al.\(^{(6)}\) applied flow visualisation techniques to study the swelling effect of polymer solution flowing through a small slit. Freakley and Wan Idris\(^{(7)}\) were the first to use a flow visualisation method to study the dynamic flow patterns during mixing of rubber in internal mixers.
1.2 Development of Rubber Mixing Machinery

1.2.1 Hancock's Masticator

The earliest contribution to the manufacture of articles from rubber was made by the indigenous inhabitants of Central and South America. Their technology largely consisted of treatment of articles to obtain rubber coatings and simple mouldings. When rubber was brought to Europe further developments were carried out. During the 16th and 17th centuries rubber was mainly used for fabricating articles made by manual cutting and sewing. As a result, a lot of rubber scraps were wasted. Not until the early 19th century were these problems partially solved by T. Hancock, a London coachmaker who became interested in rubber in 1819 and engaged in the manufacture of rubber products for thirty-six years and later became known as 'the father of the rubber industry'.

Hancock's first endeavour was to find a good solvent for producing a rubber solution, which was intended to be used in the making of effective waterproof fabric. His initial failure in this respect diverted his attention to the production of rubber articles such as shoe soles, brakes, waistcoat backs, etc., which involved the process of cutting and sewing. He found himself accumulating large quantities of waste rubber for which no use could be found. He required a method to unite not only the waste cutting resulting from the manufacture of those products, but also a large proportion of his imported material from awkward and irregular shapes to a
more convenient form. After several months of fruitless endeav­our, in the Summer of 1820 he succeeded in designing and manu­facturing his first one-man power experimental model of his 'Pickle' - the apparatus which in many respects may be regarded as the prototype of the internal mixer of today.

This device consisted of a spiked roll working inside a spiked hollow cylinder, the roll having a crank operated by hand. His first wooden model was only capable of discharging not more than 100 gm. The second machine he designed included a reduction gear and was capable of producing about 0.5 kg. Much progress was then made and in 1821 he replaced his man driven masticator by a horse driven one which was soon developed to deal with about 50 kg of rubber.

1.2.2 Two Roll-Mill

The mill consists of two horizontal rolls parallel to each other. The distance between the rolls is made adjustable by having the bearing blocks of the front roll resting against the adjusting screw. The speed of the rolls is often different and this will induce further shear between the rolls which, together with temper­ature control, facilitate the formation of a band on one of the rolls. For the mixing of natural rubber a ratio of 1:1.2\(^{(9)}\) for the front:back is normally used, whilst for synthetic rubbers a near-even speed was reported to be the best\(^{(9)}\). Sometimes an inverted friction ratio is employed for synthetic rubbers.
Cooling system is achieved by having water sprayed on the outside of an axially drilled core or through the labyrinth of passages drilled on the periphery of the rolls. Rubber is usually introduced first to the mill and followed by other ingredients. Due to the lack of axial movement during the mixing of a two roll mill, cutting and stripping are necessary.

Two roll mills were first invented by Edwin M. Chatte\textsuperscript{(10)} of America in 1836. Since then the establishment of the Hancock masticator has become less popular\textsuperscript{(11)}. The basic design of the mill was substantially unchanged from the time it was invented until the present day. The only substantial changes were the size and speed of the rolls. In 1860\textsuperscript{(10)} the size of the mill was only 500 mm in length and 254 mm in diameter. In subsequent years, other mills of lengths 762, 915, 1220, 1525, 1830 and 2030 mm were developed and in 1924 the rolls were 2540 mm long. At about this time, due to the need to replace the old method of transportation, there was an increase in demand for automobiles. The compounded rubber was needed in ever increasing volumes which gave a great impetus to the rubber industry. The two roll mill, despite its increased size and speed, which meant an increase in output, could hardly cope with the demand for compounded rubber. Apart from being slow and labour intensive, the two roll-mill required greater power input and also larger mill rooms which were dirty and polluted thus affecting the health of the operators. Hence it was found to be vital to seek a new approach for the efficient mixing for the success of rubber industry and to ensure the job satisfaction of the workers. This led to the introduction of the internal mixer.
1.2.3 Internal Mixer

The internal mixer of today is the result of many decades of practical experience of earlier generations who dedicated their life to the rubber industry. The early consideration for the internal mixer was due to the fact that the two roll mill could not provide sufficient amounts of rubber required at that time. The first group of people who initiated the development of internal mixers were Werner and Pfleiderer at their factory in England. However the first internal mixer was developed and patented by H. Banbury\textsuperscript{(12)} under his own name, who was also an employee of Werner and Pfleiderer at their factory in the USA. His patent was accepted in 1916\textsuperscript{(13)}. Figure 1.1 shows the original form of the Banbury mixer. He later returned to England and worked in a factory manufacturing rubber machinery. At this place he further improved and modified his internal mixing machine. Werner and Pfleiderer later overcame their design problems and managed to establish their own internal mixer. Among the most popular internal mixers of today is the Shaw Intermix designed by Francis Shaw and Co; Baker Perkins and a number of other companies also produce the internal mixers.

Today the internal mixer is acknowledged as being the most versatile and rapid mixing equipment, with large throughput. The working parts of the internal mixer consist of two parallel rotors, equipped with 'flight' or 'nogs', which rotate against each other in a cylindrical chamber. The rotors are driven by motor and gear. Figure 1.2 shows the basic design of the Banbury and Shaw Intermix mixers.
Banbury mixer rotors run at a small speed differential of about 1:1.2. Generally the narrow region between the rotor and chamber wall perform the task of dispersion where the flow is unidirectional with high intensity of shear stress. It also helps in incorporation and distributive mixing. In the rest of the regions
Cross Section of F270 Mixer

FIGURE 1.2: BASIC DESIGN OF BANBURY AND INTERMIX MIXERS
where the flow is generally random, relatively low intensity of shear stress occur. Palmgren(14) reported that very little or no dispersion takes place in this region. Only incorporation and distribution may take place here. However Freakley and Patel(15) found that dispersion also occurs in the sickle shaped region in front of the rotor tip.

For the Francis-Shaw Intermix, the rotor runs at even speed with the 'nogs' designed to give a friction ratio between themselves. The rotor has one large and two small nogs on each rotor. The nogs are also partly helical in shape and opposite handed so that the mix is constantly passed back and forth along the length of the mixing chamber. Friction ratio between the outside diameter of the nogs and the rotor body diameter is 1.39:1(9).

1.2.4 Continuous Mixer

There is now some philosophical debate(16,12) between the merits of continuous and batch mixers, notably the internal mixer. However at present the manufacturer of continuous mixers still fails to provide a significant impact in manufacturing an efficient and versatile mixer. Blow(9) commented that besides the capital cost of the continuous mixer being very high, the saving in labour costs is relatively low. From the operational point of view, he noted that the continuous mixer still has some difficulties in feeding the rubber and additives into the mixer. This is because the raw rubber comes in an inconvenient form which is either in bales or slabs. The vast number of different amounts of ingredients to be
weighed and fed continuously into the mixer present an immense problem.

However according to Wheelan (17) and Ellwood (18) the above problems have been partially solved, particularly with the availability of particulate rubber which is also sometimes known as powdered rubber. Alternatively the bale rubber could be granulated to the size of about 4-12 mm in diameter which is suitable for use in continuous mixers. The feeding problem can be solved by using 'live' storage systems. Ellwood also claimed that the problem of weighing has also been overcome. The saving of labour and energy costs is about 60% and 11% respectively when using the Farrel-Bridge MVX as compared to batch mixers.

The following are some of the types of continuous mixers commonly used in rubber industries which are available on the market. Transfermix (16) comprises a single screw extruder working in the barrel. The barrel and screw are both threaded, but at different parts of the chamber. As the stock progresses along the machine, the thread in the screw diminishes until it disappears completely, while the thread on the barrel develops a maximum. This phenomenon of the disappearance and development of the thread led to the transfer of the stock from the screw to the barrel and vice versa over a number of stages as required. In the process the stock is subjected to a highly intensive shear action.

One of the newly developed continuous mixers is the Farrel-Bridge MVX, which has been specially designed for mixing and
extrusion starting from particulate rubber. The units available have two separate variable-speed drive motors in order to achieve optimum conditions for both mixing and extrusion. Independent adjustment of the motor speed enables a wide range of compounds to be processed on the machine, without needing to change the screw or mixing rotor. It has an air-operated reciprocating ram to prevent powder from bridging and help to feed the mixing chamber under pressure. The vacuum vented mixing chamber consists of two delta rotors situated transversely above the relatively short (4-5D) hot feed extruder.

Other types of continuous mixer include: Farrel continuous mixer (FMC) which is in fact an elongated Banbury type mixer having two rotors, feed screws and a variable discharge orifice. In its operation the strips or pallets are warmed up before entering the mixing zone. One drawback of this machine is that it is not self-emptying and therefore requires cleaning whenever the stock is changed. The Werner-Pfleiderer EVK is also one of the popular continuous mixers. It has a single screw mixing extruder with a multiple screw flight. The flight channels are interrupted by a series of transverse barriers which produce high shear as well as good particle redistribution. The gaps in the flight direction are situated at the peripheries of the flights. Pirelli Contimix with conical barrel and screw and NRM Plastiscrew Cold Feed Extruder are among others available on the market.
1.3 Current Status of Fundamental Analyses of Internal Mixers

An early analysis of an internal mixer was given by Bolen and Colwell\textsuperscript{(20)} and this gives an expression for the torque in terms of rotor speed, viscosity of material and the geometry of the mixer. They assumed the flow is Newtonian and the rotor tip is non-tapered. Borgen\textsuperscript{(21)}, in his analysis assumed that there was no pressure flow across the rotor blade. This has been amended by Funt\textsuperscript{(22)} who showed that a tapered blade gives a higher pressure drop at the tip and found that the maximum shear stress is greater when the tip is tapered. Mohr\textsuperscript{(23)} introduces a simple relationship between power requirement and total shear which could be used in a scaling-up calculation. Guber and Shikhirev\textsuperscript{(24)} suggested that power consumption was a sufficiently accurate indication of the stage of the mixing process in Banbury type mixers. Nakajima\textsuperscript{(25)} suggested that the breaking of rubber particles to smaller and smaller size can be quantitatively related to mixing results. Zloczower\textsuperscript{(26)} et al however concentrate their analysis on the agglomerate size distribution as a key dependent variable and relate it to a host of independent variables and parameters. Details of some of these modellings are given in Chapter 3.

It was found that there has been much development in recent years but the extent to which the theory has been applied to the design of mixing machinery is difficult to ascertain. Morrel\textsuperscript{(27)} reported that machine manufacturers do not always indicate how far the theory has helped them in their modifications.
1.4 Aim of Work

The aim of this work is to provide an insight into the complex mode of flow associated with the mixing of rubber in internal mixers by flow visualisation. Mathematical modellings presented by various researchers though providing some fundamental understanding on the mixing principle, include very considerable simplifying assumptions on the rotor configuration, particulate structure and viscoelastic properties of polymers, severely limiting the practical application of these analyses.

One approach to resolving these problems is flow visualisation. One of the primary objectives of this work is to establish the mechanics of distributive mixing in a Farrel-Bridge Banbury with two wing rotors by studying the flow pattern in various regions in the mixing chamber. Also, by measuring the pressure inside the mixing chamber the stress distribution in front of the rotor wing could be estimated. Together with the study of the fracture phenomena of the material the degree of dispersion might be established.

Finally, by making a correlation between the experimental rubber used in this project with the real mix produced in industry, suggestions could be made about the future design of rotors.
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CHAPTER 2
MIXING THEORY AND PRACTICE

2.1 Introduction

Since the discovery of vulcanisation in the 19th century rubber has been a major industrial product. From its inception, the use of vulcanising agents, reinforcing fillers and other additives has been a major feature in the rubber industry. Some researchers are concerned with the recipe changes affecting the product properties, while others are concerned with the mechanical operation of mixing them. There are three basic modes of mixing polymers, namely simple mixing, dispersive mixing and distributive mixing, each participating to a greater or lesser degree and each can either be dependent or independent on the other two.

The term 'simple mixing' is used for any operation which causes the particles of a system to pass from a less probable to a more probable arrangement. Alternatively there is an increase in the configurational entropy of the system, this reaches a maximum when the state of perfect randomness is achieved. Simple mixing is usually taking place in blending powdered material. Distributive mixing on the other hand is also concerned with the increase in randomness but it normally refers to the mixing of polymers in the melt state with particulate additives. In both cases there are no reduction in particle size. The dispersive
mixing is the process of breaking down the agglomerates to small particles. The third form of mixing is the most energy intensive process.

2.2 Degree of Mixedness

In discussing the degree of mixedness uniformity the terms ultimate particle size and scale of examination need to be defined. The ultimate particles are the smallest particles of the minor component normally existing during the course of mixing and the scale of examination refers to the size of sample taken from the mixture for analysis\(^{(1)}\). With the scale of examination that is the same order as the size of ultimate particles, a sample will contain a relatively small number of ultimate particles and in appearance will be coarse grained. On the other hand with a scale of examination that is large with respect to the size of the ultimate particles, a sample will contain many ultimate particles and in appearance will be fine grain.

Take an example: in mixing a black and white polymer to form a grey product, if the article is to be a disposable consumer item such as household gloves, then it is necessary for the grey colour to appear uniform to human eye. Unaided eyes have a resolution of about 100 microns. Therefore the scale of examination is 100 microns and the ultimate particles must be smaller than 100 microns for it to appear uniform to the human eye. If the same object is to be placed under an optical microscope where the resolution is in the order of 1-10 microns, the scale of examination
has now become 1-10 microns and the ultimate particles must be smaller than 1-10 microns for it to appear uniform throughout the spacement. This enables one to place a quantitative criterion for the degree of mixing as the requirement that the ultimate particles must be smaller than the scale of examination.

2.3 Method of Determining the Mixedness of Rubber Compound

The diversity of methods for assessing the mixability of rubber compound indicates the overriding importance attached to the monitoring of the state of the mixed material. In industry, the level of mixing specified is a compromise between energy consumption combined with labour utilisation and the standard of quality imposed by the end users of the ultimate product. For convenience these wide range of tests are divided into four main groups: rheometry, dispersion measurements, cure testing and vulcanisate testing.

Rheometry:

This includes capillary, and cone and plate rheometers. Capillary rheometers are able to provide a range of practical shear rates at which polymers can be characterised. Wan Idris(2) obtained the plots of $\eta_a$ against $\gamma$ for stocks of differing mixing history as which can be generalised as shown in Figure 2.1.
Die swell is another phenomenon that could be determined using capillary rheometry. Most researchers found an increase in die swell with mixing time or energy input. Depending on the type of mix it reaches a certain maximum and then falls again. The maximum appears to correspond to the second power peak where the progressing improving filler dispersion takes place.

For cone and plate rheometer, one of the most widely used pieces of apparatus for finding processing properties of rubber mix is the Mooney viscometer. Generally the Mooney viscosity (MV) drops as the mixing is progressing. Tokita and Pliston\(^3\) state that MV decreases until the second power peak is reached.
after which it levels off. Krauss(4) and Medalia(5) propose
the concept of occluded rubber which alter the MV; at early
mixing time, the effect is that of a higher concentration of
filler, and lower concentration of rubber than is found at
longer mixing times. As a consequence, the viscosity is lower
after extended mixing.

The most recent type of rheometer being developed is the
TMS rheometer. It has a rotary biconical rotor which moves
in a cavity of set geometry. Besides stress strain rate relation­
ship, stress relaxation and creep properties can be measured.
Leblanc and Price(6) approximated the stress relaxation curves
to a power law form

\[ P = K t^{-a} \]

where: \( P \) = the decaying pressure
\( t \) = time
\( K \) and \( a \) are the characteristic parameters of the
relaxation curves.

They found that for SBR/HAF and NR/HAF systems the value of \( K \)
decreased monotonically while the value of \( a \) increases at the
beginning, then plateaus with energy input or mixing time.
Freakley(7), Basir and Freakley(8) using the same formula
and found that the value of \( K \) increases with energy
input for PVC-nitrile blend. Creep measurement is another method
for studying viscoelastic properties of polymer. Wan Idris
obtained a family of curves for SBR/SRF and NR/SRF systems with differing energy input. He found that the creep rate increases with increasing mixing.

FIGURE 2.2: THE DEPENDENCE OF CREEP BEHAVIOUR ON MIXING ENERGY

Dispersion measurement:

For many years the favourite method of assessing dispersion was by the use of the naked eye or possibly with a hand lens. Later an optical microscope was used. The technique was first
described by Leigh-Dugmore (9) and later critically reviewed by Medalia (10) who suggested some alternatives to it. Electron microscopy is also being used when the higher resolution is required. There are some practical problems in using electron microscopy for studying dispersion. The agglomerates seen in many electron microscopes are much smaller than those observed under the optical microscope and are often the primary structure of fused carbon particles rather than the aggregates which are seen in the optical microscope. Sample preparation is another problem when an extremely thin sample of about 100 nm is required for this purpose.

Radiographic technique has also been used for thicker samples, but it is not effective for examining the dispersion of carbon black because the difference in absorption between rubber is small. Electrical and thermal properties are also being used.

A new microscopic method was developed by Ebelle (11) for measuring the dispersion of carbon black in rubber mix. He used a dark field reflected light (DFRL) microscope. The technique was claimed to be quick, simple and give cheap sample preparation and does not require a skilled operator. It is non-subjective and able to discriminate throughout the whole range of dispersion levels obtainable in practice. Figure 2.4.1 shows a typical trace of a cut surface from a good dispersion, while Figure 2.4.2 shows the poor one obtained using DFRL microscopy. In the bad dispersion the trace is uneven and peaky, but for the good dispersion the trace is more even and the peak height is lower.
FIGURE 2.4.1: OSCILLOSCOPE TRACE TYPICAL OF GOOD DISPERSION

FIGURE 2.4.2: OSCILLOSCOPE TRACE TYPICAL OF POOR DISPERSION
Cure Testing:

Apart from yielding the optimum vulcanisation parameters, the assessment of cure characteristics of a rubber mix is the only technique whereby both the rheological and mechanical properties in the uncured and cured states respectively, can be obtained from a single test. The use of a cure meter such as a Monsanto Rheometer for studying the effect of curative contents and controlling the batch-to-batch variation is well known. Wan Idris\(^2\) found that the type of base polymer (SBR, NR) significantly influences the cure characteristics, particularly cure time. Railsback\(^{12}\) noted that time to 95% cure was increased with increasing mixing severity for a BR/NR/N220 stock. Scorch time is another parameter that can be obtained from cure meter tests but its significance is more to the process control than as a reliable measure of mixing.

Vulcanisate Properties:

The attainment of maximum reinforcing capacity of fine fillers is directly related to their fine distribution through the rubber matrix. However, the improvement in properties with increasing dispersion tends to level off when about 90% of the fillers are well dispersed. The relationship between extent of mixing, particularly carbon black dispersion and the various vulcanisate properties has been investigated by several workers. By far the most popular properties tested are tensile strength, elongation at break, wear resistance, tear strength, modulus and hardness. The great majority of researchers have found that tensile
strength and elongation at break were increased with increasing mixing. Some of them also noticed that tensile strength passes through a maximum and levels off. Wear resistance is increased with high level of dispersion. Boonstra and Medalia\textsuperscript{(13)} reported that tear strength appeared to be insensitive to mixing time. However Andrew and Walsh\textsuperscript{(14)} found that tearing behaviour can be used to discriminate the degree of dispersion.

In addition to considering mean values, yielded by a test sampling as being indicative of the vulcanisate properties of the population of that batch, certain researchers have also correlated the variation of those properties within a batch as an indicator of mixing. Wan Idris\textsuperscript{(2)} used tensile strength to find the dependence on mix uniformity on fill factor and found that the coefficient of variation i.e. the ratio of standard deviation to mean value is lowest for 0.7 fill factor signifying a low in-batch variation at that condition. This technique can provide a good indication of the extent of distributive mixing.

2.4 Flow Mechanism

2.4.1 Laminar Flow

In most mixing problems involving a fluid phase, the rate of mixing is markedly increased by making the fluid turbulent. The fluid flow may either be laminar or turbulent depending on the velocity and physical condition. For a given fluid flowing under a given condition, there will be a critical velocity below which the flow will always be laminar. Reynold established a
numerical formula that defined the boundary between laminar and turbulent flow (15).

\[ Re = \frac{\rho V d}{n} \] (2.1)

where: \( Re \) = Reynolds number
\( \rho \) = density of fluid
\( V \) = velocity
\( d \) = diameter
\( n \) = viscosity

The critical Re is 2100, between 2100 and 2500 the flow is transitional and above which the flow will always be turbulent. In turbulent flow the fluid particles do not move in a uniform orderly manner but have a small irregular motion which have velocity components at right angles to the direction of flow. The particles are thus continuously being interchanged between adjoining layers in fluid producing eddies, and the accompanying interchange of momentum will produce shear stress between layers moving at different velocities. In this way the mixing process is enhanced. This method of promoting mixing is widely used with gases or low viscosity liquids.

With polymer melt however, the viscosity is very high, this makes it impossible to achieve critical Re number, during a process such as mixing, therefore it always has to be carried out in laminar flow.
2.4.2 Mixing in Laminar Flow Systems

As in mixing of highly viscous fluids, diffusion is virtually of no help because there is no turbulent and eddy diffusivity. Under this condition the main mechanism of mixing is shear or elongational flow. If the mixture consists of rigid agglomerates such as carbon black dispersed through a continuous rubber matrix, under shear or elongational deformation, the agglomerates may break if the stress exerted on the agglomerates exceeds their cohesive strength. The broken agglomerates may then be distributed through the rubber matrix depending on the extent of deformation and flow pattern. Figure 2.5 shows the mechanism of agglomerate rupture under laminar flow.

FIGURE 2.5: SCHEMATIC REPRESENTATION OF AGGLOMERATE RUPTURE UNDER LAMINAR FLOW
If the material is flexible such as in blending of more than one type of rubber or in mixing of rubber with master batch the initial particles may change in shape without break up. Figure 2.6 shows the minor components exist as discrete cubes distributed in the major component. Under shear conditions induced by the movement of the rotor these particles would be stretched out and the average thickness will decrease as the surface area increases at constant volume. The distance between the particles will then decrease. This mixing mechanism is generally known as laminar shear mixing. If enough deformation was imposed the combined thickness of each pair of layers could be brought below the limit of resolution. The mixture will appear uniform under the scale of measurement (see Section 2.2).

A useful measure of shear process is the striation thickness \( r \) which is the average shortest distance between a point of maximum concentration of one component and the nearest point of maximum concentration of the same component. For large deformation the two cubes become essentially two sets of parallel planes. The striation thickness is the distance between the mid-points of each pair of planes.

However in the internal mixer elongational flow will occur due to the converging and diverging geometry of the mixer. Under these conditions the same phenomenon will happen as in the case of shear deformation. The particles will become elongated and reduce in thickness while increasing in surface area.
2.5 Mixing Stages

2.5.1 General Consideration

Ideally, a theory of mixing should permit prediction of the quality of a mixture obtained in any operation from fundamental considerations such as geometry of the system and the physical characteristics of the component being mixed. There are a number of unit processes involved during mixing of particulate additive to rubber. Palmgren(16) stated that there are four unit processes, starting from subdivision, incorporation, dispersion and simple mixing distribution, in that order, while Nakajima(19) suggests that there are only three: incorporation, dispersion and macroscopic homogenisation. The better
way of illustrating conventional mixing steps can be summarised in a flow chart as shown in Figure 2.7.

![Flow chart of conventional mixing stages](image)

**FIGURE 2.7: FLOW CHART OF CONVENTIONAL MIXING STAGES**

The following unit operations can be defined as follows:

1. Mastication: This process involves the breaking and orientation of rubber molecules followed by a rise in the temperature and reduction in viscosity.

2. Incorporation: This process involves the enclosure of powder or (liquid additives) by the rubber matrix to form a coherent mass.
3. Subdivision: This process involves the reduction in size of large groups of particle aggregates enclosed within the rubber matrix into smaller ones.

4. Dispersion: This process involves the progressive reduction of the size of agglomerates tending to their ultimate size.

5. Distribution: This process involves the spatial rearrangement of particulate additives in order to increase randomness or entropy, without changing particle size or shapes.

However in practice these unit operations occur simultaneously as shown in Figure 2.8.1. Figure 2.8.2 illustrates the steps involved during mixing of elastomer.

![Figure 2.8.1: Relative Sequence of Mixing Steps.](image-url)
FIGURE 2.8.2: STEPS INVOLVED DURING MIXING OF RUBBER
Mixing steps can also be followed by means of power consumption trace as shown in the generalised power trace during internal mixing operation of Figures 2.9.1 and 2.9.2.

FIGURE 2.9.1: GENERALISED TRACE OF POWER CONSUMPTION DURING INTERNAL MIXING (11)
2.5.2 Incorporation and Subdivision

These two phases are outside the scope of this thesis and therefore they are discussed only briefly. The incorporation process is predominant in the beginning, rapidly tapering off and ending for example after about one minute of mixing (17). Nakajima (18) suggests that there are two mechanisms by which the incorporation can take place. Mechanism (a) involves a large deformation and subsequent relaxation of rubber domains, sandwiching the carbon black aggregates, while mechanism (b) involves comminution of rubber domains and subsequent mixing with carbon black. Figure 2.10 shows both mechanisms.
FIGURE 2.10: SCHEMATIC ILLUSTRATION OF THE COMMINUTION AND LAMINATION MODELS (18)

However both mechanisms take place under the compacting pressure and therefore the pieces can be in continuous form. In reality, mechanisms (a) and (b) are not separated, both are taking place simultaneously.

The subdivision was described by Palmgren (16) as breaking of large particles to smaller ones suitable for incorporation but the latter model (19) suggests that subdivision is necessary not only for incorporation but also for dispersion.
2.5.3 Dispersion

Dispersion is often the rate determining step in mixing a particulate additive in rubber matrix. It is an energy intensive major process. After lumps of agglomerate particles were incorporated into the polymer melt they had to be broken down into their ultimate particles. Dispersion started when the power input started to increase after the first maximum\(^{(1)}\). Dispersion was largely dependent on the shear stress during the mixing process. However, Funt\(^{(20)}\) found that dispersion of ingredients in rubber mixing is achieved by a combination of both shear and extensional flow. Bolen and Colwell\(^{(21)}\) stated that the agglomerates will only rupture when the hydrodynamic separating forces exceed the cohesive forces between the aggregate due to Van de Waal forces, before that no dispersive action will take place.

The force balance has been quantified by McKelvey\(^{(1)}\) who characterised the progress of mixing by parameter \(K\), the distributive factor.

\[
K = \frac{6\pi R^2 \dot{\gamma} u}{F_a} \quad (2.2)
\]

where:  
- \( R \) = radius of particle  
- \( \dot{\gamma} \) = shear rate  
- \( u \) = fluid viscosity  
- \( F_a \) = attractive force
For Newtonian fluid:

\[ \tau = \gamma \mu \]

The magnitude of the force acting against the cohesive force of the agglomerate depends on the effective diameter of the agglomerate, the viscosity of the matrix and the shear rate. The shear rate is proportional to rotor speed. The typical range of shear rates for low intensity mixing is 100-200 s\(^{-1}\) and for high intensity mixing is 200-600 s\(^{-1}\) at the rotor tip. It is important to know the optimum shear rate as the optimum dispersion is only limited to a limited range of rotor speeds (see Section 2.6.3).

Mixing temperature also affects the rate of dispersion by exerting a very appreciable effect on the rheological properties of the mixing stock. Increasing the temperature will reduce the viscosity of the melt thus lowering the shear stress. Also excessive heat build-up increases the risk of scorching. However if the temperature is too low the melt becomes stiff and is in danger of crumbling and wall slippage. Thus it is important to control mixing temperature effectively. Equation 2.2 also shows that if the cohesive force is independent of particle size, then the parameter \( K \) is proportional to the radius of particles \( R \).
FIGURE 2.11: FORCES OPERATIVE IN THE DISPERSION OF A TWO-PARTICLE AGGLOMERATE

McKelvey\(^{(1)}\) further derived an equation to show the particle flow path as shown in equation 2.3.

\[
\left(\frac{x+y}{x_0+y_0}\right)\left(\frac{y_0}{y}\right) = \exp \left[Ky_0 \left(1 - \left(\frac{y}{y_0}\right)^2\right)\right] \quad 2R \leq r \leq r^*.
\]  

\(2.3\)

He found that the particle path depends on parameter \(K\), the critical radius \(r^*\) and the initial orientation of the agglomerate. He further concluded that high shear stress promotes dispersion; a minimum stress is required below which no dispersion can occur and only those agglomerates that are initially favourably oriented will be dispersed.
2.5.4 Distribution

When an agglomerate is broken into its ultimate particles, they have to be distributed evenly throughout the rubber matrix. This process is known as distributive mixing. Distributive mixing depends on the total deformation and the flow pattern occurring inside the mixing chamber. As in dispersion, correct rotor design is also important in distributive mixing. The designer should provide a system whereby the continuum would be distorted from the initial orientation by the flow pattern. The deformation of the continuum by shear and tensile action must be such that the increase in interfacial area leads to a decrease in the scale of segregation. The increase in number of flights from two to four may increase the rate of dispersion but may give a negative effect on rate of distribution (22).

The distributive stage of mixing can be considered as a homogenisation process. It occurs predominantly after the second peak of the power input curve, where theoretically there is no more agglomerate rupture.
2.6 Factors Influencing Mixing Performance

2.6.1 General Consideration

The term mixing in polymer processing is applied when there are two or more identifiable components involved and are to be combined together in a homogeneous phase. The component having the higher overall concentration is the major component and the others are the minor components. Today commercially produced rubber compounds are generally a mixture of a blend of two or more elastomers and a number of organic and inorganic particulate or liquid additives. The dispersion and distribution of these additives significantly influences the final properties of the vulcanisate. In fact, in the course of the production of a vulcanisate the mixing stage introduces more variance to the vulcanisate properties than the combination of all the other steps put together. Thus the mixing process has the primary objective of dispersing and distributing the compounding ingredients. The optimum properties are achieved at a high level of dispersion.

However, the problems associated with the mixing process are tremendous. The physical state of rubber and additive are not always in the right form which can be easily fed into the mixer. The quality of rubber and additive must properly comply with the specification required. If these substances need to be stored, the storage must be proper as many of the mixing ingredients are hygroscopic in nature. Natural rubber should be stored at or above 15°C, to prevent crystallization.
The ingredients must be weighed accurately before feeding them into the mixer. The accuracy of weighting is an important factor in maintaining the quality of the product and its cost effectiveness\(^{(25)}\). Feeding the material into the mixer also needs expert judgement by the operator, as direct handling of large amounts of powder can cause health and safety hazards. When a batch is dropped from the internal mixer it has to be shaped in the required form by either two roll-mill or extruder. In addition to this, continuous mixers such as the Transfermix are also being used in some large factories. In many cases sulphur is not added directly into the internal mixer for fear of scorching. It is usually added to the mill. The stock is usually tested for its quality before despatching to the next processing area. The mixing process is completed only when all the properties of the mix are thoroughly checked and passed.

After taking into account all the above problems, attention is now focussed on the mixing operation itself, to determine the optimum conditions under which the machine should operate. Depending on the type of polymer and the amount of filler, mixing technique can either be conventional, upside down or side by side. Two stage mixing is also employed especially when preparing a scorchy compound. However one of the primary decisions that needs to be considered in undertaking the mixing operation is its process variables and their effect on the final vulcanisate. The main mixing variables are: rotor speed, fill factor, ram pressure, starting temperature and dump criteria. In this dissertation only fill
factor and rotor speed are considered in detail while others are described briefly.

2.6.2 Fill Factor

Fill factor is defined as the fraction of the free volume of mixer which is occupied by polymer and additives at the final stage of mixing.

\[ F.F = \frac{M}{F \times S.G} \]  

(2.4)

where:  
- \( M \) = mass of batch  
- \( F \) = free volume of mixer  
- \( S.G \) = the average specific gravity of the batch.

In general a fill factor between 0.6 to 0.85\(^{(11)}\) is usually employed during mixing of rubber. However the optimum degree of filling depends on several criteria such as rotor and mixer geometry, mix viscosity, type of filler and the nature of mix required. Dizon\(^{(26)}\), Freakley and Wan Idris\(^{(27)}\), and Funt\(^{(20)}\) reported that optimum filling for most stocks is 0.7.

Due to the particulate nature and low bulk density of powdered ingredients, their apparent volume at the beginning of the mixing cycle is usually larger than their true volume. As the powders are being incorporated into the rubber the apparent volume decreases until the incorporation process is completed and the true volume achieved. The choice of the right degree of
filling during mixing is paramount. Over filling results in an inefficient incorporation process, causes some material to be retained underneath the ram and thus reduces the rate of both dispersive and distributive mixing. Both Palmgren\(^{(16)}\) and Carver\(^{(28)}\) reported that overfilling undermines the mix uniformity and produces bad dispersion, high energy consumption, increase in dump temperature, high power level and longer mixing time. On the other hand underfilling reduces the effect of ram pressure thus lowering the shear stress generation and slippage occurs. In both cases longer mixing time is required, which means that the mixing process is less efficient. Correct batch size should provide shorter mixing time, small in-batch and batch-batch variation and good dispersion. It is generally accepted by most researchers that a fill factor of less than unity is essential because the 'empty space' leads to the mix being turned around in the mixing chamber and this is good for distributive mixing. However, a fill factor of more than unity was also reported\(^{(29)}\) being used without bringing any adverse effects on the mix variability.

### 2.6.3 Rotor Speed

Variation in rotor speed is one of the essential features in internal mixers. In olden days the internal mixer only had a single speed but now they are generally equipped with two speed drives and variable speed systems are now becoming more common. In a mixing process a minimum number of rotor revolutions are needed\(^{(16,30)}\). Beach et al\(^{(30)}\) proposed that the
mixing time will be a simple function of rotor speed since the increase in rotor speed affects shear rate, this relationship can only be valid up to a certain limit of rotor speed. Equation (2.5) shows a simple relationship between the shear rate and rotor speed:

\[ \dot{\gamma} = \frac{v}{h} \]  

where: \( \dot{\gamma} \) = shear rate  
\( v \) = rotor speed  
\( h \) = clearance between the rotor and chamber wall.

Epschtein\(^{(21)}\) et al reported that an increase in rotor speed required a longer number of revolutions. However Comes\(^{(32)}\) argued that proportionate reduction in mixing time with increase in rotor speed is only limited to soft stock. Whitaker\(^{(33)}\) found that rotor speed had no effect on dispersion.

It is a well known concept that in mixing of polymer a high shear stress is required for good dispersion. To generate high shear stress, a high shear strain rate is required. Equation (2.6) provides the relationship between shear stress and shear strain rate for a pseudo plastic (non-Newtonian) material.

\[ \tau = K\dot{\gamma}^n \]  

where: \( \tau \) = shear stress
\( K \) = consistency index

\( \dot{\gamma} \) = shear rate

\( n \) = power law index

A typical range of shear rates is between 100 \( s^{-1} \) to 500 \( s^{-1} \)\(^{(27)} \) and for \( K \) and \( n \) are between 80 KPa s to 150 KPa s and 0.25 to 0.35\(^{(16)} \) respectively. Since the power law index is less than one, the increase in shear stress is much slower than that of shear strain rate and thus the rate of dispersion.

Increasing rotor speed also results in increase in stock temperature and reduces its viscosity. Equation (2.7) shows the relationship between viscosity and temperature (Arrhenius equation)

\[
\eta = Ae^{(E/RT)}
\]

where:

- \( \eta \) = viscosity
- \( A \) = constant
- \( E \) = activation energy
- \( R \) = gas constant
- \( T \) = absolute temperature

Reducing the viscosity will lower the shear stress generated within the matrix at constant shear rate thus reducing the dispersive mixing. From this evidence it signifies that the optimum dispersion condition lies only in the limited range of rotor speed. If rotor speed is set too low the shear stress will
be inadequate to overcome the cohesive force of the agglomerates thus dispersion will not occur. However at too high a rotor speed, due to the non-Newtonian properties of the material, will not increase the shear stress substantially but on the other hand will increase the temperature of the melt. This will affect the temperature sensitive material and may cause some polymer degradation and premature vulcanisation may take place if curatives are present.

2.6.4 Other Variables

These include ram pressure, starting temperature and dump criteria.

The ram pressure: The ram was first introduced by F. Banbury in order to prevent material flying out of the machine while the mixer is in operation. At the early stage of mixing where the apparent volume is high, increasing ram pressure will help to increase the contact force between rubber and rotor or chamber wall thus reducing the wall slippage. This will help to increase the rate of incorporation. Increased ram pressure also reduces void size within the mixture and increases the speed of engagement between the material in the mixer, this will reduce mixing time and increase the output.

In general, reducing the ram pressure will increase the wall slippage and decrease shear stress and thus affect the rate of dispersion. On the other hand an increase in ram pressure will reduce wall slippage, resulting in higher shear stress thus
improving the rate of dispersion. However there must be a maximum ram pressure above which no significant increase in output could be obtained since maximum contact has been achieved both between material and mixer and between material and material(23).

Starting temperature: Until the advent of tempering units mixing was started with a cooled mixer. Too low a temperature, particularly at the beginning of the mixing cycle will cause slippage between rubber and mixing chamber due to condensation on rotor and chamber. There are conflicting arguments about the effect of starting temperature on mixing efficiency. Some observed that high temperatures were beneficial, while others found a negative effect on mixing. Dolezal et al(34) reported that mixing temperature does not affect either stock properties or power consumption.

Dump criteria: Knowing when to terminate the mixing process is very important for both mix quality and cost. This is determined by the dump criterion which is one of the main process variables(10). There are currently four methods in which the dump criteria are commonly based(14):
1. Time - the batch is dumped after a preset time.
2. Temperature - the batch is dumped when a predetermined temperature is reached.
3. Heat history - this is measured by a 'process controller' in which the times the batch spends at different temperature are weighted according to their influence on the curing reaction, and transformed to electric impulses which are then accumulated. The batch is dumped at a preset number of impulses.
4. Unit work - batch is dumped when a predetermined amount of energy has been spent in mixing.

Many conflicting viewpoints were expressed in the literature regarding preference for one criterion over another, in order to guarantee the quality of each product, avoid over-mixing and reduce variation between batches.

Traditionally time alone was the only means of monitoring mixing process, thus it was generally used as dump criterion. However time alone does not guarantee against the effect of temperature changes and also does not provide an indication of mixer responses to various process functions, which then lead to batch-to-batch variation. Temperature alone does not provide a good technique of judging the dump criterion because batch temperature depends on external influences; and is only consistent with good water tempering. (See Section 2.6.4 on Starting temperature). The combination of time and temperature which is
known as heat history offer a better method but not satisfactorily because it still does not solve the problem of time-temperature criteria. Method (4) which relates unit work directly to mixing behaviour in an internal mixer has become the main method as a dump criterion in modern rubber industry.
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CHAPTER 3
CRITICAL REVIEW OF THE MATHEMATICAL
MODELLING OF INTERNAL MIXERS

3.1 Introduction
Mixing of rubber in an internal mixer is undoubtedly an extremely complex process, so that a complete hydrodynamic analysis is still unfeasible. In the batch operated internal mixer conditions are very rarely constant and not easily defined. The complicated construction of the rotors contributes, to a large degree, to the complex conditions prevailing in the mixing chamber. All of the analyses are restricted to only the small nip region or the sickle-shaped zone in the mixing chamber. Other regions, which are also responsible for the modes of deformation and contribute significantly to the mixing action are not considered.

3.2 Hydrodynamic Analysis of Internal Mixers
An early analysis of an internal mixer was given by Bolen and Colwell in 1958(1). With this mathematical model a new era in the analysis of the fundamentals of internal mixing came to light. They used a simplified geometry as shown in Figure 3.1.

In their analysis they made several assumptions:
1. The mixer is full i.e. the fill factor of unity.
2. No axial flow.
3. The effect of entrance losses going from the channel to the tip region may be neglected.
4. The material is Newtonian.
5. The tip clearance is constant.

Assuming the outer cylinder rotates in a clockwise direction, the material tends to accumulate at the left side of the flight and the pressure $P_2$ is developed. At the right of the flight the material tends to be dragged away and the pressure $P_1$ is less i.e. $P_2 > P_1$.

This causes a reverse pressure flow in the channel and forward pressure flow in the tip region. The direction of the four flow components was shown in Figure 3.1. It is assumed that the radius of the rotor is large compared to the gap clearance so that the flow can be treated locally as flow between parallel plates in a Cartesian coordinate system. Under these assumptions the
drag and pressure flow rate are given as follows:

\[ Q_1 = \pi D_c \, Sh \, N/2 \] \hspace{1cm} (3.1)

\[ Q_2 = \pi D_t \, Sg \, N/2 \] \hspace{1cm} (3.2)

\[ Q_3 = -Sh^3 \Delta P/12\pi D_c \, \mu_C \] \hspace{1cm} (3.3)

\[ Q_4 = Sg^3 \Delta P/12e \, \mu_t \] \hspace{1cm} (3.4)

where:

- \( Q_1 = \) drag flow in the channel
- \( Q_2 = \) drag flow at the flight tip
- \( Q_3 = \) pressure flow in channel
- \( Q_4 = \) pressure flow at tip
- \( D_c = \) diameter at shaft
- \( D_t = \) diameter at tip
- \( S = \) length of rotor
- \( h = \) channel clearance
- \( g = \) tip clearance
- \( N = \) rotor speed
- \( \Delta P = \) pressure drop across flight
- \( \mu_t = \) viscosity of fluid at tip
- \( \mu_C = \) viscosity of fluid at channel
- \( e = \) tip width.

Assuming the material to be non-compressible, material balance

\[ Q_1 + Q_3 = Q_2 + Q_4 \] \hspace{1cm} (3.5)
Substituting equations (3.1-3.4) to equation (3.5) to solve for pressure drop:

\[
\Delta P = \frac{6\pi N (D_c H - D_t g)}{(\frac{h^3}{\pi D_c H} + \frac{\varepsilon^3}{eu_t})}
\]  

The average shear stress was obtained from the shear rate vs shear stress curves at the flow average shear rate:

\[
\dot{\gamma} = \frac{\int_0^h |u\dot{y}| dy}{\int_0^h |u| dy}
\]  

(3.7)

This is the same as mass-average shear rate.

Let the ratio of pressure to drag flow be

\[
\phi = \frac{Q_{\text{pressure}}}{Q_{\text{drag}}}
\]

then

\[
\dot{\gamma} = \frac{V}{H} f(\phi)^{(2)}
\]  

(3.8)

where \( f(\phi) \) is a function of \( \phi \) as shown in Figure 3.2.
Finally the average stress for both channel and tip regions could be calculated using the general flow curves formula:

\[ \tau_c = \mu_c \gamma \]  

(3.9)

\[ \tau_t = \mu_t \gamma \]  

(3.10)

where the subscripts c and t refer to channel and tip respectively.

Considering the assumption made by Bolen and Colwell more critically, a main simplifying assumption is the fill factor of unity, even though in practice the fill factor is always less than unity. It is also assumed that there is no axial flow of material inside the chamber which is erroneous since the flight is situated at an angle to the direction of rotation, and the negligible pressure loss at the entrance of the tip region from the channel is also wrong. The assumption that the material is Newtonian is unrealistic. The assumption that the rotor tip is not tapered also results in smaller predicted values of shear.
stress and underestimates the rate of dispersion in comparison with a tapered rotor\(^{(3)}\).

Bergen\(^{(4)}\) in his analysis makes similar assumptions as Bolen and Colwell, but considers the rotor tip to be tapered. He further assumed that there was no pressure flow across the rotor tip and derived a formula for the shear stress at the blade surface for the tapered channel as:

\[
\tau = \frac{2\mu Q}{h_0^2} \left( \frac{1}{1-\beta \rho} \right)^2
\]

(3.11)

where:

- \(Q\) = volume flow rate
- \(\beta = \frac{a-1}{a}\)
- \(a = \frac{h_0}{h_L}\)
- \(\rho = \frac{x}{L}\)
- \(h_0\) = channel depth at exit
- \(h_L\) = channel depth at entry
- \(x\) = blade-tip width
- \(L\) = channel length.
Since his analysis did not include pressure flow, the analysis is not correct because the change in the gap between the rotor and chamber wall cause the pressure to build up.

Funt\(^{(3)}\) suggests that corrections could be made to the Bolen and Colwell original analysis by incorporating the change in blade tip clearance. He found that there is no change in the pressure and drag flow in the channel as derived by Bolen and Colwell. He then derived the flow at the tip region as:

\[
Q_2 = S \int_0^g \frac{\pi ND_t}{g} Y \, dy \tag{3.12}
\]

\[
Q_4 = S \int_0^g \frac{y(g-y)}{2 \mu} \frac{dp}{dz} \, dy \tag{3.13}
\]

Assuming the tip clearance decreases linearly with distance

\[
g(z) = g_o - mz/e \tag{3.14}
\]

He then obtained an equation for \(\Delta P\) for tapered clearance as:

\[
\Delta P = -6 \mu t_e \left[ \frac{\xi}{S} \frac{(m-2g_o)}{g_o^2 (g_o-m)^2} - \frac{\pi ND_t}{g_o(g_o-m)} \right] \tag{3.15}
\]

where: \(\xi = Q_1 + Q_3 = Q_2 + Q_4\)

and the maximum shear rate as:
The maximum shear stress depends upon the geometry and operating parameters in a complicated manner as shown by combining equations 3.15 and 3.16. However, he found that the ratio of maximum shear stress with and without taper is of the order of \( O(3) \)

\[
\tau_{\text{taper}} = \frac{T_{\text{taper}}}{T_{\text{constant}}} = \frac{g_0}{g_0 - m}
\]

(3.17)

3.3 Agglomerate Rupture in the Rotor Tip Region

A theoretical modelling of dispersive mixing in an internal mixer was expounded by Zloczower(5) et al by analysing the mechanism of agglomerate rupture caused by extensional and shear flow in a narrow-gap high-shear field i.e. tip region. They assumed that the agglomerate break-up was a repetitive process i.e. a large agglomerate ruptures first into two equal size fragments, then each fragment again divides into two and so on until the ultimate size is reached where it could no longer be broken by available hydrodynamic forces. The fused particles are considered to have 'random flight' configuration thus the root mean square distance from the centre of gravity is given by

\[
S^2 = \frac{\eta_f}{6}
\]

(3.18)
where: \( \lambda = \) flight length \( \equiv \) diameter

\( n_f = \) number of flights \( \equiv \) number of particles in aggregate.

It is worthwhile to note here the agglomerates contain large numbers of aggregates which are held together by London-Van-der Waal's force. Therefore the purpose of dispersion is to rupture these agglomerates into individual aggregates and distribute them uniformly throughout the rubber phase.

Assuming the aggregates are spherical in shape, the expression for the attractive cohesive force between two spheres can be approximated by \(^{(7)}\)

\[
F = \frac{A}{12z^2} \frac{d_1 d_2}{(d_1 + d_2)}
\]

where: \( F = \) cohesive forces

\( A = \) Hamaker constant for the interaction between two bodies

\( d_1 \) and \( d_2 = \) diameter of the two bodies.

\( z = \) physical adsorption separation distance between two interacting bodies.

Further, it is assumed that these aggregates are of the same size, and join together to form elongated agglomerates. In this situation Zloczower et al \(^{(3)}\) suggest that the most likely rupture to occur is at the centre of the plane where the hydrodynamic tension is largest. The cohesive force of the agglomerate
along its large axis is given by:

\[
F_c = \frac{9}{8} \left( \frac{1 - \varepsilon}{\varepsilon} \right) C_0 \frac{d}{S}
\]  

(3.20)

where:
- \( \varepsilon \) = the volume void fraction
- \( C_0 \) = a numerical value ranging from \( 4.06 \times 10^{-12} \) to \( 4.78 \times 10^{-12} \) N/A
- \( d \) = diameter of sphere
- \( S \) = the cross-sectional contact area at the rupture plane.

Before the agglomerate could rupture the hydrodynamic force must be greater than the cohesive force. Consider a single, freely suspended axisymmetric particle in a homogeneous shear flow field of an incompressible Newtonian liquid, the force along the axis that one half of a particle exerts on the other is given by:

\[
F_h = \chi \pi \mu \dot{\gamma} C^2 \sin^2 \theta \sin \phi \cos \phi
\]  

(3.21)

where:
- \( \chi \) = numerical constant which depends on particle shape
- \( \mu \) = viscosity of liquid
- \( \dot{\gamma} \) = local shear rate
- \( C \) = dimension characterising the size of the particle
- \( \theta \) and \( \phi \) = instantaneous orientation Euler angles defined in Figure 3.3
FIGURE 3.3: EULER ORIENTATION ANGLES

From equations 3.20 and 3.21 both $F_e$ and $F_h$ are proportional to the cross-sectional area of the agglomerates. Note that from equation 3.21 ($\mu \dot{\gamma} = \tau$) where $\tau$ is the shear stress. This indicates that the separating force increases linearly with shear stress. Agglomerates will rupture when the hydrodynamic separating forces exceed the cohesive forces i.e. $F_h > F_c$. The ratio of the hydrodynamic separating force can be obtained by dividing equation 3.21 by 3.20.

$$\frac{F_h}{F_c} = Z \sin^2 \theta \cos \phi \sin \phi \tag{3.22}$$

where:

$$Z = \frac{8}{9} \pi \mu \dot{\gamma} \left( \frac{e}{1-e} \right) \frac{d}{c_0} \tag{3.23}$$
$Z$ is a dimensionless group

From equation 3.23 the value of $Z$ is directly proportional to the diameter of the aggregates $d$. Thus smaller aggregates give smaller $F_h:F_c$ ratio, making it difficult for the agglomerates to rupture. It is significant that the high structure carbon black exhibits a high shear force during the dispersion stage while low surface area black possesses low cohesive force.

The fraction of broken particles during one pass through the high shear zone depends on the probability of the agglomerates axes being oriented between $\theta_0$ to $\theta + d\theta_0$ and $\phi_0$ to $\phi_0 + d\phi_0$ and during their residence time experiencing $F_h > F_c$. The fraction of broken agglomerates is given by

$$W = \int_{\theta_0^*}^{\theta_0^*} \int_{\phi_0^*}^{\phi_0^*} f(\theta_0,\phi_0) d\theta_0 d\phi_0$$  \hspace{1cm} (3.24)

where: $W = \text{fraction of broken agglomerates}$

$\theta_0^*$ and $\phi_0^*$ = the intervals over the surface of initial orientation in which $F_h > F_c$ is met during the path.

The total fraction of broken agglomerates during one pass through the gap is obtained using the equation 3.25:

$$X = \int_0^1 W(\xi) f(\xi) d\xi$$  \hspace{1cm} (3.25)
\[ \xi = \frac{Y}{H} \]  
(3.26)

\[ f(\xi) \, d\xi = \frac{dq}{q} = \frac{U_x(\xi) \, d\xi}{\int_0^\xi U_x(\xi) \, d\xi} \]  
(3.27)

where:  
- \( q \) = flow rate per unit width in the gap
- \( Y \) = Cartesian coordinate
- \( H \) = height of the gap

During mixing the number of times each agglomerate passes through the high shear zone varies from zero to infinity. The probability that a given fluid particle passes through the high shear zone can be approximated by Poisson distribution(8). If \( G_K \) is the volume fraction of the fluid in the chamber that in time \( t \) has passed \( K \) times through high shear zone, the Poisson distribution thus

\[ G_K = \frac{(t/\bar{\tau})^K}{K!} \, e^{-t/\bar{\tau}} \]  
(3.28)

where:
- \( t/\bar{\tau} = \frac{Qt}{V} \)  
(3.29)
- \( t \) = time
- \( \bar{\tau} \) = average residence time
- \( Q \) = volumetric flow rate
- \( V \) = volume of the chamber
They further assumed that the agglomerate rupture into two equal halves and that each fragment acquires the same shape as the initial agglomerate, thus the ratio of the parent agglomerate to its fragment is given by:

\[
\frac{D_i}{D_{i+1}} = (2)^{1/3}
\]  

(3.30)

Thus the size of agglomerate after \( i \) ruptures is given by

\[
D_i = \frac{D_0}{((2)^{1/3})^i}
\]

(3.31)

where:
- \( D_0 \) = initial size of agglomerates
- \( D_i \) = size of agglomerate after \( i \) rupture
- \( i = 0,1,2,... \)

Hence after \( K \) passes through the high shear zone there will be a distribution of sizes \( D_i \) where \( i \) varies from 0 to \( K \). If for a certain passes \( m \) where \( m < K \), the corresponding \( D_m \) reaches individual aggregate sizes, no more rupture occurs and the agglomerate size will vary from \( D_0 \) to \( D_m \) as shown in Figure 3.4.
FIGURE 3.4: SCHEMATIC ILLUSTRATION OF DISTRIBUTION OF AGGLOMERATE SIZES AFTER CERTAIN NUMBER OF PASSES
They show that after K passes the volume fraction of agglomerates with size $D_j$, will be

$$U_j = \frac{K! \chi^j (1-\chi)^{K-j}}{(K-j)! j!} \quad J=0 \ldots K \quad m > K$$
$$J=0 \ldots m-1 \quad m < K \quad (3.32)$$

The volume fraction of agglomerates which do not reach ultimate particle size after K passes will be the summation of $U_i$ where $i$ varies from 0 to $m-1$.

Therefore the volume fraction of agglomerates reaching ultimate size (aggregate) will be

$$U_m = 1 - \sum_{i=0}^{m-1} U_i \quad m < K \quad (3.33)$$

They further show that from equations 3.28, and 3.32, the volume fraction of agglomerates of size $D_j$ in the mixer after time $t$ will be

$$Y_j = \sum_{K-J}^{\infty} G_K U_j \quad (3.34)$$

where: $J = 0, 1, 2, \ldots m$

Substituting equations 3.28, 3.32 and 3.33 into equation 3.34, the volume fraction of agglomerate particles which do not reach ultimate particle size after time $t$ will be
\[ Y_j = \frac{(Xt^*)^j e^{-Xt^*}}{j!} \quad j = 0, 1, 2, \ldots m-1 \quad (3.35) \]

\( t^* = t/\tau \) dimensionless mixing time

and the volume fraction of agglomerates reaching ultimate particle size will be

\[ Y_m = P(m, Xt^*) = 1 - \sum_{i=0}^{m-1} Y_i = 1 - \sum_{i=0}^{m-1} \frac{(Xt^*)^i e^{-Xt^*}}{i!} \quad (3.36) \]

Equation 3.35 also indicates that the fraction of agglomerates \( Y_0 \) of the initial size \( D_0 \) drops exponentially with time as shown by this equation (3.37):

\[ Y_0 = e^{-Xt^*} \quad (3.37) \]

whereas equation 3.36 indicates that the volume fraction of agglomerates reaching ultimate particle size \( D_m \) increases monotonically with mixing time and approaches a value of 1.0 at infinite time.

Finally Zloczower et al established an equation for critical size above which the agglomerates are considered undispersed as

\[ \psi = 1 - P(n+1, Xt^*) \quad (3.38) \]

where \( \psi \) is the volume fraction of agglomerates which are considered undispersed.
In their analysis Zloczower et al too made several simplifying assumptions to render the analysis tractable. In the event of making these assumptions the mathematical model reproduced here may not be very accurate. However the fundamental analysis is very important in order to gain an insight into the problems of mixing processes. Their approach is a step forward in the understanding of these problems.

The simplifying assumptions made by them are as follows:

1. The intensive mixing only occurs at the high shear region between the rotor tip and chamber wall, which is not truly valid. It has been found out that the whole converging region in front of the rotor tip is responsible for dispersive mixing\(^{(9)}\). By neglecting the latter, the model obviously overestimates the mixing time.

2. Newtonian flow behaviour was assumed during the calculation of hydrodynamic separating force and is a rather severe simplifying assumption because freely suspended particles floating in viscoelastic fluids exhibit a more complex behaviour than those floating in Newtonian fluid.

3. The assumption that the volume between the rotors behaves as a perfectly well mixed vessel will overestimate the mixing efficiency. This assumption obviously neglects the importance of rotor design.
4. The process of agglomerate rupture into two equal halves and having the same shape as the original agglomerate was also assumed. This assumption is not valid because in the real process the splitting of agglomerates is much more complex.

5. The size of the agglomerate was assumed to be uniform at the start of the mixing process; this is also not true because agglomerates of fillers such as carbon black have a substantial distribution of sizes.

6. In this analysis they only considered two unit processes i.e. dispersion and distribution of particles and neglected the earlier processes. This made the analysis incomplete. The next step is to look at the approach made by Nakajima where the process of incorporation is also included.

3.4 Energy Balance

Nakajima in his model tries to relate the energy required during mixing to the fundamental properties of material, such as viscoelastic and ultimate properties. In his analysis he only considers the rubber in powdered form. Firstly he has assumed that the rubber particles break uniformly during the whole course of each rotor revolution. The average size reduction per revolution is given by:
\[ f_1 = \left( \frac{\phi_f}{\phi_0} \right)^n \]  

(3.39)

where:  
\[ \phi_0 = \text{average particle diameter before mixing} \]  
\[ \phi_f = \text{average particle diameter after mixing} \]  
\[ n = \text{number of revolutions}. \]

He further assumed that the particles always broke into two equal halves and then derived an equation for the average size reduction per revolution \((f_o)\) in terms of volume fraction as

\[ 1/f_o = 2V_b + V_u = V_b + 1 \]  

(3.40)

where:  
\[ V_b + V_u = 1 \]  
\[ V_b = \text{volume fraction of broken particles} \]  
\[ V_u = \text{volume fraction of unbroken particles}. \]

Next he assumed that the dispersion process takes place primarily between the rotor tip and the chamber wall and this region is always filled with rubber. Then the volume of the material swept through the gap per revolution will be:

\[ V_s = 2\pi DSL (1 - F) \]  

(3.41)

where:  
\[ D = \text{diameter of the chamber} \]  
\[ S = \text{gap height} \]  
\[ L = \text{length of the chamber} \]  
\[ F = \text{the fraction of the circumference of the two chambers which is open between them}. \]
The behaviour of material is assumed to be in elastic state. Hence when the ultimate strain is reached it will break and undergo complete recovery to the original particle shape. The size distribution of the initial and final particles was neglected. The schematic diagram of deformation process is shown in Figure 3.4 below:

![Diagram of deformation process]

**FIGURE 3.5: SCHEMATIC DIAGRAM OF DEFORMATION PROCESS**

He then derived the formula for the total energy required in breaking the rubber particles for the entire period of the mixing cycle, which he designated as effective mixing energy.

\[ W_m = W_b V_b n \quad (3.42) \]
where: \( W_b \) = unit energy constant
\( V'_b \) = actual volume of rubber broken
\( n \) = number of revolutions

He further assumed that the frictional force between carbon black and rubber and among carbon black as well as the cohesive force of carbon black aggregate is small compared to the deformation energy. Thus:

\[
W_D = W_o - W_m
\]  

(3.43)

where: \( W_D \) = energy required to deform the rubber
\( W_o \) = total energy input

The effective energy of mixing, \( W_m \) may be converted to the wattage input as

\[
E_m = W_m / t_m
\]

Figure 3.5 shows the various wattage regions responsible for each individual mixing process.
FIGURE 3.6: A SCHEMATIC ENERGY DIAGRAM FOR MIXING OF POWDER RUBBER WITH CARBON BLACK

(a) = effective energy of mixing - breaking of rubber particles.
(b) = effective energy of deformation relaxation process without rupturing rubber particles.
(c) = energy spent for incorporation of carbon black.
(d) = energy spent by the elastomer for breaking up carbon black agglomerates and distribution in the polymer matrix.

Nakajima's analysis, though in a very simplified form, may offer the right path in making mathematical modelling for mixing. He made his analysis with reference to the flow visualisation both in the static(10) and dynamic(11) behaviour. However he also made some simplifying assumptions. First he assumed that the behaviour of rubber in internal mixers is in a purely elastic
state, this is not true because rubber in an internal mixer exists in both viscous and elastic states. Next he assumed that the parent particles split into two genetically similar particles; this is neither true nor realistic.

In his study he introduced a hypothetical distribution of energy input for each unit process during mixing. This provides valuable information to both machine designers and product manufacturers. For example: if it was found that the fraction of energy responsible for breaking up carbon black agglomerates is very small, this indicates that dispersion process is inefficient, then the machine designer has to improve the situation (maybe by adding extra flights to the rotor). On the other hand if one found that the process of incorporation is inefficient, one should find ways of improving the surface area of the rubber at the start of the mixing process.

So far, from the various mathematical models reviewed it has been found that most researchers concentrate their models based on either rupture of either additives or rubber and none consider them both at the same time. The logical progression is to undertake the description of a model which does this.
3.5 Experimental Design Approach

A new concept of mathematical modelling was undertaken by Freakley and Patel (9) by adopting an experimental approach to the problem. In their work they investigated the influence of fill factor and rotor speed on the flow of a rubber mix by measuring the pressure and temperature at various points inside the mixing chamber. They assumed that the viscous flow predominated in the region in front of the rotor and suggested the relationship between shear stress and shear rates as:

\[
\tau = \eta_0 \dot{\gamma}^n
\]

(3.44)

where:
- \( \tau \) = shear stress
- \( \dot{\gamma} \) = shear rate
- \( \eta_0 \) = reference viscosity
- \( n \) = power law index

They also found that the slip velocity at the rotor and chamber wall play a significant role in influencing the material movement. The slip velocity can be obtained from TMS rheometer by measuring the stress-strain rate relationship using both grooved and polished rotors. A grooved rotor is assumed to give zero slip, whilst a polished rotor allows slip to occur. The difference in speed between these two types of rotors to achieve a given shear stress is therefore attributed to wall slip as:
\[ V_s = R(\omega_s - \omega_g) \]  \hspace{1cm} (3.45.1)

where:

- \( V_s \) = slip velocity
- \( R \) = radius of rotor
- \( \omega_s \) and \( \omega_g \) = angular velocity of polished and grooved rotors respectively
- \( \tau \) = shear stress.

They further assumed that the wall slip behaviour is adequately described by the power-law equation:

\[ V_s = C \tau^m \]  \hspace{1cm} (3.45.2)

where \( C \) and \( m \) are the constants of the equation.

From pressure measurements and rheological properties, they managed to establish the flow behaviour in the mixer taken at equilibrium conditions where stable rheological behaviour and uniform temperature profiles were achieved. At this condition the influence of unit work due to incorporation and dispersion were negligible.

The schematic set-up of the equipment showing the various points where the pressure and temperature measurements were made is shown in Figure 3.6.
FIGURE 3.7: DIAGRAM SHOWING WHERE PRESSURE AND TEMPERATURE MEASUREMENTS WERE TAKEN WITH RESPECT TO MIXING CHAMBER
The fill factor and rotor speed level as shown in Table 3.1 were set up using a factorial design.

TABLE 3.1: EXPERIMENT DESIGN

<table>
<thead>
<tr>
<th>Factorial Points</th>
<th>Rotor Speed rpm</th>
<th>Fill Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>71</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>71</td>
<td>0.84</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>0.84</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Star Points</th>
<th>Fill Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>0.75</td>
</tr>
<tr>
<td>20</td>
<td>0.75</td>
</tr>
<tr>
<td>50</td>
<td>0.6</td>
</tr>
<tr>
<td>50</td>
<td>0.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Centre Point</th>
<th>Fill Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Figure 3.8 shows the circumferential and axial pressure profiles in the region in front of the rotor tip.

FIGURE 3.8: CIRCUMFERENTIAL AND AXIAL PRESSURE PROFILE

--- circumferential pressure profile
---- axial pressure profile
The velocity profile for pressure flow can be calculated from expression for flow between parallel plates:

\[ V_y = \frac{H}{2(1/(n+1)) \left[ \frac{H \Delta P}{2\eta_0 L} \right]^{1/n}} \left[ 1 - \left( \frac{2y}{H} \right)^{1/n+1} \right] \]  

(3.46)

where:  
- \( H \) = radial distance from rotor to chamber wall  
- \( Y \) = distance from the centre plain between them  
- \( \Delta P/L \) = pressure gradient

and the drag velocity profile can be calculated from the product of angular velocity and radius of rotor, taking into account the slip velocity at both rotor and chamber wall (reiteration method). The flow behaviour in the mixing chamber is shown in Figures 3.9-3.13.

**FIGURE 3.9: CIRCUMFERENTIAL VELOCITY PROFILES**
FIGURE 3.10: AXIAL VELOCITY PROFILES AT A4

FIGURE 3.11: CIRCUMFERENTIAL SHEAR RATE PROFILES

FIGURE 3.12: CIRCUMFERENTIAL SHEAR STRESS PROFILES
where power density is the product of shear rate and shear stress.

The pressure profile in Figure 3.5 indicates that the axial material flow is not simple and that the flow rate and flow directions will change with position. Equation 3.47 shows how the axial flow rate can be calculated:

\[
Q = \frac{WH^2}{2\left(\frac{1}{n}+2\right)} \left[\frac{H}{2\rho_0 L}\right]^{1/n}
\]

(3.47)

where: \( W \) = width of the channel.

They found that both slip velocity and axial flow influence the characteristics of flow in internal mixers. Both axial flow rate and flow direction change with position as shown in Figure 3.10 where at points 1 and 4 the flow is negative and at points 2 and 3 the flow is positive. (Note: positive flow refers to flow toward the centre of the chamber and negative away from the centre of the chamber).
Considering the assumptions more critically, the assumption that the flow in front of the rotor tip is predominantly shear flow may have some negative effect when considering mixing efficiency. Theodorou (14) predicted high force for extensional flow compared to shear flow, which from his point of view, the former becomes the major cause of dispersive mixing. The experiments were carried out at equilibrium conditions, thus eliminating the effect of incorporation and dispersion on the flow characteristics of the mix. Therefore the flow characteristics presented here may not be representative of the real process. Finally all the profiles they presented were calculated based on parallel plate expression. This is only true if the ratio between the diameter of the rotor to tip and channel clearance is very large.

3.6 General Comments

From the various mathematical models reviewed, it was found that until now the mathematical modellings were still at an exploratory stage. The basic approach among researchers with respect to the mechanism of agglomerate rupture is not unanimous. There are different views regarding where the process of dispersion takes place. Some assume that the intensive mixing is dominated by agglomerate rupture which occurs within the vicinity of the narrow gap high shear field, while others suggest that dispersion is dominated by elongational flow fields which are controlled by the separation of closely spaced agglomerate
fragments which occur in the entrance region upstream from the narrow gap. Freakley and Patel\textsuperscript{(9)} suggested that the dispersion can occur throughout the whole region in front of the rotor wings. This is based on the uniform shear stress occurring over the whole region in front of the rotor wings. The initial stages of the mixing process such as incorporation and subdivision are generally excluded in the model.

A complete mathematical model which is intended to predict the progress of the mixing process and its efficiency should include various fundamental considerations such as:

a) Polymer
   - Generally polymer exhibits viscoelastic properties rather than wholly viscous behaviour.
   - It is in various forms and sizes e.g. slab or powder.
   - If powder, its size distribution is critical.
   - The mechanism and rate of breaking and coalescence is also needed to be considered.

b) Additives
   - The most important is the size and size distribution of agglomerates.
   - The nature of agglomerates, whether they are interacting or non-interacting particles.
   - The complex mechanism of fragmentation, not just simple division from one agglomerate into two identical fragments.
   - The nature of cohesive forces - the weakest point is not always in the middle because of cracks and other imperfections in the structure.
c) Mixes
- The influence of the interaction among polymers and additives to the mixes during mixing operation are also required to be considered – as in practice mixes are based on multi-components systems rather than dual systems.
- The amount of loading of each individual additive is not the same in particular mixes, thus attention is also required in this matter.

d) Interaction between mixes and mixer
- The influence of slip velocity at the rotor and chamber wall to the pressure and drag flow profiles.
- Heat transfer from mix to mixer and vice versa: not isothermal.

e) Other considerations

These include economic and technical factors. In practice the rate of dispersion drops so rapidly with decreased particle size\(^{(15)}\) that economic and other technical considerations stop the mixing cycle well short of ultimate dispersion\(^{(5)}\).
References

CHAPTER 4
EVALUATION OF FLOW PATTERNS

4.1 Introduction

Since the 1950s a considerable amount of progress has been made in establishing fundamental concepts of mixing process (1,2,3), though applications of these concepts have not yet been widely accepted. This provides some framework for studying flow patterns and shearing characteristics of several widely used mixing devices (1). However the flow pattern studied here was based on the mathematical models of various workers (4,5,6,7) who made several simplifying assumptions on both material properties and rotor geometry.

It can be seen that a very considerable gap exists between the requirement of the processor and the capabilities of current flow analyses to fulfil those requirements. The fundamental problems are those of complexity of the rheological behaviour of rubber and the intentionally imposed 'disorder' of flow in the internal mixer. Boundary conditions and justifiable assumptions are difficult to determine due to non-steady state conditions. Here an attempt was made to study the flow pattern of rubber in the mixing chamber by means of flow visualisation. By this method the difficulties of boundary conditions and the simplifying assumption can be largely eliminated and the true phenomena of the mechanics of flow can then be observed. With this a more viable mathematical modelling may be constructed in the future.
FIGURE 4.1.1A: CROSS-SECTION VIEW OF BANBURY VISUALISATION RIG

FIGURE 4.1.2A: SIDE VIEW OF BANBURY VISUALISATION RIG
4.2 Description of the Banbury Visualisation Rig

The visualisation rig is a modified Midget Banbury with two rotors and a chamber of 0.366 litres free volume. The mixing chamber is made of transparent perspex, having similar shape to that of modern F-series Banbury's. The ram is made of perspex but conforming with the Farrel-Bridge practice, the bottom was cut slightly off centre. Figures 4.1.1 and 4.1.2 show the cross-section and side view respectively of flow visualisation rig.

FIGURE 4.1.2: SIDE VIEW OF BANBURY VISUALISATION RIG
FIGURE 4.1.1: CROSS-SECTION VIEW OF BANBURY VISUALISATION RIG
(Letters refer to various regions identified in the discussion)
The rotors were connected to a 1.12 kW motor drive having a variable speed drive ranging from 0 to 32 rpm. Each rotor rotates in the opposite direction and at different speeds. The speed ratio between the slow and fast rotors is 1:1.2, making one complete cycle to be 5 and 6 revolutions of slow and fast rotors respectively. Each rotor has two tapered flights one on each end which are situated at an angle to the direction of rotation (helix angle). The long flight is 30° while the short flight is 37°. The inner ends of the flight are situated at about 180° to each other. The rotor is 100 mm wide with a diameter of 60 mm as measured at the tip of the flight.

The chamber resembles two circles having a diameter of 64 mm and the centres at 70 mm apart. The centre portion had to be removed making the two lobes joined together to form one chamber. On the wall of the mixing chamber there were two holes where the pressure transducer could be sited to measure the pressure inside the chamber. The holes were located at 25 mm and 75 mm, measured from the front of a 100 mm wide mixing chamber as shown in Figure 4.1.2. The mixing chamber was made up of two equal widths (50 mm each) of perspex. The front plate was also made of perspex with 50 mm thickness. The back plate was of metal which was attached to the rest of the driving system. The mixer had a maximum channel and a tip clearance of 20 mm and 2 mm respectively.
The ram pressure was introduced by means of a lever system as shown in Figure 4.2. Weights could be attached to the end of the lever in order to get the required pressure.

![Diagram of ram lever system](image)

**FIGURE 4.2: RAM LEVER SYSTEM**

A rotary potentiometer was attached to the back of the fast rotor to determine its position during operation. This was done by amplifying the potentiometer signal and then transmitting it to a chart recorder. The initial position was set at zero potential and it went through 5V maximum just before
reaching the original position where it dropped to zero again. In this way the position of the rotor could be monitored at any time.

4.3 Method of Analysis

**Setting up of axes**

For the analysis of flow patterns of the material flowing between the rotor and the chamber wall, the rotor was assumed to be stationary and the following axes were set up. Since the rotor is basically cylindrical in shape, its coordinate system can best be presented in cylindrical polar coordinate system \( r\theta z \). For the purpose of measurement, the arbitrary origin was chosen on the left hand rotor to be as follows:

- \( r \) = radius of the rotor, measured from the longitudinal axis.
- \( \theta \) = angle of rotation, measured at 145° or 75 mm from the edge of the long flight (refer to diagram Figure 4.3).
- \( z \) = axial distance along rotor, measured from the front end of the rotor (refer to diagram Figure 4.3).

To make the presentation on paper easier the cylindrical polar coordinate system \( r\theta z \) will be transformed to rectangular coordinate system \( xyz \) where \( x = \theta \), \( y = r \) and \( z = z \).

Since the movement in the \( r \) direction was neglected at this stage due to some difficulty with measurement, the coordinate system could be presented only in two dimension i.e. \( x \) and \( z \).
where \( x = \frac{\pi r \theta}{180} \) \hspace{1cm} (4.1)

\( r \) was taken to be equal to 30 mm which is the radius of the rotor at the flight tip.

**Definition of region in mixing chamber**

The flow patterns in the mixing chamber were analysed by identifying various regions inside the chamber, which were then analysed separately by means of flow visualisation technique. The following are the various regions in the mixing chamber.

Region A: The region immediately in front of the rotor tip sometimes known as the sickle shaped region (refer to Figure 4.1.1).

Region B: The region immediately behind the rotor tip sometimes known as the void region (refer to Figure 4.1.1).

Region C: The circumferential S-shaped region round the end of the rotor wings (refer to Figure 4.3).

Region D: The region between the two rotors sometimes known as the bridge region (refer to Figure 4.1.1).

**Computer analysis method**

The flow pattern of the material at the bridge position and the movement of single marker were analysed using computer graphics. To make the analysis possible some modification of the axes were made. The value of \( \theta \) was resolved to Cartesian coordinate.
FIGURE 4.3: DEVELOPMENT OF THE PERIPHERY OF THE ROTOR
(Letters refer to various regions identified in the discussion)
FIGURE 4.4.1
FRONT VIEW

FIGURE 4.4.2
UNDER VIEW

FIGURE 4.4: COORDINATE SYSTEM OF ROTORS ADOPTED DURING THE ANALYSIS OF SINGLE MARKERS
system x and y as shown in Figures 4.4.1 and 4.4.2.

The new origin is now as follows:

\[
\begin{align*}
    x &= x + 20 \\
    y &= y + 20 \\
    z &= z + 20
\end{align*}
\]

Note: The addition of the 20 to x, y and z axes is to avoid error from GINO-graphic computer package(8).

The computer program can be found in Appendix 1. It is an interactive program and is capable of drawing three-dimensional plots. The viewing angle can also be altered as required.

4.4 Experimental Method

In a practical Banbury mixer, the chamber is made of thick steel designed to withstand high pressure and moderate temperature. The availability of transparent material capable of withstanding such conditions is quite limited. To overcome these constraints, the operating conditions are limited to lower rotor speed (maximum 30 rpm) and operating at room temperature. The elastomer used was transparent silicone gum (ICI grade SE 33) which is designed to yield lower shear stresses than a conventional rubber mix. In order to study the flow pattern in various regions in the mixing chamber, four separate experiments were designed for this purpose.
4.4.1 Flow Pattern Between Rotor and Chamber Wall

In this experiment small cubes of coloured vulcanised rubber were incorporated into the silicon gum to act as markers. The rubber was then introduced into the mixing chamber via the throat of the mixer. The ram was then introduced. The mixer was operated at equilibrium ram pressure. (The equilibrium ram pressure is defined as being the condition when upward and downward forces on the ram are practically equal, and a small amount of ram movement occurs due to transient difference between these forces). When the machine was switched on the movement of the markers was recorded using a Polaroid Polarvision cine camera placed directly at the side of the mixer. The resulting films were studied using a Polarvision viewer having four different speeds and capable of running frame by frame. The $\theta$ and $z$ coordinates of the marker movement were traced at small intervals on a transparent sheet which is placed on the viewing screen. The value of $x$ was then calculated. The experiment was carried out on the left hand rotor at 0.7 fill factor and 16.7 rpm rotor speed (20 rpm on the fast rotor).

The aim of this experiment is to establish the flow pattern when the material passes between the rotor and chamber wall of the internal mixer.
4.4.2 Experiment at Bridge Position

In this experiment the silicone rubber was first introduced into the mixing chamber. The mixer was then run for some time and switched off again so that it stopped at a preset position. The ram was then removed from its position. Eleven markers were placed at equal intervals (10 mm apart), as shown in Figure 4.5.1, along the z-axis by creating small holes at the centre of the mixing chamber just below the ram position. It was important to close the holes so that the markers did not touch the ram as soon as it was placed again. Precaution was taken not to cause any flow during the placing of the ram. The mixer was then rotated for one revolution on the fast speed rotor. The final positions of the markers were then located. The experiment was carried out for six relative rotor positions as shown in Figure 4.5.2.

The aim of this experiment is to investigate the flow pattern at the bridge position and establish how the material is transferred from one lobe of the mixing chamber to the other.

FIGURE 4.5.1: POSITIONS OF THE MARKERS WITH RESPECT TO z-AXIS (TOP VIEW)
4.4.3 To Investigate the Interaction Between Various Regions

4.4.3.1 To investigate the interaction between regions A, B and C

In this experiment, the procedure was somewhat similar to the experiment in Section 4.3.2, but without markers. The silicone rubber was loaded into the mixer at the required fill factor and the machine was then started for about two minutes. It was then stopped and the boundary lines (flow fronts) were sketched as shown in various figures in Section 4.5.3.1. The experiment
was carried out at 0.5, 0.7 and 0.9 fill factor for three relative rotor positions as shown in Figure 4.6.

Arrows show tip positions

FIGURE 4.6: THE THREE RELATIVE POSITIONS AT WHICH THE FLOW FRONTS WERE SKETCHED
(Drawn at Z = 0).
4.4.3.2 To investigate the interaction at bridge position

In this experiment the objective was to study the flow profile of the material at bridge position. The machine, with the same materials from the experiment in Section 4.4.3.1, was started again for about two minutes and then stopped at a preset position. The flow profiles at the bridge position were then recorded. This was done by observing the orientation of air bubbles formed during the mixing operation. However the orientation of air bubbles for 0.5 and 0.7 fill factor was not obvious, thus only the flow profile of 0.9 fill factor could be drawn.

The experiment was carried out for a complete cycle (i.e. six revolutions on the fast rotor and five revolutions on the slow rotor) at each respective relative rotor position. Altogether a set of 30 relative rotor positions were carried out and their relative rotor positions are shown in Figures 4.19.1 to 4.19.30.

4.4.4 Movement of Single Marker

In this section two sets of experiments were carried out. The first was aimed at finding the average number of revolutions needed for the marker to change from one lobe to another. This was done by drawing a straight line parallel to the Z-axis at the bottom of each lobe, as shown in Figure 4.7. One marker was then introduced into the mixing chamber loaded with silicone rubber. The machine was then started. The time was noted every time the marker passed these lines. Knowing the rotor speed the number of revolutions could be calculated.
FIGURE 4.7: BOTTOM VIEW OF MIXING CHAMBER

The second experiment was to locate the coordinate \((\theta, Z)\) of marker movement inside the chamber. In this experiment the machine was put to the on-off system at every revolution on the fast rotor. When the rotor was stopped, the coordinate of the marker was noted. The flow path of the marker is shown in various figures in Section 4.5.4.

4.5 Results and Discussion

4.5.1 Flow Pattern Between Rotor and Chamber Wall

4.5.1.1 Region A

Region A (refer to diagram Figure 4.1) is sickle-shaped in areas well away from the bridge. The sickle shape is formed by the curved surface of the rotor and the cylindrical wall of the mixing chamber. Due to the motion of the rotor this region is constantly filled with material (refer to 0.7 fill factor or above). Referring to Figure 4.3, there are two regions A i.e. in front of the long and short flights.
FIGURE 4.8: FLOW PATTERN BETWEEN ROTOR AND CHAMBER WALL AS OBSERVED FROM THE MOVEMENT OF MARKERS.
Figure 4.8 shows the general flow pattern of the markers flowing between the rotor and the chamber wall. Each line represents a flow path of a marker. In order to see the overall flow pattern the path of the markers was plotted on the same axis, although these were taken from different revolutions. The rotor is assumed to be stationary at the specific coordinate axis as described in Section 4.2.1. From this plot it is apparent that the markers flow at an angle to the direction of rotation or in the direction about normal to the helix angle. This result was consistent with the result found by Freakley and Patel\textsuperscript{(9)}. This phenomena can be explained more clearly by resolving the velocity components parallel and perpendicular to the direction of rotation and assuming that the rotor is moving with respect to the stationary chamber as shown in Figure 4.9.

\begin{center}
\includegraphics{figure49}
\end{center}

**FIGURE 4.9: RESULTANT VELOCITY**
where: \( V_c \) = velocity component parallel to the direction of rotation (circumferential velocity)  
\( V_L \) = velocity component perpendicular to the direction of rotation (lateral velocity)  
\( V_R \) = resultant velocity.

This explains the reason why the material in front of the rotor wing flow towards the centre of the mixing chamber. Ignoring the radial movement, the flow here is unidirectional which suggests that less distributive mixing occurs here than in other regions.

Since region A is always filled with material streamlined flow will occur, which is due to both pressure and drag flow. The pressure flow is caused by the converging effect of the rotor and chamber wall, while the drag flow is caused by the motion of the rotor relative to the chamber wall.

Close observation of Figure 4.8 shows that some of the markers move upstream in relation to the stationary rotor. This indicates that in practice there are some markers moving faster than the rotor itself. In addition to that, a wide range of velocities of markers found in this region indicates that the velocity profile in front of the flight tip is rather complex. The wide ranges of velocities is also due to the narrow gap between the rotor and the chamber wall within the vicinity of the rotor tip; a small change in the position in the radial direction can cause a tremendous change in the circumferential and lateral
movement. From these observations it is evident that there is a high rate of deformation occurring in this region which is important for dispersive mixing.

This phenomenon was also observed by Wan Idris\(^{(10)}\) for Brabender plastograph. He illustrated the flow profile by inserting a few strips of coloured markers (coloured silicone rubber) across the gap between the rotor and the chamber wall. As the rotor rotated there was a considerable distortion of this profile when the markers moved in a rapidly decreasing aperture. He also found a considerable velocity differential between 'adjacent stream lines'. This points to high stresses and effective mechanism for breaking down and dispersing filler aggregates.

Adjacent to region A is the tip region. This region is very small and it is less important as far as distributive mixing is concerned. However when the markers reached the tip region they generally deflected from the direction perpendicular to the helix angle to the direction of rotation. The flow over the tip is described as being equivalent to the leakage flow occurring over the flight tips in an extruder.

Both region A and the tip region are most amenable to mathematical analysis because of the orderly flow which occurs and they are also the prime areas where dispersive mixing is considered to be taking place. However in forming mathematical analysis in these regions, several factors have to be taken into account with respect to the geometry and its interaction with polymer melt. The most important is the angle at which the flight is set, with respect to
the direction of rotation. Thus the axial flow is important. It was found that slip velocity at the rotor and the chamber wall not only existed, but also varied from location to location\(^\text{(9)}\). This must certainly influence the movement of material and heat transfer between the mixer and the melt. The tapered tip, which causes a considerable elongation flow, also has a significant influence on the flow profile in region A.

4.5.1.2 Region B

Region B (refer to Figure 4.11) is the void positions, which are situated directly behind the rotor tips. The formation of voids is one of the significant phenomena during the mixing of rubber in an internal mixer. They are always formed as long as the fill factor is less than unity. The size of the voids is inversely proportional to the fill factor. Figure 4.10 shows a schematic diagram of the region inside the mixing chamber where the voids are likely to form. The void region can be considered to stretch from just behind the flight tip down to the flow front.

From visual observation, the markers in this region move more slowly than those in region A; they flow in the direction of rotation. Figure 4.8 also indicates that when the markers passed the flight tip they tended to flow in the direction of rotation.

Depending on the fill factor and rotor speed the silicone rubber inside the void region may be fractured, thus the flow of
FIGURE 4.10: SCHEMATIC DIAGRAM SHOWING DISTRIBUTION OF VOIDS INSIDE MIXING CHAMBER
material in this region may not be continuous. In the void region itself there is not much mixing taking place, however the presence of voids is important for creating disorder in the flow pattern, which contributes to the effective distributive mixing. More details of these phenomena are discussed in Chapter 5.

4.5.1.3 Region C

The reason for calling this region S-shaped is that the markers seem to move in the S-shaped pattern relative to the stationary rotor. Figure 4.3 shows that this region occurs along the strip of dotted lines. It lies between the flow front and region A. The S-shaped pattern is caused by the action of the two flights situated on the opposite ends of the rotor. Thus this region provides an ideal transfer of material in the axial direction i.e. from front to back and vice versa of the same rotor. From visual observation it is also found that this region is normally filled with material (referring to 0.7 fill factor and above) therefore the flow of material in this region is continuous.

It was also noticed qualitatively that both magnitude and direction of the velocity of the markers in this region varies with radial distance. Markers which were nearer to the rotor not only move faster than the markers which are further away from the rotor with respect to the chamber, but also tend to move in the direction of rotation. However the markers which
are nearer to the chamber tend to deflect away from the direction of rotation or they tend to move in the direction perpendicular to the flight. Figure 4.11 shows a schematic drawing of the relative magnitude and direction of the markers with respect to radial distance. This observation provides another item of information with regard to the importance of axial movement inside the mixing chamber. It also indicates the complexity of the flow pattern in this region which contributes to distributive mixing.

Since the gap between the rotor and chamber wall in this region is large, the shear rate will be low, thus the magnitude of shear stress is substantially lower in comparison to the shear stress in region A and the tip region. Most researchers assumed that this region provided little importance for dispersive mixing. However, with large gaps between the rotor and chamber wall, the extent of shear deformation is large, this provides a good mechanism for distributive mixing.

In mathematical modelling of this region it is necessary to consider all the above factors, such as axial movement with respect to radial distance and the flow pattern. However, so far no mathematical analysis has been done specifically for this region. This indicates the lack of study in the mechanism of distributive mixing.
FIGURE 4.11: SCHEMATIC DRAWING SHOWING THE RELATIVE MAGNITUDE AND DIRECTION OF MARKERS VELOCITIES WITH RESPECT TO RADIAL DISTANCE (ASSUMED ROTOR IS MOVING)
4.5.2 Flow Pattern at Bridge Position

One of the primary functions of the flow of material in this region is to provide the mechanism of exchange of material between the two lobes of the mixing chamber. Figures 4.12.1-4.12.6 show the flow patterns at the bridge position at positions 1, 2, 3, 4, 5 and 6 respectively. It seems that the flow patterns at this region are more complex than any other region in the mixing chamber. It was found that the markers can either move to the right or left lobe after one revolution, indicating that the transfer of material is taking place into both lobes at the same time. From Figures 4.12.1-4.12.6 it was also found that relative rotor position is one of the prime factors that control the transfer of material from bridge position to either left or right lobe. However the markers which are situated adjacent to the front or back wall (where \(Z = 0\) or 100 respectively) of the mixing chamber do not move significantly from their original positions, indicating that very little movement occurs around these positions.

It was also observed that the material at the centre of the mixing chamber does not move significantly to either left or right lobe but its location varies along the Z-axis.

Figures 4.12.1-4.12.6 also indicate that there was a wide variation in the distance travelled by the markers for one revolution. It varied from insignificant movement to about half a
FIGURE 4.12.1: THE PROFILES OF MARKERS’ MOVEMENT BEGINNING FROM BRIDGE POSITION FOR ONE REVOLUTION STARTING AT RELATIVE ROTOR POSITION ONE (refer to Figure 4.5.2)
FIGURE 4.12.2: THE PROFILES OF MARKERS' MOVEMENT BEGINNING FROM BRIDGE POSITION FOR ONE REVOLUTION STARTING AT RELATIVE ROTOR POSITION THO (REFER TO FIGURE 4.5.2)
FIGURE 4.12.3: THE PROFILES OF MARKERS' MOVEMENT BEGINNING FROM BRIDGE POSITION FOR ONE REVOLUTION STARTING AT RELATIVE ROTOR POSITION THREE (refer to Figure 4.5.2)
FIGURE 4.12.4: THE PROFILES OF MARKERS' MOVEMENT BEGINNING FROM BRIDGE POSITION FOR ONE REVOLUTION STARTING AT RELATIVE ROTOR POSITION FOUR (REFER TO Figure 4.5.2)
FIGURE 4.125: THE PROFILES OF MARKERS' MOVEMENT BEGINNING FROM BRIDGE POSITION FOR ONE REVOLUTION STARTING AT RELATIVE ROTOR POSITION FIVE (refer to Figure 4.5.2)
FIGURE 4.12.6: THE PROFILES OF MARKERS' MOVEMENT BEGINNING FROM BRIDGE POSITION FOR ONE REVOLUTION STARTING AT RELATIVE ROTOR POSITION SIX (REFER TO FIGURE 4.5.2)
revolution, indicating that a large deformation had occurred. This phenomenon is important for effective distributive mixing. Generally the markers movement for 0.9 fill factor is relatively less than 0.7. This further confirms the earlier\textsuperscript{(10)} observation that there is a little exchange of material between the lobes of the chamber at higher fill factors.

Figures 4.13.1-4.13.18 show the detail of the individual paths of each marker movement from the bridge position when the rotor was rotated for one revolution. However since only the initial and final positions of each marker were noted, the path indicated by these figures might not be the true path of the marker. Figures 4.13.1-4.13.18 also indicate that there were two stages of marker movements. The first stage is the movement of the marker across the bridge position. This movement is due to the pressure gradient across the bridge position, where the material normally flows from high pressure regions to the lower pressure regions. There are several possible relative rotor positions that can create pressure gradients across the bridge position. The most effective position is when the flight of one rotor moves towards the bridge position while the flight of the other rotor moves away from the bridge position. Further discussion on pressure gradient across the bridge position is to be found in Section 4.5.3.2.

It was also observed that the transfer of the marker across the bridge position may occur more than once, i.e. the marker may first go to the right then to the left and then
FIGURE 4.13: FLOW PATHS OF MARKER AT BRIDGE POSITION AFTER ONE REVOLUTION WITH RESPECT TO RELATIVE ROTOR POSITION AT DIFFERENT FILL FACTORS

Figure 4.13.1: POS 1 - 0.5
Figure 4.13.2: POS 1 - 0.7
Figure 4.13.3: POS 1 - 0.9
Figure 4.13.4: POS 2 - 0.5
Figure 4.13.5: POS 2 - 0.7
Figure 4.13.6: POS 2 - 0.9
Figure 4.13.7: POS 3 - 0.5
Figure 4.13.8: POS 3 - 0.7
Figure 4.13.9: POS 3 - 0.9
Figure 4.13.10: POS 4 - 0.5
Figure 4.13.11: POS 4 - 0.7
Figure 4.13.12: POS 4 - 0.9
Figure 4.13.13: POS 5 - 0.5
Figure 4.13.14: POS 5 - 0.7
Figure 4.13.15: POS 5 - 0.9
Figure 4.13.16: POS 6 - 0.5
Figure 4.13.17: POS 6 - 0.7
Figure 4.13.18: POS 6 - 0.9

Note: POS = relative rotor position
0.5, 0.7 and 0.9 are the fill factors used in experiments.
right again. This phenomena normally occurs more prominently at a higher fill factor, suggesting that the transfer of material is less efficient at higher fill factors.

The second stage of movement is the transfer of the marker from the bridge position into the lobe of the mixing chamber. This phenomenon will occur if the material carrying the marker is pumped across the bridge position by the flight of one rotor into the path of the flight of another rotor. In this case the flight of the former must pass the bridge position first, then followed by the latter. For Brabender type rotors\(^{(10)}\) it appears to be necessary for the former rotor to pump the material directly into the void behind the tip of the latter rotor in order to obtain effective exchange of material. This phenomenon does not show a very significant effect for Banbury type rotors. The reason may be due to the insignificant development of voids at the bridge position at about 0.7 fill factor or above. The other reason may be due to the distance between the rotors, which is greater in the case of the Banbury.

### TABLE 4.1: Number of Markers with Respect to their Locations

<table>
<thead>
<tr>
<th>Lobe</th>
<th>Left</th>
<th>Right</th>
<th>Not Moving</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st 5 points</td>
<td>54</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>Centre point</td>
<td>8</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>Last 5 points</td>
<td>30</td>
<td>43</td>
<td>14</td>
</tr>
<tr>
<td>TOTAL:</td>
<td>92</td>
<td>72</td>
<td>31</td>
</tr>
</tbody>
</table>
Table 4.1 shows the total number of markers transferred to the left and right or remaining at the bridge position for positions one to six and fill factors 0.5, 0.7 and 0.9 summed together. For the first five points the markers were placed on the front side while the last five points were placed on the back side along the Z-axis of the rotor as shown in Figure 4.5.1. It was found that for the first five points the total number of markers transferred to the left was more than the number of markers transferred to the right. However for the last five points the reversed situation occurs. Referring to the rotor geometry it was found that the long flight of the left hand rotor is situated towards the front of the mixing chamber while the long flight of the right hand rotor is situated towards the back of the mixing chamber. This clearly shows that the size of the flight has a significant influence on the mechanism of material exchange between the two lobes.

It was also found that from Table 4.1 the total number of markers transferred to the left and right lobe was 92 and 72 respectively. This difference may be due to the effect of rotor speed differential between the two rotors. The speed ratio between LHR:RHR is 1:1.2 and the ratio of the total number of markers transferred to the left and right is 1.3:1. If it is assumed that the total amount of material passing through the left and right lobes for the whole mixing cycle is the same, it is expected that the amount of material in the left and right lobes at any time in the cycle will be in the ratio of 1.2:1. This may be the reason why more markers were found to be in the left lobe than the right lobes.
4.5.3 Interaction Between Various Regions

The interaction between regions is very important for effective distributive mixing due to the fact that the material in different regions undergoes different modes of action, e.g. if the material passes under the rotor tip it will experience a high stress concentration, thus the agglomerate may rupture. However if the material passes around the end of the flight it will not be subjected to such a high shear stress, therefore it is unlikely that the agglomerate will rupture. For effective distributive mixing a mechanism must be provided in order for the material from these two regions to interact with each other.

An example where the material from different regions can interact with each other is at the flow front. This happens when the flight passes the bridge position, it will carry a certain amount of material from the bridge position with it. This material, which can either be from the same or opposite lobes, will form the flow front 'in front' of the flight tip. It was also observed that the material inside the void region, which was subjected to high shear stress when it passed under the flight tip, was also an important source of material that contributed to the formation of the flow front. Thus the two sources of material meet at the flow front. Other areas include the interaction between the region in front of the flight and the S-shaped region.
FIGURE 4.14: SCHEMATIC DRAWING OF GENERAL FLOW PATTERN ASSUMING ROTOR IS STATIONARY
4.5.3.1 Interaction of the flow mechanisms which occur between the rotors and the chamber wall

Figure 4.14 shows the schematic drawing of the general flow pattern of rubber with respect to a stationary rotor for material which is not in contact with the rotor and chamber wall. However this is only true if it is far away from the bridge position. Here it shows clearly that the function of the flight is to pump the material toward the centre of the mixing chamber. Considering that the flow begins in front of the long flight, the material flows diagonally towards the centre of the mixing chamber. When it reaches the end of the flight it will be in contact with the circumferential flow front caused by the short flight, which is situated on the opposite side of the rotor. The material will then flow in the direction of rotation until it will be deflected again toward the centre by the short flight. However if the material reaches the bridge position there is a probability that it will transfer to the other lobe.

From Figure 4.14 it can be seen that the circumferential flow front is caused by the action of the flight situated on the same side of the flow front while the lateral flow front is caused by the material flowing around the end of the opposite flight.
Effect of flight position on flow front

Figures 4.15.1-4.15.3 show the effect of flight position on the flow front. This sketch was taken at 0.7 fill factor and 10 rpm rotor speed from LHR at positions 1, 2 and 3 (Figure 4.6) where the position of the RHR was left constant. It was found that the size of the circumferential flow front decreases as the flight moves away from the bridge position. Figure 4.16.1 shows the relative size of the flow fronts, taken under the same conditions as above, and their respective positions with respect to mixing chamber. It was also found that the rubber just after the bridge position did not move until the flight position rotated about 180° from the middle of the mixing chamber, measured at the tip end (either 0 or 100 mm on Z-axis) as shown in Figure 4.16.2. This front can be termed the stagnant front. It was also found that the previous flow front disappeared from the top of the mixing chamber at about the same time as the stagnant front started to move from the bottom of the mixing chamber for 0.7 fill factor.

Effect of fill factor on flow front

Figures 4.17.1-4.17.3 show the effect of fill factor on the flow front taken at position 2 for 20 rpm rotor speed. It shows that the length of the boundary of the circumferential flow front is inversely proportional to the fill factor. From Figures 4.13.1-4.13.3 and Figures 4.15.1-4.15.3, it can be seen that the size of the circumferential flow front depends on the extent of the axial
FIGURE 4.16.1: SCHEMATIC DRAWING OF FLOW FRONT SHOWING ITS RELATIVE SIZE AS IT MOVES AWAY FROM BRIDGE POSITION FROM THE BOTTOM OF THE MIXING CHAMBER

FIGURE 4.16.2: SHOWING THE FLIGHT POSITION AT WHICH THE STAGNANT FRONT IS ABOUT TO MOVE AND FLOW FRONT ABOUT TO DISAPPEAR (FFO.7)
flow front, caused by the action of the opposite rotor moving towards the centre of the mixing chamber. It could be deduced that the reduction of the size of the circumferential flow front can be related to the amount of material flowing round the end of the flight. More discussion on this will be found in Chapter 5.

**Effect of relative rotor position on flow front**

Figures 4.18.1-4.18.3 show the effect of relative rotor position on the flow front taken at 10 rpm on RHR for 0.7 fill factor. The position of the RHR was kept constant, while the position of the LHR was placed at positions 1, 2 and 3 (Fig.4.6). It was found that the stagnant front appeared just behind the short flight for all the three relative rotor positions. There was no obvious difference between the flow front for positions 1 and 2. However for position 3 the flow front on the left hand side of the rotor (Z = 0) i.e. the flow front vertically above the short flight, stretched about half a revolution (180°) whereas for positions 1 and 2 their flow front stretched for only about \( \frac{1}{3} \) revolution. There was no obvious demarcation point where the circumferential and axial flow fronts met for position 3 for both the left and right sides of the flow front.

Looking at the relative positions in more detail, it was found that the long flight of LHR at position 3 was just past the bridge position, thus the relative amount of material in the left lobe is expected to be more than in the right lobe (see
Section 4.4.2). Since the amount of material in the right lobe is less when the rotor is at position 3, as compared to the other two positions, it is expected that the length of the boundary of the flow front at position 3 will be longer than that of positions 1 and 2.

**Effect of rotor speed on flow front**

Figures 4.19.1-4.19.3 show the effect of rotor speed on the flow front. This experiment was carried out at 30, 20 and 10 rpm rotor speed and 0.7 fill factor at position 2. There is no obvious difference in the shape of the flow front situated 'behind' the long flight for all the three conditions. However it was found that the flow front situated behind the short flight was longer for 30 rpm rotor speed than the other two. In this case there is no obvious explanation to be given on this phenomenon except that since the rotor is expected to stop at the same position for all the three conditions before the sketch was drawn, due to the effect of momentum, the machine was switched off earlier when operated at fast speed. This introduced some inconsistencies in the experiment. As the rotor was switched off, it still rotated very slowly before it stopped completely, however the flow front was hardly moving due to the elastic recovery. Thus it appears that the void size is bigger for 30 rpm than 20 and 10 rpm rotor speed. This phenomenon may be the cause of apparent long flow front found when operating at higher speeds.
FIGURE 4.15: EFFECT OF FLIGHT POSITION ON FLOW FRONT (left hand rotor)

- Material always present (Bridge region)
- Material outside void region
- Material inside void region
- No material present (due to fracture)
FIGURE 4.17: EFFECT OF FILL FACTOR ON FLOW FRONT (left hand rotor)

- Material always present (Bridge region)
- Material outside void region
- Material inside void region
- No material present (due to fracture)
FIGURE 4.18: EFFECT OF RELATIVE ROTOR POSITION ON FLOW FRONT (right hand rotor)

- Material always present (Bridge region)
- Material outside void region
- Material inside void region
- No material present (due to fracture)
FIGURE 4.19: EFFECT OF ROTOR SPEED ON FLOW FRONT (right hand rotor)

- Material always present (bridge region)
- Material outside void region
- Material inside void region
- No material present (due to fracture)
4.5.3.2 Interaction occurring between the two rotors

Figures 4.20.1-4.20.30 show the interaction of the flow pattern occurring in between the two rotors with respect to the relative rotor position. For ease of explanation these interactions are divided into three categories:

1. When both flights are moving towards the bridge position.
2. When one flight is moving towards the bridge position, while the other is moving away.
3. When both flights are moving away from the bridge position.

For condition 1, high pressure will be developed around the bridge region. Depending on which flight is nearer to the bridge region, the flow pattern profile will be skewed towards the opposite side. Figures 4.20.3, 4.20.8, 4.20.9 show that the flight of the left hand rotor is nearer to the bridge region thus the flow pattern profile is skewed to the right, while in Figure 4.20.19 the situation is opposite. It was also found that if the distance between the bridge region to either flight is about the same, the flow profile is symmetrical. Figures 4.20.13 and 4.13.14 show just that. It is expected that when the rotors are at these positions, the flow of material at that particular location will be limited.

For condition 2, high pressure will be developed on the side where the flight is moving to the bridge region. Thus the flow pattern profile is skewed towards the opposite side where low pressure region occurs. Figures 4.20.1, 4.20.2, 4.20.4,
4.20.7, 4.20.18, 4.20.20, 4.20.21, 4.20.23-4.20.28 and 4.20.29 all show the same principle. In general at condition 2, the maximum transfer of material from one lobe to another occurs. This is because the void may occur just after the bridge position where the rotor has just passed through. This will create an empty space here, ready to be filled with the material carried in front of the flight of the opposite rotor.

For condition 3, a low pressure region will be developed around the bridge region. It was also found that the skewness of the flow pattern at this condition is less compared with the other two conditions. However from Figures 4.20.10, 4.20.11, 4.20.12, 4.20.16, 4.20.17, 4.20.22 and 4.20.30 it was found that the flow pattern at condition 3 is rather complex. The complexity is caused by the disordered flow occurring behind the rotor tip (void region).

Another significant phenomenon that occurs at the bridge region is the vortex flow due to the interaction of the material coming from each lobe. This interaction is important as far as distributive mixing is concerned because the material from two different lobes will combine here and, depending on the flow profile, it can either be transferred to the left or right lobes.
FIGURE 4.20: FLOW PATTERN PROFILE AT BRIDGE POSITION WITH RESPECT TO RELATIVE ROTOR POSITIONS (FLOW STREAMLINES)

| Figure 4.20.1: | POSITION 1 |
| Figure 4.20.2: | POSITION 2 |
| Figure 4.20.3: | POSITION 3 |
| Figure 4.20.4: | POSITION 4 |
| Figure 4.20.5: | POSITION 5 |
| Figure 4.20.6: | POSITION 6 |
| Figure 4.20.7: | POSITION 7 |
| Figure 4.20.8: | POSITION 8 |
| Figure 4.20.9: | POSITION 9 |
| Figure 4.20.10: | POSITION 10 |
| Figure 4.20.11: | POSITION 11 |
| Figure 4.20.12: | POSITION 12 |
| Figure 4.20.13: | POSITION 13 |
| Figure 4.20.14: | POSITION 14 |
| Figure 4.20.15: | POSITION 15 |
| Figure 4.20.16: | POSITION 16 |
| Figure 4.20.17: | POSITION 17 |
| Figure 4.20.18: | POSITION 18 |
| Figure 4.20.19: | POSITION 19 |
| Figure 4.20.20: | POSITION 20 |
| Figure 4.20.21: | POSITION 21 |
| Figure 4.20.22: | POSITION 22 |
| Figure 4.20.23: | POSITION 23 |
| Figure 4.20.24: | POSITION 24 |
| Figure 4.20.25: | POSITION 25 |
| Figure 4.20.26: | POSITION 26 |
| Figure 4.20.27: | POSITION 27 |
| Figure 4.20.28: | POSITION 28 |
| Figure 4.20.29: | POSITION 29 |
| Figure 4.20.30: | POSITION 30 |
4.5.4 Movement of a Single Marker

Tables A2.1-A2.3 detail the movement of a typical marker inside the mixing chamber for 0.5, 0.7 and 0.9 fill factor respectively. The results show that the speed of the marker is about 3 to 4 times slower than the speed of the rotor. They show quite significantly that the marker for 0.7 fill factor moves relatively faster than the markers for 0.5 and 0.9 fill factors. This can be observed from the number of rotations each marker made during the course of 200 revolutions of the fast rotor. In this case the number of marker rotations for 0.7 fill factor was 61, while for 0.5 and 0.9 it was 53 and 49 respectively. This observation indicates that the extent of flow of material for 0.7 fill factor is more than for 0.5 and 0.9. This is an important criterion since the extent of flow determines the flow pattern and the total deformation, which directly affects the distributive mixing. This implies that 0.7 fill factor is a better condition for distributive mixing.

It also shows that the number of times the marker exchanges from one lobe to another is substantially higher for 0.7 fill factor than for 0.9. This indicates that the material for 0.9 fill factor flows in a more orderly manner, resulting in less effectiveness in distributive mixing. However there is no significant difference for 0.5 and 0.7 fill factors indicating that the rate of material exchange is effective even at 0.5 fill factor. Table 4.4 also shows that the percentage of the
marker exchanged from one lobe to the other is higher at low fill factor. It can be deduced that the percentage of material exchange is also higher at low fill factor. One of the possible reasons for this phenomenon may be related to the void size, where a larger void causes the flow to be more disordered, which is one of the criteria for effective distributive mixing. However, from visual observation and pressure measurement it was found that there is a discontinuity in the flow for 0.5 fill factor. More discussion on this will be found in Chapters 6 and 7. This limits the extent of deformation thus making distributive mixing less efficient at this fill factor even though the flow pattern is complex.

The low percentage of material exchanged between the lobes for 0.9 fill factor suggests that the streamline flow phenomenon is persistent at this fill factor. This argument is further enlightened by the fact that the average number of times a marker rotates in each lobe before transfer to the other lobe is more for 0.9 fill factor than that of the 0.5 and 0.7 fill factors.
TABLE 4.4

<table>
<thead>
<tr>
<th>Fill factor</th>
<th>0.5</th>
<th>0.7</th>
<th>0.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-X-bridge</td>
<td>14</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>N-marker rev</td>
<td>53</td>
<td>61</td>
<td>49</td>
</tr>
<tr>
<td>A-RS/MS</td>
<td>3.77</td>
<td>3.28</td>
<td>4.08</td>
</tr>
<tr>
<td>A-N-Rev/Lobe</td>
<td>3.53</td>
<td>3.81</td>
<td>6.00</td>
</tr>
<tr>
<td>A-N-Rotor Rev.</td>
<td>13.3</td>
<td>12.5</td>
<td>22.2</td>
</tr>
<tr>
<td>% marker X-bridge</td>
<td>26.4</td>
<td>24.6</td>
<td>16.3</td>
</tr>
</tbody>
</table>

N-X-Bridge: Number of times each marker crosses the bridge position either from right or left.

N-marker rev: Number of times each marker makes a complete rotation or pass through the bottom line.

A-RS/MS: Average ratio of fast rotor speed: speed of marker: i.e. 200 rev/N-marker rev.

A-N-Rev/lobe: Average number of times a marker rotates in each lobe before transfer to the next lobe.

A-N-Rotor rev: Average number of revolutions (rotor revolutions) before a marker transfers from one lobe to the next.

% marker X-bridge: Percentage of marker crossing the bridge with respect to the number of times each marker makes a complete rotation, i.e. (N-X-bridge/N-marker rev) x 100.
Results from the second experiment in this section are given in Tables A2.4 and A2.5, which show the coordinates of the marker for each revolution for 30 revolutions. It was found that the average number of markers transferred across the bridge position is about the same as the previous experiment. This shows that the on and off experiment is valid.

Figures 4.21.1-4.21-30 show the typical movement of a single marker for 0.9 fill factor. In this experiment the coordinates of the marker were noted only once in each revolution, therefore the paths shown may not be the true paths of the marker. However from visual observation it was found that the true paths did not run very far from the drawing especially when the marker moved only for a short distance. Figures 4.22.1 and 4.22.2 show the movement of a marker for 0.7 and 0.9 fill factor drawn on large scale drawing for 30 revolutions.

Figures 4.23.1-2, Figures 4.24.1-2 and Figures 4.25.1-2 show the effect of fill factor on the marker movement at positions 1, 2 and 4 for one revolution. The initial positions of the marker were placed randomly in the mixing chamber. It was found that the marker movement for 0.9 fill factor seemed to be less than for 0.7 fill factor especially for position 1. However from visual observation it was found that the extent of the marker movement depended more on the radial distance (r-axis) with respect to the chamber rather than fill factor. But since the initial positions of the marker were located randomly in the mixing chamber, the above findings may be relevant as far as distributive mixing is concerned where 0.7
fill factor is generally reported to be more efficient than the 0.9 fill factor.

(Note that the change of colour from red to blue and blue to red of Figures 4.21 and 4.22 is to indicate one revolution of the fast rotor. The dotted lines indicate that the flow of the marker is towards the bridge position, while the solid line is away from the bridge position).
FIGURE 4.21: MOVEMENT OF SINGLE MARKER FOR 0.9 FILL FACTOR

Figure 4.21.1: POS 1 - R0  Figure 4.21.21: POS 3 - R20
Figure 4.21.2: POS 2 - R1  Figure 4.21.22: POS 4 - R21
Figure 4.21.3: POS 3 - R2  Figure 4.21.23: POS 4 - R22
Figure 4.21.4: POS 4 - R3  Figure 4.21.24: POS 5 - R23
Figure 4.21.5: POS 5 - R4  Figure 4.21.25: POS 6 - R24
Figure 4.21.6: POS 6 - R5  Figure 4.21.26: POS 1 - R25
Figure 4.21.7: POS 1 - R6  Figure 4.21.27: POS 2 - R26
Figure 4.21.8: POS 2 - R7  Figure 4.21.28: POS 3 - R27
Figure 4.21.9: POS 3 - R8  Figure 4.21.29: POS 4 - R28
Figure 4.21.10: POS 4 - R9  Figure 4.21.30: POS 5 - R29
Figure 4.21.11: POS 5 - R10
Figure 4.21.12: POS 6 - R11
Figure 4.21.13: POS 1 - R12
Figure 4.21.14: POS 2 - R13
Figure 4.21.15: POS 3 - R14
Figure 4.21.16: POS 4 - R15
Figure 4.21.17: POS 5 - R16
Figure 4.21.18: POS 6 - R17
Figure 4.21.19: POS 1 - R18
Figure 4.21.20: POS 2 - R19

Note: POS = relative rotor position
R = number of revolutions.
FIGURE 4.22.1: SHOWS THE FLOW PATH OF A MARKER FOR 30 REVOLUTIONS AT 0.7 FILL FACTOR
FIGURE 4.22.2: SHOWS THE FLOW PATH OF MARKER MOVEMENT FOR 30 REVOLUTIONS AT 0.9 FILL FACTOR
FIGURE 4.23: EFFECT OF FILL FACTOR ON MARKERS' MOVEMENT FOR ONE REVOLUTION STARTING AT RELATIVE ROTOR POSITION ONE
FIGURE 4.24: EFFECT OF FILL FACTOR ON MARKERS’ MOVEMENT FOR ONE REVOLUTION STARTING AT RELATIVE ROTOR POSITION TWO
FIGURE 4.25: EFFECT OF FILL FACTOR ON MARKERS' MOVEMENT FOR ONE REVOLUTION STARTING AT RELATIVE ROTOR POSITION FOUR
References


5.1 Introduction

As stated in Section 4.4.1.3 void formation is one of the most significant phenomena during mixing of rubber in an internal mixer. The position of voids formed in the internal mixer and their size is very important with respect to mixing efficiency. Its function in this respect is to introduce disorder in the flow of rubber. However if the void is too large the flow will be discontinuous and as such the flow of material will be limited and this will offset the mixing efficiency.

The boundary of the void can be defined lying between the rotor tip at the 'top', the circumferential flow front at the 'bottom' and lateral flow front at the 'side' as shown in Figure 5.1. The void is partially filled with material which has just passed under the flight tip. This material, which has been subjected to high stresses (both shear and elongational), will be incorporated into the flow front. It was reported\(^{(1)}\) that for effective mixing it is important that this material retains its integrity until it combines with the flow front. A rubber having a low extensibility before fracture would break up here and create the problem of mixing failure due to crumbling and filler separation.

The importance of melt elasticity, and tearing and crumbling of elastomer at the tip region has been discussed from a qualitative viewpoint by Tokita and White\(^{(2,3,4)}\). These authors perceive
FIGURE 5.1: VOID AND ITS BOUNDARY REGIONS (SIDE VIEW)

the three following regimes as shown in Figure 5.2:

Regime 1

Regime 2

Regime 3

FIGURE 5.2: BEHAVIOUR OF RUBBER AT TIP REGION OF AN INTERNAL MIXER
1. Melt smoothly deform and flows.
2. Melt refuses to enter the tip region.
3. Melt tears apart into powder and cannot be massed.

The best mixing is regime 1. Regime 2 is due to high melt elasticity while regime 3 is associated with poor ultimate properties. However in practice a combination of the above situations occurs.

Knowing the rate of flow of material under the rotor tip is very important because it could predict the rate of dispersive mixing. Most researchers have assumed that the rate of dispersive mixing depends on the rate of draining at the tip region. However it was also suggested that dispersive mixing also occurs in the sickle shaped region\(^{(5)}\).

It was also observed that the material that flows around the end of the flight is the main source of material that contributes to the formation of the flow front. As it passes through the end of the flight it will be 'pumped' to the centre of the mixing chamber by the incoming flight situated at the opposite end of the rotor. The amount of material that flows round the end of the flight, together with the circumferential flow front, will determine the size and shape of the void.
5.2 Experimental Method

5.2.1 Void Formation

There were two sets of experiments carried out in the study of void formation. The first set was carried out by taking still photographs viewing from three different directions (i.e. left, right and bottom). Three different speeds (10, 20 and 30 rpm on the test rotor) and three different fill factors (0.5, 0.7 and 0.9) were chosen. In this experiment the position of the right hand rotor (fast rotor) was kept at a fixed position while the position of the left hand rotor (slow rotor) was changed to its respective relative rotor position. Figures 5.3.1-5.3.6 show the relative positions of the rotor. To highlight this phenomena some of the photographs are produced in the discussion (Section 5.3).

The second set of experiments was to enable sketches of the shape of the void along the cross-section of the mixing chamber at 25 mm, 50 mm and 75 mm along the Z-axis to be drawn (refer to Section 4.3 for the definition of Z-axis). When the silicone rubber was loaded in the mixing chamber at the required fill factor, the machine was then started for about two minutes and stopped at the appropriate position. The experiment was carried out at positions 1, 3 and 5 for 10, 20 and 30 rpm rotor speed and 0.5, 0.7 and 0.9 fill factor.
FIGURE 5.3 SHOWS THE SIX RELATIVE ROTOR POSITIONS WHERE PHOTOGRAPHS WERE TAKEN
5.2.2 To Find the Amount of Material Flowing Under the Flight Tip and Around the End of the Rotor

5.2.2.1 Under the flight tip

The mixer, filled with the required amount of silicone rubber, was first rotated for about 2 minutes. It was then stopped at the specified position. The reference point was noted where the rotor stopped. The rotor was then rotated again for about 60°. The front plate and the first half of the mixing chamber were removed. The material which had flown over the flight tip between the initial and final positions was taken out and weighed. Figures 5.4.1 and 5.4.2 show the positions where the material was taken. The experiments were carried out for 0.6, 0.7 and 0.8 fill factor and three relative rotor positions, as shown in Figure 5.4.3.

FIGURE 5.4.1: FRONT VIEW SHOWING INITIAL AND FINAL ROTOR POSITION
5.2.2.2 Flow around the end of the rotor

Again the mixer was filled with the required amount of silicone rubber and was rotated for about two minutes. It was then stopped at a specified position. The front plate and the first half of the mixing chamber was removed. Precautions were taken not to disturb the material at the end of the flight. Exactly 5 mm strip of material adjacent to the end of the flight was removed and weighed. It was decided arbitrarily to take a strip of material of 5 mm thickness (the tip width is also 5 mm). Figure 5.2.2 shows the position with respect to the rotor where the material was taken. The experiments were carried out for 0.6, 0.7 and 0.8 fill factor and three relative rotor positions, as shown in Figure 5.1.1.
FIGURE 5.4.3: THE THREE RELATIVE ROTOR POSITIONS AT Z = 0 mm FOR EXPERIMENT 5.2.2.1

FIGURE 5.5.1: THE THREE RELATIVE ROTOR POSITIONS AT Z = 100 mm FOR EXPERIMENT 5.2.2.2.
5.3 Results and Discussion

5.3.1 Effect of Fill Factor on Void Formation

Considering the whole mixing chamber, the total sum of the volume of the voids formed inside the mixing chamber will be inversely proportional to the fill factor. Equation 5.1 provides the relationship between void size and fill factor:

\[ V = \frac{M}{SG} (1 - FF) \]  \hspace{1cm} (5.1)

where:  
- \( V \) = volume of void (referred to as void size)
- \( M \) = total mass of material
SG = average specific gravity of melt
FF = fill factor.

Figure 5.6 is a plot of circumferential length of the void against fill factor. This length was measured on the pressure trace where there was no pressure development occurring (refer to Section 6.3.1.1). The plot indicates that there is a linear relationship between the circumferential length of the void and fill factor. It was also found that the length of the void behind the long flight is always longer than the length of the void behind the short flight which implies that the size of the void follows accordingly.

Figures 5.7.1-5.7.3 show the effect of fill factor on the size and shape of voids for 0.5, 0.7 and 0.9 fill factor respectively as viewed from the bottom of the mixing chamber, while Figures 5.8.1-5.8.3 were viewed from the front and operated under the same conditions. It was found that the void formation at 0.9 fill factor was insignificant. This suggested that the efficiency of distributive mixing at this condition is less effective, as found by most researchers. For 0.7 fill factor the formation of the voids are very apparent. From visual observation as well as from photograph Figure 5.7.2 the material inside the void at this fill factor is always associated with fracture. However, the flow of material at 0.7 fill factor is more disordered than 0.9. This will increase the mixing efficiency. For 0.5 fill factor the formation of the voids was very pronounced and large in size. They also appeared even in
FIGURE 5.6: EFFECT OF FILL FACTOR ON VOID SIZE
FIGURE 5.7: EFFECT OF FILL FACTOR ON VOID FORMATION (BOTTOM VIEW) TAKEN AT POSITION 1, (refer to Figure 5.3.1).

FIGURE 5.7.1
FILL FACTOR = 0.5

FIGURE 5.7.2
FILL FACTOR = 0.7

FIGURE 5.7.3
FILL FACTOR = 0.4
FIGURE 5.8: EFFECT OF FILL FACTOR ON VOID FORMATION (SIDE VIEW) (TAKEN AT POSITION 3, refer to Figure 5.3.3)
front of the flight tip. This clearly shows that the flow of material was not continuous and thus hindered the mixing efficiency.

Freakley and Wan Idris\(^6\) explained qualitatively the dynamics of using different fill factors by means of colour photographs of rubber undergoing rotor action. They found that an extremely well ordered flow, is indicated by the tracer material, unless some mechanism for disordered flow regimes is included. Reducing the fill factor thus increasing the void size behind the rotor tip provides this mechanism. However at too low a fill factor (around 0.5) the region between the rotor and chamber wall had large voids with little flow passing the rotor tip. The flow was analogous to milling, material passing between the rotor and not through the high shear stress areas.

From Figures 5.18-5.26 it was found that there was no fracture occurring at the rotor tip for all cases. This indicates that the deformation which occurs at the tip region does not exceed the ultimate strain. The fluid behaviour is similar to Tokita and White's regime 1 (Figure 5.2). However the fracture generally occurs as the rubber enters the void region. The fracture is more severe at low fill factor especially at 0.5. This indicates that the material cannot retain its integrity before being incorporated into the flow front. However the fracture seems to occur even at 0.9 fill factor, but to a lesser extent. This may suggest that mixing of silicone rubber may be efficient even at high fill factor. Previous work using a
Francis Shaw Intermix(9) indicates that mixing of silicone rubber is efficient even at 0.9 fill factor. This may be due to the low extensibility of silicone rubber which requires high fill factor for efficient mixing. This phenomenon is also observed in some other types of rubber (e.g. butyl, EPDM and some grades of NBR) where it is generally believed that better mixing is obtained at high fill factor due to fracture which occurs behind the rotor tip.

5.3.2 Effect of Relative Rotor Position on Void Formation

As the speed of the two rotors is not the same, it is expected that the amount of material transfer from one lobe to the other is not the same at any one time during the mixing operation. This will affect the size of the voids formed (i.e. with more material the size of the void will be smaller and vice versa).

Figure 5.9 is a plot of circumferential length of the void taken on the right hand rotor (RHR), with respect to the relative position of the left hand rotor (LHR), while Figure 5.10 is taken on the LHR with respect to the RHR. The reading was taken at 25 mm on the Z-axis from the pressure trace. The relative rotor positions are shown in Figures 5.11.1 and 5.11.2 for the right and left respectively. It was found that there was a constant variation in the void size with respect to relative rotor positions.

First consider Figure 5.9 and take positions 4 and 5; as the RHR starts to move the pressure transducer will immediately experience the void region, thus no pressure development occurs.
FIGURE 5.10: EFFECTS OF RELATIVE ROTOR POSITION ON VOID SIZE AT DIFFERENT FILL FACTORS
(refer to Figure 5.11.2)
FIGURE 5.9: EFFECT OF RELATIVE ROTOR POSITIONS ON VOID SIZE AT DIFFERENT FILL FACTORS
(refer to Figure 5.11.1)
FIGURE 5.11.1: RELATIVE POSITION OF RHR WITH RESPECT TO THE LHR

FIGURE 5.11.2: RELATIVE POSITION OF LHR WITH RESPECT TO THE RHR

FIGURE 5.11: SHOWS RELATIVE ROTOR POSITION WITH RESPECT TO PRESSURE TRANSUDER
(Front View - at 25 mm from the front of mixing chamber)
FIGURE 5.12.1: POSITION 3 (refer to Figure 5.3.3)

FIGURE 5.12.2 POSITION 5 (refer to Figure 5.3.5)

FIGURE 5.12: EFFECT OF RELATIVE ROTOR POSITION ON VOID FORMATION
At this position the long flight of LHR is moving towards the bridge position, thus the material will be 'pushed' to the right lobe. This will make the size of the void which was formed behind the tip of the RHR, at these relative rotor positions, smaller than at other relative rotor positions. At other positions the flight is either moving away from the bridge position or situated far away from it. Similar phenomena were found for the LHR with respect to the RHR.

Photographs of Figures 5.12.1 and 5.12.2 reveal that if the long flight is moving towards the bridge position, the void formed on the opposite rotor will be smaller than if it were the short flight moving towards the bridge position. In these photographs Figure 5.12.1, the short flight of LHR is moving toward the bridge position while Figure 5.12.2, the long flight is moving toward the bridge position. These photographs show clearly that the void found in Figure 5.12.1 is larger than the void found in Figure 5.12.2.

Figures 5.18, 5.19 and 5.20 are the sketches of the voids formed at 0.5 fill factor and at positions 1, 3 and 5 respectively. There seems to be very little change of the fracture behaviour of rubber with respect to relative rotor position.

5.3.3 **Effect of Rotor Speed on Void Formation**

Rotor speed also plays an important part in void formation. However it seems that there is no effect on the size of the void with respect to rotor speed as is indicated by Figure 5.13, 5.14, 5.15 and 5.16. However from photographs of Figures 5.17.1-5.17.3
FIGURE 5.13: EFFECT OF ROTOR SPEED ON VOID SIZE AT DIFFERENT FILL FACTORS (MEASURED ON LHR Z = 25 mm)
FIGURE 5.14: EFFECT OF ROTOR SPEED ON VOID SIZE AT DIFFERENT FILL FACTORS (MEASURED ON LHR Z = 75 mm)
FIGURE 5.15: EFFECT OF ROTOR SPEED ON VOID SIZE AT DIFFERENT FILL FACTORS (MEASURED ON RHR Z = 25 mm)
FIGURE 5.16: EFFECT OF ROTOR SPEED ON VOID SIZE AT DIFFERENT FILL FACTORS (MEASURED ON RHR Z = 75 mm)
FIGURE 5.17: EFFECT OF ROTOR SPEED ON VOID FORMATION
(Taken at position 4, refer to Figure 5.3.4)
it appears that there is a reduction in void size with respect to an increase in rotor speed. This apparent reduction may be due to fractured material occupying some of the void space. This indicates that at higher strain rates more fracture could occur. However this fracture may not affect mixing efficiency because at higher rotor speeds (within limits) more disordered flow can be introduced.

From Figures 5.21, 5.22 and 5.23 it can also be seen that there is not much affect of rotor speed on void formation. However it is seen that the speed ratio has some effect on the fracture of material inside the void region. It was found that from Figures 5.21, 5.22 and 5.23 more fracture occurs in the right hand lobe, which corresponds to the fast rotor. This further shows that the extensibility of silicone rubber is very low.

5.3.4 Void Distribution with Respect to Absolute Rotor Position

The voids are always formed at a specific location with respect to rotor position. With reference to 0.9 fill factor and below, there was more than one void formed at all times during the mixing operation. These voids were generally different in size and shape. Table 5.1 shows the different size of the voids formed behind the four flight tips at different fill factors. It shows clearly that even for the same fill factor, the size of the voids were different at different locations. On average the largest is at number 3 which corresponds
to the long flight of the LHR, then followed by number 2, which corresponds to the long flight of the RHR. However there seem to be an insignificant difference in the average size of the void formed behind the two short flights.

In general the longer flights create larger voids than the shorter ones. There are two possible reasons that account for this difference. The first is the obvious one, where it is expected that shorter flights will create smaller voids than longer flights. The second reason is related to the amount of material flowing round the end of the flight. In this situation the material flowing around the end of one flight will occupy the void formed by the opposite flight, since the long flight can sweep more material than the short flight into the void formed by the short flight. Furthermore the material will be pushed by the long flight further to the other end of the mixing chamber, thus occupying more space in the void adjacent to it. On the other hand an opposite explanation could be given to explain for the phenomenon occurring at the short flight.

Referring to the LHR of Figures 5.12.1 and 5.12.2 a similar phenomenon was observed where the void appearing behind the short flight (Figure 5.12.1) was smaller than the void appearing behind the long flight (Figure 5.12.2). The position of the RHR is the same for both figures. This confirms the above explanation.

Figures 5.18-5.26 show the typical distribution of voids inside the mixing chamber at three different rotor positions. It was observed that besides the void formed behind the flight,
TABLE 5.1: CIRCUMFERENTIAL LENGTH OF VOID (mm) FORMED BEHIND THE FOUR FLIGHTS

<table>
<thead>
<tr>
<th>Fill Factor Location</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>77.2</td>
<td>46.7</td>
<td>49.3</td>
<td>32.0</td>
<td>51.3</td>
</tr>
<tr>
<td>2</td>
<td>125.1</td>
<td>109.1</td>
<td>93.0</td>
<td>72.9</td>
<td>51.4</td>
<td>90.3</td>
</tr>
<tr>
<td>3</td>
<td>150.7</td>
<td>126.1</td>
<td>103.1</td>
<td>89.1</td>
<td>59.3</td>
<td>105.7</td>
</tr>
<tr>
<td>4</td>
<td>99.2</td>
<td>53.3</td>
<td>45.0</td>
<td>41.0</td>
<td>35.3</td>
<td>50.8</td>
</tr>
</tbody>
</table>

Location 1 = RHR - 25 mm - short flight
2 = RHR - 75 mm - long flight
3 = LHR - 25 mm - long flight
4 = LHR - 75 mm - short flight

(Note: All measurements were measured from the front of the mixing chamber).

depending on rotor position and fill factor, it may also occur at the top of the mixing chamber. Figure 5.18 shows a typical example where voids are found at the top of the mixing chamber. It was also found that the size of the void varies with respect to location where it occurs in the mixing chamber. It is seen that no significant void formation occurs at the bridge position.
FIGURE 5.18: Voids distribution at relative rotor position 1 (for FF = 0.5 - 20 RPM)
FIGURE 5.19: VOIDS DISTRIBUTION AT RELATIVE ROTOR POSITION 3
FOR FF = 0.5 - 20 RPM

Z = 25 mm

Z = 50 mm

Z = 75 mm
FIGURE 5.20: VOIDS DISTRIBUTION AT RELATIVE ROTOR POSITION 5
(FOR FF = 0.5 - 20 RPM)
FIGURE 5.21: VOIDS DISTRIBUTION AT RELATIVE ROTOR POSITION 1
(FOR FF = 0.7 - 10 RPM)
FIGURE 5.22: VOIDS DISTRIBUTION AT RELATIVE ROTOR POSITION 1
(FOR FF = 0.7 - 20 RPM)
FIGURE 5.23: Voids Distribution at Relative Rotor Position 1
(FOR FF = 0.7 - 30 RPM)
FIGURE 5.24: Voids Distribution of Relative Rotor Position 1
(FOR FF = 0.9 - 20 RPM)
FIGURE 5.25: Voids Distribution at Relative Rotor Position 3
(for FF = 0.9 - 20 RPM)
FIGURE 5.26: Voids Distribution at Relative Rotor Position 5
(FF = 0.9 - 20 RPM)
5.3.5 Amount of Material Flowing Under Flight Tip

As was mentioned in Section 5.3.1 it is a common assumption that the amount of material flowing under the flight tip determines the rate of dispersion. As such, several theoretical methods have been introduced to find the flow rate at this region from pressure measurements, rotor geometry and properties of material. Several existing methods were discussed in Chapter 3.

The amount of material flowing under the flight tip can be calculated by considering Figures 5.4.1 and 5.4.2

Let θ be the angle between $P_1$ to $P_2$.
Let $A$ be the length of $\frac{1}{2}$ of mixing chamber.
Let $M_E$ be the weight of material flowing under the flight tip between $P_1$ to $P_2$.

assuming the amount of material flowing under the flight tip is constant. Therefore the amount of material flowing under the flight tip per revolution will be:

$$M = M_EL(1-F) \frac{360\theta}{A}$$  \hspace{1cm} (5.2)

where $F$ = fraction of the circumference of the two chambers which is open between them.
$L$ = perpendicular distance between the two ends of the flight.

$M =$ weight of material passing under one flight per revolution.
From Table 5.2 it was found that the material flowing under the flight tip does not vary much with fill factor. This indicates that the material in front of the flight tip is always full at these fill factors. It was also found that relative rotor position has no effect on the amount of material flowing under the flight tip.

Nakajima\(^8\) derived a formula which can calculate the amount of material passing under the flight tip (see equation 3.41). Using his formula the calculated amount of rubber flowing under this flight is about 19 gm. Despite drag and pressure flow being in the same direction, a smaller value of material was found experimentally to be passing under the rotor tip than predicted by Nakajima's equation, which only considers drag flow. The difference can only be attributed to wall slip.

Table 5.3 shows the total amount of material passing under the four flight tips as a percentage of mix volume per revolution,
assuming that the amount of material flowing under the flight tip depends only on unit length of the flight. In this case the sum of the length of the four flights is 220 mm.

TABLE 5.3: PERCENTAGE OF MATERIAL PASSING UNDER FLIGHT TIP PER REVOLUTION

<table>
<thead>
<tr>
<th>RRP</th>
<th>POS 1</th>
<th>POS 2</th>
<th>POS 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>FF</td>
<td>0.6</td>
<td>27.0</td>
<td>24.3</td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>24.7</td>
<td>22.5</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>23.7</td>
<td>25.6</td>
</tr>
</tbody>
</table>

It was found that about 25 percent of the material flows under the flight tip per revolution. It is also important to note here that once the material flows under the flight tip its viscoelastic properties will change. This material then has a greater tendency to pass under the flight tip again in the next revolution than the rest of the material. This will offset the mix uniformity unless some mechanism of disorder flow could be introduced during mixing.

*Note: RRP = Relative rotor position (refer to Figure 5.4.3).*
5.3.6 Amount of Material Flowing Around the End of the Rotor

The material which is flowing round the end of the flight is one of the factors that influences the size and shape of the void formed behind the opposite flight. Figures 5.7.1-5.7.3 show the position of the rotor at which the material passed round the end of the flight for 0.5, 0.7 and 0.9 fill factor respectively. In this case the relative rotor position and rotor speed were kept constant (Position 1 and 10 rpm). It was clear from these photographs that fill factor had a strong influence on the amount of material passing around the end of the flight.

To calculate the amount of material flowing round the end of the flight, let us consider Figure 5.5.2.

Let \( T \) be the width of the rotor tip.

Let \( W \) be the weight of a strip of material found at the end of the flight.

It is assumed that the weight of the strip of material is constant with respect to the rotor position and also assumed that the movement of material is very small as compared to the movement of the rotor. Therefore the amount of material flowing around the end of the flight at this condition will be:

\[
A_0 = \frac{W \pi D (1-F)}{T}
\]  

(5.3)

where \( D \) = diameter of the chamber.

However it was observed that the average speed of the material is about one-fourth of the speed of the rotor (refer to Section 4.3).
Therefore the amount of material flowing round the end of the rotor at this condition will be

\[ A_1 = \frac{W \pi D (1-F) 0.75}{T} \] (5.4)

Table 5.3.1 shows the weight of the strip of material found at the end of the flight and Tables 5.3.2 and 5.3.3 show the amount of material passing round the end of the flight per revolution calculated based on equations 5.3 and 5.4 respectively. It was found that the amount of material flowing round the end of the flight depends on the fill factor. This result is consistent with that of Figure 5.2.7. However there is no significant variation with respect to relative rotor position, especially at high fill factor.

Figure 5.28 shows the mechanism of material flowing round the end of the flight. This material is coming from two directions: one is in the direction of circumferential flow front and the other is from the region in front of the rotor. However if the fill factor is small (0.7 or less) the material that passes the end of the flight tip will only come from the region in front of the flight. Figure 5.29 shows a schematic drawing of the material found at the end of the flight for high and low fill factor.

It is clear that the region around the end of the flight is the meeting point between various regions inside the mixing chamber, therefore it is very critical as far as distributive mixing is concerned. The material which has flowed under the
flight tip and subjected to high shear stress will then be incorporated into the flow front of the same flight and this material will again combine with material flowing out from the region in front of the opposite flight. Thus vigorous mixing will always take place at the end of the flights.

The average amount of material flowing under the long flight tip as a percentage of the material flowing around its end is about 37, 34 and 29 percent for 0.6, 0.7 and 0.8 fill factor respectively. It is expected that the percentage of material flowing under the short flight is even smaller. Thus this result is consistent with the result shown in Table 5.3.

From this result it is found that the amount of material passing under the flight tip per revolution is relatively large. However from the movement of a single marker (refer to Section 4.5.4) it was found that it tends to pass under the same flight tip for a number of revolutions before it is transferred to the other flight or flowing round the end of the flight. It can be deduced from here that even though about 25 percent of the material flows under the flight tip per revolution, only a small percentage of new material (i.e. material that has not yet been subjected to high shear stress) that actually passed the flight tip per revolution. However more detailed studies in this field are required in the future.
FIGURE 5.28: MECHANISM OF MATERIAL FLOWING AROUND FLIGHT TIP

TABLE 5.3.1: WEIGHT OF MATERIAL AT THE END OF FLIGHT

<table>
<thead>
<tr>
<th>FF</th>
<th>POS 1</th>
<th>POS 2</th>
<th>POS 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>1.93</td>
<td>1.82</td>
<td>1.98</td>
</tr>
<tr>
<td>0.7</td>
<td>2.03</td>
<td>2.42</td>
<td>2.23</td>
</tr>
<tr>
<td>0.8</td>
<td>2.68</td>
<td>2.65</td>
<td>2.70</td>
</tr>
</tbody>
</table>

TABLE 5.3.2: WEIGHT OF MATERIAL PASSING THE END OF FLIGHT PER REVOLUTION (according to equation 5.3)

<table>
<thead>
<tr>
<th>FF</th>
<th>POS 1</th>
<th>POS 2</th>
<th>POS 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>57.9</td>
<td>54.6</td>
<td>59.4</td>
</tr>
<tr>
<td>0.7</td>
<td>60.9</td>
<td>72.6</td>
<td>66.9</td>
</tr>
<tr>
<td>0.8</td>
<td>80.4</td>
<td>79.5</td>
<td>81.0</td>
</tr>
</tbody>
</table>
TABLE 5.3.3: WEIGHT OF MATERIAL FLOWING ROUND THE END OF FLIGHT PER REVOLUTION (according to equation 5.4)

<table>
<thead>
<tr>
<th>FF</th>
<th>POS 1</th>
<th>POS 2</th>
<th>POS 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>43.4</td>
<td>41.0</td>
<td>44.6</td>
</tr>
<tr>
<td>0.7</td>
<td>45.7</td>
<td>54.5</td>
<td>50.2</td>
</tr>
<tr>
<td>0.8</td>
<td>60.3</td>
<td>59.6</td>
<td>60.8</td>
</tr>
</tbody>
</table>

*Note: For relative rotor position refer to Figure 5.5.1.

FIGURE 5.29: SCHEMATIC DRAWING OF MATERIAL FLOWING AROUND THE END OF FLIGHT

(Note: A and B are the relative flow fronts for low and high fill factor respectively)
References


CHAPTER 6
PRESSURE MEASUREMENTS AND STRESS DISTRIBUTION INSIDE MIXING CHAMBER

6.1 Introduction

There are various causes for the pressure to develop during mixing in an internal mixer.

1. The polymer is a viscoelastic material where it generates normal stresses under shear condition.

2. The hydrostatic pressure caused by the action of the ram.

3. The effect of material which is constantly being 'pushed forward' due to the action of the rotor.

The first two causes do not influence the fluctuation of pressure in a Banbury mixer very much. It is the effect of rotor configuration that actually gives rise to the pressure fluctuation in the mixing chamber. As the rotor is turned counterclockwise (equivalent to moving to the left as shown in Figure 6.1) the material tends to accumulate at the left side of the flight and the pressure $P_2$ is developed. At the right of the

![Schematic Diagram of Rotor Tip](image_url)

FIGURE 6.1: SCHEMATIC DIAGRAM OF ROTOR TIP
flight material tends to be dragged away and the pressure at $P_1$ is less. The material tends to flow from the region of high pressure to the region of low pressure by two routes: over the flight tip and back through the surface surrounding the rotor. Bolen and Colwell\cite{1} refer to these flows as tip and channel flow.

6.2 Experimental Method

6.2.1 Pressure Measurement

The pressure measurement in the mixing chamber was recorded by means of a Dynisco Pressure transducer located in the wall of the mixing chamber. The pressure measuring diaphragm of the transducer was adjusted until it was flush with the inner chamber wall. The pressure was recorded at four different locations i.e. 25 mm and 75 mm on the z-axis and at the centre line on the y-axis as shown in Figure 4.1.2 for both sides of the mixing chamber.

Since the speed ratio between the slow (left) and fast (right) rotors is 1:1.2, therefore for one complete cycle there will be five and six revolutions for slow and fast rotor respectively. The experiment was carried out for 0.5, 0.6, 0.7, 0.8, 0.9 and 1.0 fill factor and 10, 15, 20, 25, 30 rpm rotor speed (fast rotor) for at least three cycles.

6.2.2 Characterisation of Silicone Rubber

The characterisation of silicone rubber was carried out using a TMS rheometer at the Avon Rubber Company. Figure 6.2 is the schematic drawing of the TMS rheometer. This is a variable speed
FIGURE 6.2: SCHEMATIC DIAGRAM OF TMS RHEOMETER
biconical rotor machine, giving an approximately uniform shear rate throughout the test sample. The closed cavity and transfer cylinder arrangement permit a precise control of hydrostatic pressure and enable the test cavity to be closed prior to injection of rubber, ensuring that the clearances between the cavity and rotor remain constant from test to test.

Before testing, the upper platen was raised and the required rotor was inserted into the testing cavity. The rubber (about 25 gm) was introduced into the mould cavity. The upper platen together with the piston was then lowered to close the test cavity. The rubber was then injected into the test cavity at 550 KPa for six seconds. After six seconds the pressure dropped automatically to the preset testing pressure (207 KPa). After conditioning the sample for 15 seconds, the rotor was started. The test was run at steps of 1, 5, 10, 15, 20, 30, 40 rpm rotor speed for 8 seconds each.

6.3 Results and Discussion

6.3.1 Pressure Variation in Mixing Chamber

6.3.1.1 Relationship between pressure and rotor position

Figure 6.3 is a typical pressure trace in relation to the rotor position. Starting from point A which corresponds to the rotor tip, the pressure drops drastically to zero as the pressure transducer passes the rotor tip. This indicates that there is no material touching the pressure transducer tip. From visual observation the zero pressure was found to correspond to the void region.
Secondary peak

Transducer path with respect to rotor

FIGURE 6.3: RELATIONSHIP BETWEEN PRESSURE PROFILE AND ROTOR POSITION
After passing the void region the pressure started to develop again. It increased progressively as the flight moved towards the pressure transducer tip and dropped again after passing through the peak to make one complete revolution at point B. The peak pressure occurs at about 10 mm in front of the flight tip measured from the centre of the flight tip. This signifies that drag and pressure flow at the tip region flows in the same direction.

Figure 6.3 also shows that the shape of the trace seems to be asymmetric tailing toward the left. Another phenomenon that is observed is the development of the secondary peak occurring between the void region, where there is no pressure development, and the primary peak. Referring to Figure 6.3, the secondary peak occurs when the opposite flight is just about to pass through the pressure transducer. This suggests that there is an axial flow occurring around this region. This phenomenon was also observed by Freakley and Patel\(^3\) where they found that there was a pressure gradient along the z-axis. After the secondary peak the pressure trace passes through an inflection indicating that the axial flow is reduced. Referring to the rotor position the inflection occurs when the opposite flight passes the pressure transducer. These two phenomena are directly related to the S-shaped pattern discussed in Section 4.5.3. After the inflection the pressure trace increases drastically. This section corresponds to the sickle-shaped region. The high pressure phenomena in this region indicate that the flow of material is continuous.
6.3.1.2 Effect of rotor speed on pressure profiles

Figures 6.4-6.9 show the pressure profiles with respect to rotor speed for 0.5, 0.6, 0.7, 0.8, 0.9 and 1.0 fill factor for one revolution measured at 8.33, 16.7 and 25.0 rpm rotor speeds on the left hand rotor. It was found that there was little change in pressure profile with respect to rotor speed, especially at low fill factor (i.e. 0.5, 0.6 and 0.7), except at the peak pressure where it seemed to decrease as the rotor speed was increased. However there is an increase in pressure profile with respect to increase in rotor speed at high fill factor (i.e. 0.8, 0.9 and 1.0).

At high fill factor the pressure development is caused by both pressure wave and material transfer. It is expected that at high rotor speed the pressure wave will be greater, thus causing the pressure development inside the mixing chamber to be increased. Also at high fill factor the rate of material transfer is less as compared to low fill factor because the free space is relatively limited. Thus the predominant factor in pressure development at high fill factor will be pressure waves.

6.3.1.3 Effect of fill factor on pressure profiles

Figures 6.10-6.11 show typical pressure traces for 16.7 and 25.0 rpm respectively taken at different fill factors. There is a similarity in the general pattern of pressure profile with respect to fill factor i.e. each profile passes one secondary peak and one primary peak. However the size of the profiles is proportional to fill factor.
Figure 6.4: Pressure trace for one revolution at 0.5FF
FIGURE 6.5: PRESSURE TRACE FOR ONE REVOLUTION AT 0.6FF
FIGURE 6.6: PRESSURE TRACE FOR ONE REVOLUTION AT 0.7FF
FIGURE 6.7: PRESSURE TRACE FOR ONE REVOLUTION AT 0.8FF
FIGURE 6.3: PRESSURE TRACE FOR ONE REVOLUTION AT 0.9FF
FIGURE 6.9: PRESSURE TRACE FOR ONE REVOLUTION AT 1.0FF
FIGURE 6.10: EFFECT OF FILL FACTOR ON PRESSURE PROFILE AT 16.7RPM
FIGURE 6.11: EFFECT OF FILL FACTOR ON PRESSURE PROFILE AT 25RPM
For 0.5 fill factor the pressure rises slowly at the initial stage followed by a drop and rises again with a steeper slope. In general the peak pressure is small and not consistent, sometimes disappearing altogether. It suggests that the flow of material in front of the flight tip is not continuous. This indicates that the amount of material swept in front of the rotor wing is irregular and varies from revolution to revolution. The secondary peak is very small and sometimes occurs as a separate peak. This indicates that the axial movement is very limited. It can be concluded that at this fill factor both distributive and dispersive mixing is very poor due to the fact that the flow is limited and the shear stress at the tip is low.

For 0.7 fill factor, the rise in the pressure is steeper than 0.5 fill factor. After passing the secondary peak there is only an inflection in the pressure trace then it rises again. The overall high pressure and the consistent appearance at peak pressure at this fill factor indicates that the flow of material is continuous. This suggests that the material in front of the flight tip is full and the filling is more consistent than 0.5 fill factor.

The secondary peak at 0.7 fill factor is also more prominent than at 0.5 fill factor, indicating that there is a high axial movement. With a consistent pressure development and more flow occurring at 0.7 fill factor, it can be concluded that mixing at this fill factor is more efficient than at 0.5 fill factor.
For 0.9 fill factor the overall pressure development is higher than 0.7, however the difference between the secondary peak pressure and the primary peak pressure is lower as compared to 0.7 fill factor.

For 1.0 fill factor the pressure profile is very high. It is also observed that the difference between the secondary peak and the primary peak is very small and sometimes the secondary peak is higher than the primary peak. Freakley and Wan Idris\(^2\) reported that the pronounced shoulder which occurs at 1.0 fill factor is attributed to the effect of pressure wave rather than material transfer.

It is important to note that the flow of material does not depend on the pressure but on the difference in pressure between two points (i.e. pressure gradient). Figure 6.14 shows a typical pressure profile for high and low fill factor (typical example of 0.9 and 0.7 fill factors). For high fill factor there was a wide variation in pressure gradients at various points along the pressure line with respect to the rotor. In some cases the pressure gradient can be negative even in the region far away from the tip region. Thus at certain points the effect of pressure flow is very significant, while at other points the effect is very small. However at low fill factor the variation in pressure gradient is smaller as compared to high fill factor. This will make the flow at low fill factor more consistent than at high fill factor. More discussion on the velocity profiles will be found in Section 6.3.3.1.
6.3.1.4 Variation in pressure profile with respect to relative rotor position

Since the speed ratio between the two rotors is not the same they take different positions with respect to each other for each revolution and come back to the same position after each cycle; in this case five revolutions for the slow rotor and six revolutions for the fast rotor. Figure 6.13 shows that the pressure profile is different for each turn.

From the characteristic of high pressure profile developed when the flight of the opposite rotor moves toward the bridge position and low when the flight moves away, it could be deduced that the variation of pressure profile with respect to relative rotor position is dependent upon the amount of material found in each lobe for each revolution. This was indicated by the effect of fill factor on pressure profile (see Section 6.3.1.3). Another
FIGURE 6.13: EFFECT OF RELATIVE ROTOR POSITION ON PRESSURE PROFILES (refer to Figure 5.11.1)
FIGURE 6.14: EFFECT OF FLIGHT SIZE ON PRESSURE PROFILE AT FF0.7/25.0RPM
FIGURE 6.15: EFFECT OF FLIGHT SIZE ON PRESSURE PROFILE AT FF0.7/16.7 RPM
FIGURE 6.16: EFFECT OF FLIGHT SIZE ON PRESSURE PROFILE AT FF0.7/8.33RPM
possibility is due to the high pressure developed at the bridge position as the flight moves towards it. This will influence the pressure in the opposite lobe.

6.3.1.5 Effect of flight size on pressure profiles

Figures 6.14-6.16 show the pressure profiles taken at 0.7 fill factor and 8.33, 16.7 and 25.0 rpm rotor speed respectively (slow rotor). It shows that for the short flight the pressure profile is lower than that of the long flight, especially at low rotor speed. However at higher rotor speed there are some cases where the pressure profile is lower for the long flight (long flight of LHR at 16.7 and 25.0 rpm) than short flight. It also found that the pressure development starts earlier in the case of the short flight than the long flight. This result is consistent with the observation found in Chapter 5 that the void size formed behind the short flight is smaller than the void formed behind the long flight. This was signified by the early development of the pressure at short flight.

6.3.2 Rheological Analysis of Silicone Rubber

The main aim of this analysis is to determine the reference viscosity ($\eta_0$) and the power law index ($n$) of silicone rubber. The phenomena of wall slip will also be investigated in this experiment. The rubber was assumed to follow power law fluid behaviour, where the stress-strain rate relationship can be represented as in equation 6.1:
\[ \tau = \eta_0 \dot{\gamma}^n \]  

(6.1)

where: \( \tau \) = shear stress 
\( \dot{\gamma} \) = rate of shear strain

From the plot of log shear stress and log rate of shear strain as shown in Figure 6.17, the value of \( \eta_0 \) and \( n \) were found i.e.

\[ \eta_0 = 25.7 \text{ kPa's} \]
\[ n = 0.29 \]

In a typical flow curve of a mix, to obtain slip velocity \( (V_s) \) the apparent shear stress was plotted as a function of rotor speed for both grooved and polished rotors as shown in Figure 6.18. The slip velocity can be calculated from the difference in the two speeds as shown in the equation 6.2:\( ^{(4)} \)

\[ V_s = R (\omega_p - \omega_g) \]  

(6.2)

where: \( R \) = radius of rotor 
\( \omega_p \) = angular velocity for polished rotor 
\( \omega_g \) = angular velocity for grooved rotor

However from this experiment it was found that the slip velocity for silicone rubber was insignificant. This is due to the fact that there was a very small difference between the \( \omega_p \) and \( \omega_g \) with respect to shear stress as shown in Figure 6.17. It is also important to note that this experiment was carried out at room temperature.
Figure 6.17: Flow curve for silicone rubber used in this experiment.
$f(V_s) = \text{Function of slip velocity}$

**FIGURE 6.18:** TYPICAL FLOW CURVE OF A MIX MEASURED WITH GROOVED AND POLISHED ROTOR (4)
(22\(^\circ\)C). This is to make it consistent with the experiments carried out using the internal mixer.

6.3.3 Stress Distribution Inside Mixing Chamber

In the analysis of stress distribution in the mixing chamber four arbitrary points were chosen as follows.

Point 1 - corresponds to the region at the rotor tip.
Point 2 - corresponds to the region around the end of the flight.
Point 3 - corresponds to the S-shaped region.
Point 4 - corresponds to the region in front of the flight tip or the sickle-shaped region.

Figure 6.19 shows the four points in relation to the rotor position.

**FIGURE 6.19: THE FOUR POINTS IN RELATION TO THE ROTOR POSITION**
6.3.3.1 Velocity profiles

From the discussion in Section 6.3.2 it was found that the silicone rubber used in this experiment does not exhibit a slip velocity for the polished rotor of the TMS rheometer. Therefore it is reasonable to assume that the slip velocity at the rotor and chamber wall of the mixer used in this experiment is also zero. The drag velocity can then be calculated using equation 6.3:

\[ V_d = \omega (R - H) \]  

(6.3)

where:
- \( V_d \) = drag velocity
- \( \omega \) = angular velocity
- \( R \) = radius of the chamber
- \( H \) = radial distance between rotor surface and chamber wall

Assuming the ratio between the radius of the rotor and the radial distance between the rotor and chamber wall is sufficiently large, then the assumption of the flow between parallel plates could then be made. Using the lubrication approximation in one dimensional, the velocity profile for pressure flow can be calculated using equation 6.4:

\[ V_p(y) = \frac{n}{n+1} \left( \frac{1}{n_0} \frac{dp}{dz} \right)^{1/n} \left( \frac{H}{y} \right)^{(n+1)/n} \left[ \left( \frac{2y}{H} \right)^{n+1} - 1 \right] \]  

(6.4)
where: \( V_p \) = pressure velocity
\( \eta_0 \) = reference viscosity
\( n \) = power law index
\( y \) = the clearance gap size at the point of measurement (ranging from \( H/2 \) to 0)
\( \frac{dp}{dl} \) = pressure gradient at each point.

From the drag and pressure flow profiles the resultant flow profiles were calculated by means of vector addition of drag and pressure velocities.

The plots of these velocity profiles at the four points in the mixing chamber are shown in Figures 6.20-6.39. It was found that in general the flow was dominated by drag flow except in some cases where the pressure flow occurred significantly. Detailed discussions of the flow profiles at the four points chosen now follow.

**Point 1**

Figures 6.20-6.24 show the velocity profiles at the tip region. It was found that an increase in fill factor increased in the pressure flow profile. Both drag and pressure flow profile act in the same direction i.e. in opposite direction to the rotation as shown in Figures 6.20, 6.23 and 6.24. This phenomenon has been observed by many researchers for various models of internal mixers. Thus the resultant velocity profile will be greater than just the drag flow. However Figures 6.21, 6.22 and 6.25 show that there is no effect of rotor speed on pressure profile, thus the resultant profile will be the same as the drag velocity profiles.
Point 2

Figures 6.25-6.29 show the velocity profiles at the region around the end of the flight. It was found that in general both pressure and drag flow occur in this region, but they are in opposite directions. Figures 6.25, 6.28 and 6.29 show that an increase in fill factor is seen to increase the effect of pressure flow. At 0.5 and 0.7 fill factors the existence of the pressure flow profile is very small compared to the 0.9 fill factor. Figures 6.20, 6.21 and 6.22 show that at rotor speeds 8.33 and 16.7 rpm the pressure flow is significant in comparison with drag flow, but at 25 rpm the drag flow is dominant.

Point 3

Figures 6.30-6.34 show the velocity profiles at the S-shaped region. It was found that in all cases only drag flow profile appears. Referring to the pressure trace (Section 6.3.1) it was found that there was an inflection in the pressure trace at this point, thus making \( \Delta p \) very small. This indicates that at this region the flow is due to drag flow.

Point 4

Figures 6.35-6.39 show the velocity profiles at the sickle-shaped region. Figures 6.35, 6.38 and 6.39 show that an increase in fill factor increased the flow profile due to pressure. Figures 6.36, 6.37 and 6.38 show that as the rotor speed is increased, only drag flow is increased but there is no effect on pressure flow.
FIGURE G.2: VELOCITY PROFILES FOR FF0.5/25RPM AT POINT 1
FIGURE 6.21: VELOCITY PROFILES FOR FF0.7/8.33RPM AT POINT 1
FIGURE 6.22: VELOCITY PROFILES FOR FF0.7/16.7 AT POINT 1
FIGURE 6.23: VELOCITY PROFILES FOR FF0.7/25.0 RPM AT POINT 1
FIGURE 6.24: VELOCITY PROFILES FOR FF0.9/25.0 RPM AT POINT 1
FIGURE 6.25: VELOCITY PROFILES FOR FF0.5/25RPM AT POINT 2
FIGURE 6.26: VELOCITY PROFILES FOR FF0.7/8.33RPM AT POINT 2
FIGURE 6.27: VELOCITY PROFILES FOR FF0.7/16.7RPM AT POINT 2
FIGURE 6.23: VELOCITY PROFILES FOR FF0.7/25.0RPM AT POINT 2
FIGURE 6.29: VELOCITY PROFILES FOR FF0.9/25RPM AT POINT 2
FIGURE 6.30: VELOCITY PROFILES FOR FF0.5/25RPM AT POINT 3
FIGURE 6.31: VELOCITY PROFILES FOR FF0.7/8.33RPM AT POINT 3
FIGURE 6.32 VELOCITY PROFILES FOR FF0.7/16.7 RPM AT POINT 3
FIGURE 6.33: VELOCITY PROFILES FOR FF0.7/25.0 RPM AT POINT 3
FIGURE 6.34: VELOCITY PROFILES FOR FF0.9/25.0RPM AT POINT 3
FIGURE 6.35: VELOCITY PROFILES FOR FF0.5/25RPM AT POINT 4
FIGURE 6.36: VELOCITY PROFILES FOR FF0.7/8.33RPM AT POINT 4
FIGURE 6.37: VELOCITY PROFILES FOR FF0.7/16.7RPM AT POINT 4
FIGURE 6.38: VELOCITY PROFILES FOR FF0.7/25.0 RPM AT POINT 4
FIGURE 6.39: VELOCITY PROFILES FOR FF0.9/25RPM AT POINT 4
6.3.3.2 Shear stress distribution

From the resultant velocity profiles the shear rate at particular points along the radial distance (y) can be calculated using equation 6.5:

$$\dot{\gamma} = \frac{dV}{dy}$$

(6.5)

and the shear stress can be calculated using equation 6.1.

Figures 6.40-6.44 show the stress distribution taken at the four points inside the mixing chamber at different fill factors and rotor speeds. As expected the higher stress occurs at the tip region (Point 1), followed by the sickle-shaped region (Point 4), the S-shaped region (Point 3) and the region around the end of the flight (Point 2). In general the stress distribution varies inversely proportional to the gap clearance between the rotor and the chamber wall, however it appears that the stress is not constant across the gap. It was also found that on average the difference in the shear stress between the tip region and the sickle-shaped region is of the order of about 30%. The average shear stresses at the four points are shown in Table 6.1.

From this observation it confirms the earlier(3) suggestion that some dispersive mixing may take place at the sickle-shaped region. However the average stress at points 2 and 3 is much lower than that at the tip region i.e. of the order of more than 50% lower. Therefore it is reasonable to suggest that in the
S-shaped region and in the region around the end of the flight only distributive mixing is taking place.

**TABLE 6.1: AVERAGE SHEAR STRESS (KPa) AT THE FOUR POINTS**

<table>
<thead>
<tr>
<th>CONDITION</th>
<th>POINT 1</th>
<th>POINT 2</th>
<th>POINT 3</th>
<th>POINT 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>FF0.5/25 rpm</td>
<td>74.6</td>
<td>29.5</td>
<td>39.5</td>
<td>66.6</td>
</tr>
<tr>
<td>FF0.7/8.33 rpm</td>
<td>46.4</td>
<td>17.0</td>
<td>29.0</td>
<td>33.4</td>
</tr>
<tr>
<td>FF0.7/167 rpm</td>
<td>66.8</td>
<td>21.8</td>
<td>35.0</td>
<td>39.6</td>
</tr>
<tr>
<td>FF0.7/25 rpm</td>
<td>64.0</td>
<td>35.4</td>
<td>39.4</td>
<td>44.6</td>
</tr>
<tr>
<td>FF0.9/25 rpm</td>
<td>60.8</td>
<td>24.0</td>
<td>39.6</td>
<td>44.6</td>
</tr>
</tbody>
</table>

Figures 6.40, 6.43 and 6.44 show the influence of fill factor on stress taken at 25 rpm rotor speed and 0.5, 0.7 and 0.9 fill factor respectively. In general the increase in fill factor will increase the stress development occurring at the tip and sickle-shaped regions. However there seems to be no effect on the stress distribution at the other two points. This indicates that increase in fill factor does not help to improve the dispersive mixing at the S-shaped region and the region around the end of the flight.

Figures 6.42, 6.43 and 6.49 show the influence of the rotor speed on stress distribution taken at 0.7 fill factor and 8.33, 16.7 and 25 rpm rotor speeds respectively. It was found that, in all cases, an increase in rotor speed will increase the shear stress development. However the increase in the rotor speed did
FIGURE 6.39: CIRCUMFERENTIAL SHEAR STRESS PROFILES
(FOR FF = 0.5 - 25 RPM) + 1 mm = 2 KPa
FIGURE 6.40: CIRCUMFERENTIAL SHEAR STRESS PROFILES
(FOR FF = 0.7 - 8.33 RPM) +1 mm = 2 KPa
FIGURE 6.41: CIRCUMFERENTIAL SHEAR STRESS PROFILES
(FOR FF = 0.7 - 16.7 RPM) + 1 mm = 2 kPa
FIGURE 6.42: CIRCUMFERENTIAL SHEAR STRESS PROFILES
(FOR FF 0.7 - 25 RPM) $1 \text{ mm} = 2 \text{ KPa}$
FIGURE 6.43: CIRCUMFERENTIAL SHEAR STRESS PROFILES
(FOR FF = 0.9 - 25 RPM) + 1 mm = 2KPa
not follow a linear relationship with the increase in shear stress. Figures 6.42 and 6.43 show that doubling the rotor speed only increases the shear stress around 20% at the tip region. However in the sickle-shaped region the increase is about 35%. This is because the shear rate at the tip region is always higher than the shear rate at the sickle-shaped region under the same mixing conditions. Due to the effect of non-Newtonian behaviour of silicone rubber, an equal increase in shear rate will increase the shear stress at the sickle-shaped region more than at the tip region.
References

CHAPTER 7
GENERAL DISCUSSION, CONCLUSIONS
AND RECOMMENDATIONS

7.1 General Discussion

The study of flow mechanisms of rubber inside a mixing chamber requires systematic analysis of flow in various regions inside the mixing chamber. It is important that in mathematical modelling of an internal mixer, the mode of action has to be considered separately in each region during the mixing operation. It was found that the flow pattern, which influences the rate of distributive mixing, is different in each of these regions.

It was found that the most complex flow patterns occur at the bridge region and in the S-shaped region. Due to the lower stress levels at these two regions little dispersive mixing can take place here, therefore these regions are largely responsible for distributive mixing. The void region, though no mixing takes place here, also contributes to enhance the distributive mixing.

The high stress levels which occur at the tip region and in the sickle-shaped region are mainly responsible for dispersive mixing. The flow pattern in these two regions is not very complex, thus little distributive mixing can take place here.

It was also observed that from the movement of single markers, an element of material tends to flow under the same
rotor tip for a number of revolutions before it is transferred elsewhere in the mixing chamber. This indicates that the flow of material in the mixing chamber is not vigorous enough. However this experiment was carried out at low rotor speed and the result here may not be representative of the industrial mixing process where the rotor speed is much higher.

Void formation is one of the significant phenomena in establishing the disordered flow in the mixing chamber. Its size is inversely proportional to fill factor. The distribution of voids depends on absolute rotor position. To a lesser extent, the relative rotor position and rotor speed also affect void formation. From here it shows that the correct selection of mixing variables is of paramount importance in order to obtain efficient mixing. Fill factor was found to be one of the most important mixing variables. Under-filling will cause the flow to be discontinuous, even in front of the rotor tip and thus affect dispersive mixing. On the other hand over-filling will cause the flow to be less disordered and this will affect distributive mixing. Thus both under-filling and over-filling will reduce mixing efficiency. Rotor speed is another important variable during mixing process. It was found that an increase in rotor speed will increase the shear stress inside the mixing chamber.

It was also found that dispersive mixing and distributive mixing are complementary to each other. Bad distributive mixing will not randomise the flow, i.e. the fraction of material which
is being subjected to high stress will always be subjected to high stress and vice-versa throughout the whole mixing. Thus only a fraction of material will be subjected to dispersive mixing. On the other hand if there is little dispersive mixing, the agglomerates will not rupture thus no distributive mixing can take place. However these two modes of mixing have entirely different mechanisms. The distributive mixing depends on the extent of deformation and flow pattern while the dispersive mixing depends on the magnitude of stresses. In most cases the region which is good for distributive mixing will not be good for dispersive mixing and vice-versa. Thus the machine designers and mixing processors are facing with this two contradicting problems. Their task is to establish the optimum conditions where two modes of mixing mechanism are balanced.

7.2 Conclusions

Flow visualisation has proved to be a very powerful tool in studying the flow behaviour of rubber inside the mixing chamber. In this study the exact behaviour of rubber can be observed. The flow pattern can be recorded and the complexity of the flow can be identified.

By means of measurement of pressure and the rheological properties of rubber, the stress distribution in the circumferential direction along the pressure line can be calculated at various fill factors and rotor speeds. Thus from flow patterns and stress distribution, the mode of mixing in each region can
be established to be as follows: the tip region and the sickle-shaped region are responsible for dispersive mixing; the S-shaped region (this includes the region around the end of the flight) and the bridge region are responsible for distributive mixing; the void region is not responsible for either mode of mixing, but the formation of the voids helps to enhance the distributive mixing.

7.3 Recommendations for Future Work

Further work is required to establish the amount of new material passing under the rotor tip per revolution. This information is very important in order to find out how much dispersive mixing takes place per revolution. This information will help the machine designer to find the optimum ratio between the area required for distributive mixing to that of dispersive mixing.

Further work is also necessary to look into the flow pattern in the radial direction, as in this project only the circumferential and axial flows were analysed. Finally it is also important to carry out the experiments at higher rotor speeds in order to analyse the behaviour of material at a shear stress equivalent to those in an industrial mixer.
APPENDIX 1

COMPUTER PROGRAMS FOR ANALYSIS OF THE FLOW PATTERN AT BRIDGE POSITION AND MOVEMENT OF SINGLE MARKER

A1.1 Programme for computing the data for the analysis of flow pattern at bridge position

Input variables:

N = Number of markers
NR = 1 or 2 for left or right rotor
B and D = initial and final points respectively on Z axis
C = e (angle of marker rotation) as shown in Figure 4.4.1.
EDIT MODE NUM
p99

00001: DIMENSION B(10), C(10), D(10), X(10), Y(10), Z(10), XX(10)
00002: DIMENSIONXA(10), YA(10), YY(10), ZZ(10)
00003: READ(5,*) N
00004: DO 10 I=1, N
00005: READ(5,*) NR, B(I), C(I), D(I)
00006: X(I)=85.0
00007: Y(I)=74.2
00008: YA(I)=50.0
00009: Z(I)=20.0+B(I)
00010: GAMA=3.141592*C(I)/180.0
00011: IF(NR.EQ.2) GOTO 7
00012: XA(I)=X(I)-5.0
00013: XX(I)=50.0+(30.0*COS(GAMA))
00014: GOTO 8
00015: 7 XX(I)=90.0+(30.0-(30.0*COS(GAMA))
00016: XA(I)=X(I)+5.0
00017: 8 YY(I)=50.0-(30.0*SIN(GAMA))
00018: ZZ(I)=20.0+D(I)
00019: CONTINUE
00020: DO 4 I=1, N
00021: K=2
00022: WRITE(1,6)K, X(I), Y(I), Z(I), XA(I), YA(I), Z(I)
00023: 6 FORMAT(I3,6F10.2)
00024: CONTINUE
00025: DO 5 I=1, N
00026: K=2
00027: WRITE(1,9) K, XA(I), YA(I), Z(I), XX(I), YY(I), ZZ(I)
00028: 9 FORMAT(I3,6F10.2)
00029: CONTINUE
00030: CALL EXIT
00031: END

BOTTOM
Al.2 Programme for computing the data for analysis of the movement of single marker

Input variables:

N = number of rotor revolutions
A = θ (angle of marker rotor) as shown in Figure 4.4.1
B = point on Z axis

```
EDIT
MODE NUM
p99

DIMENSION A(150), B(150), Z(150), X(150), Y(150), XX(150), YY(150), ZZ(150)

READ(5,*) N
NM1 = N-1

DO 10 I=1, N
READ(5,*) NR, A(I), B(I)
THE = 3.141592 * A(I) / 180.0
IF(NR.EQ.2) GOTO 103
X(I) = 50.0 + (30.0 * COS(THE))
Y(I) = 50.0 - (30.0 * SIN(THE))
CONTINUE

DO 100 I=1, NM1
XX(I) = X(I+1)
YY(I) = Y(I+1)
ZZ(I) = Z(I+1)

DO 101 I=1, NM1
WRITE(1,4) K, X(I), Y(I), Z(I), XX(I), YY(I), ZZ(I)
FORMAT(I3,6F10.2)

CALL EXIT
END
```
A1.3 Programme for drawing flow paths of single marker and flow path of marker movement at bridge position

00001: DIMENSION NT(40)
00002: WRITE(1,190)
00003: 190 FORMAT(2X,'1=TA010 2=VDU 3=PLOTTER 4=SERVOG0R'//)
00004: WRITE(1,19)
00005: 19 FORMAT(2X,'PLEASE SUPPLY DEVICE TERMINAL'//)
00006: READ(1,*)IDIV
00007: IF(IDIV.EQ.1)GOTO 11
00008: IF (IDIV.EQ.2)GOTO 22
00009: IF (IDIV.EQ.3)GOTO 33
00010: IF (IDIV.EQ.4)GOTO 44
00011: 11 CALL TA010
00012: CALL PICLE
00013: GOTO 300
00014: 22 CALL VDU
00015: GOTO 300
00016: 33 CALL C1051N
00017: GOTO 300
00018: 44 CALL SE281
00019: GOTO 300
00020:C
00021:C PAPER DIMENSION
00022:C
00023: 300 WRITE(1,9)
00024: 9 FORMAT(2X,'PLEASE INPUT X AND Y FOR PAPER DIMENSION'//)
00025: READ(1,*)XX,YY
00026: XXP=XX/2-85
00027: YYP=YY/2-50
00028: CALL PAPENQ(XX,YY,I)
00029: CALL SHIFT2(XXP,YYP)
WRITE(1,15)
FORMAT(2X,'PLEASE SUPPLY AXIS AND ANGLE OF ROTATION')
READ(1,*)IA,AN
CALL ROTAT3(IA,AN)
WRITE(1,12)
FORMAT(2X,'PLEASE SUPPLY ANGLES ALPHA AND BETA')
READ(1,*)ALP,THE
A=3.141592*ALP/180.0
B=3.141592*THE/180.0
DZ=COS(A)
DX=SIN(A)*COS(B)
DY=SIN(A)*SIN(B)
CALL VPARAL(DX, DY, DZ, 0.0, 0.0, 0.0)
CALL VIEW
CALL PENSEL(1,0.0,0)
CALL PICLE
CALL SCALE(1.0)
CALL MOVTO3(0.0,0.0,0.0)
CALL LINTO3(150.0,0.0,0.0)
CALL CHAHOL('X*')
CALL MOVTO3(0.0,0.0,0.0)
CALL LINTO3(0.0,150.0,0.0)
CALL CHAHOL('Y*')
CALL MOVTO3(0.0,0.0,0.0)
CALL LINTO3(0.0,0.0,150.0)
CALL CHAHOL('Z*')
CALL BROKEN(1)
CALL MOVTO3(20.0,50.0,20.0)
CALL ARCTO3(50.0,50.0,20.0,80.0,50.0,20.0,0.0,1.0,0.0)
CALL MOVTO3(150.0,50.0,20.0)
CALL ARCTO3(120.0,50.0,20.0,90.0,50.0,20.0,0.0,1.0,0.0)
CALL BROKEN(0)
CALL MOVTO3(80.0,50.0,20.0)
CALL ARCTO3(50.0,50.0,20.0,20.0,50.0,20.0,0.0,-1.0,0.0)
CALL MOVTO3(80.0,50.0,120.0)
CALL ARCTO3(50.0,50.0,120.0,80.0,50.0,120.0,0.0,-1.0,0.0)
CALL MOVT03(90.0, 50.0, 20.0)
CALL ARCT03(120.0, 50.0, 20.0, 150.0, 50.0, 20.0, -1.0, 0.0)
CALL MOVT03(90.0, 50.0, 120.0)
CALL ARCT03(120.0, 50.0, 120.0, 90.0, 50.0, 120.0, 0.0, 0.0)
CALL MOVT03(20.0, 50.0, 20.0)
CALL LI:NT03(90.0, 50.0, 120.0)
CALL LI:NT03(80.0, 50.0, 120.0)
CALL MOVT03(90.0, 50.0, 20.0)
CALL LI:NT03(90.0, 50.0, 120.0)
CALL MOVT03(150.0, 50.0, 20.0)
CALL LI:NT03(150.0, 50.0, 120.0)
WRITE(1,3)
FORMAT(2X,'PLEASE INPUT TITLE'/)
READ(1,2)(NT(I),I=1,15)
FORMAT(15A1)
WRITE(1,6)
FORMAT(2X,'PLEASE INPUT X, Y AND Z POSITIONS'/)
READ(1,*)X,Y,Z
CALL CHAA1(NT,15)
WRITE(1,100)
FORMAT(2X,'PLEASE SUPPLY NUMBER OF POINTS'/)
L=NO OF POINTS
READ(1,*) L
DO 10 LR=1,L
READ(5,*)K,X1,Y1,Z1,XX2,XY2,XZ2
CALL MOVT03(X1,Y1,Z1)
CZP=(Z1+XZ2)/2
IF(K.EQ.1) GOTO 501
IF(K.EQ.2) GOTO 502
IF(K.EQ.3) GOTO 503
501 CALL PENSEL(1,0.0,0)
CALL LI:NT03(XX2,XY2,XZ2)
GOTO 10
502 CALL PENSEL(4,0.0,0)
503 IF(X1.EQ.85.0) GOTO 101
504 IF(X1.EQ.90.0) GOTO 102
IF(X1.EQ.80.0) GOTO 103
CALL LINT03(XX2,XY2,XZ2)
GOTO 10
CALL ARCT03(120.0,50.0,CZP,XX2,XY2,XZ2,0.0,-1.0,0.0)
GOTO 10
CALL ARCT03(50.0,50.0,CZP,XX2,XY2,XZ2,0.0,-1.0,0.0)
GOTO 10
IF((-1)**LR .EQ. -1) GOTO 110
IF((-1)**LR .EQ. 1) GOTO 120
CALL PENSEL(2,0.0,0)
GOTO 130
CALL PENSEL(4,0.0,0)
CALL MOVTO3(X1,Y1,Z1)
IF(XX2.EQ.X1) GOTO 70
IF(XX2.GT.90.0) GO TO 20
IF(X1.EQ.90.0 .AND. XX2.EQ.80.0) GOTO 40
IF(X1.EQ.80.0 .AND. XX2.EQ.90.0) GOTO 60
IF(XX2 GT X1) GOTO 140
IF(XX2 LT X1) GOTO 150
CALL BROKEN(1)
IF(X1 .GT. 50.0) GOTO 142
CALL ARCT03(50.0,50.0,CZP,XX2,XY2,XZ2,0.0,1.0,0.0)
GOTO 10
CALL ARCT03(50.0,50.0,CZP,XX2,XY2,XZ2,0.0,-1.0,0.0)
GOTO 10
CALL BROKEN(0)
IF(X1 .GT. 120.0) GOTO 172
CALL ARCT03(120.0,50.0,CZP,XX2,XY2,XZ2,0.0,-1.0,0.0)
00168: CALL ARCT03(120.0,50.0,CZP,XX2,XY2,XZ2,0.0,1.0,0.0)
00169: GOTO 10
00170: CALL BROKEN(0)
00171: IF(X1.GT.120.0) GOTO 210
00172: CALL ARCT03(120.0,50.0,CZP,XX2,XY2,XZ2,0.0,-1.0,0.0)
00173: GOTO 10
00174: CALL ARCT03(120.0,50.0,CZP,XX2,XY2,XZ2,0.0,1.0,0.0)
00175: GOTO 10
00176: GOTO 10
00177: CALL LINT03(XX2,XY2,XZ2)
00178: GOTO 10
00179: CONTINUE
00180: CALL LINT03(XX2,XY2,XZ2)
00181: GOTO 10
00182: CONTINUE
00183: CALL LINT03(XX2,XY2,XZ2)
00184: CONTINUE
00185: CONTINUE
00186: CALL DEVEND
00187: CALL EXIT
00188: END
## APPENDIX 2

### MOVEMENT OF SINGLE MARKERS

#### TABLE A2.1: MARKER MOVEMENT FOR 0.5 FILL FACTOR

<table>
<thead>
<tr>
<th>Time/ sec</th>
<th>Lobe</th>
<th>No. of Revs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>START (L)</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>L = Left</td>
<td>2</td>
</tr>
<tr>
<td>15</td>
<td>L</td>
<td>5</td>
</tr>
<tr>
<td>31</td>
<td>L</td>
<td>10.3</td>
</tr>
<tr>
<td>44</td>
<td>L</td>
<td>14.7</td>
</tr>
<tr>
<td>53</td>
<td>L</td>
<td>17.7</td>
</tr>
<tr>
<td>62</td>
<td>L</td>
<td>20.7</td>
</tr>
<tr>
<td>68</td>
<td>L</td>
<td>22.7</td>
</tr>
<tr>
<td>77</td>
<td>R = Right</td>
<td>25.7</td>
</tr>
<tr>
<td>86</td>
<td>L</td>
<td>28.7</td>
</tr>
<tr>
<td>99</td>
<td>L</td>
<td>33.0</td>
</tr>
<tr>
<td>107</td>
<td>L</td>
<td>35.7</td>
</tr>
<tr>
<td>116</td>
<td>L</td>
<td>38.7</td>
</tr>
<tr>
<td>122</td>
<td>L</td>
<td>40.7</td>
</tr>
<tr>
<td>134</td>
<td>L</td>
<td>44.7</td>
</tr>
<tr>
<td>138</td>
<td>L</td>
<td>46.0</td>
</tr>
<tr>
<td>147</td>
<td>L</td>
<td>49.0</td>
</tr>
<tr>
<td>155</td>
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<td>51.7</td>
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<tr>
<td>167</td>
<td>R</td>
<td>55.7</td>
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<tr>
<td>184</td>
<td>R</td>
<td>61.3</td>
</tr>
<tr>
<td>195</td>
<td>L</td>
<td>65.0</td>
</tr>
<tr>
<td>203</td>
<td>R</td>
<td>67.7</td>
</tr>
<tr>
<td>218</td>
<td>R</td>
<td>72.7</td>
</tr>
<tr>
<td>226</td>
<td>R</td>
<td>75.3</td>
</tr>
<tr>
<td>254</td>
<td>L</td>
<td>84.7</td>
</tr>
<tr>
<td>258</td>
<td>L</td>
<td>86.0</td>
</tr>
<tr>
<td>270</td>
<td>L</td>
<td>90.0</td>
</tr>
<tr>
<td>282</td>
<td>L</td>
<td>94.0</td>
</tr>
<tr>
<td>293</td>
<td>L</td>
<td>97.7</td>
</tr>
<tr>
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<td>L</td>
<td>100.0</td>
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<td>307</td>
<td>L</td>
<td>102.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time/ sec</th>
<th>Lobe</th>
<th>No. of Revs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>314</td>
<td>L</td>
<td>104.7</td>
</tr>
<tr>
<td>325</td>
<td>R</td>
<td>108.3</td>
</tr>
<tr>
<td>338</td>
<td>R</td>
<td>112.7</td>
</tr>
<tr>
<td>345</td>
<td>L</td>
<td>115</td>
</tr>
<tr>
<td>375</td>
<td>L</td>
<td>125</td>
</tr>
<tr>
<td>380</td>
<td>L</td>
<td>126.6</td>
</tr>
<tr>
<td>400</td>
<td>L</td>
<td>133.3</td>
</tr>
<tr>
<td>411</td>
<td>L</td>
<td>137</td>
</tr>
<tr>
<td>425</td>
<td>L</td>
<td>141.7</td>
</tr>
<tr>
<td>440</td>
<td>R</td>
<td>146.7</td>
</tr>
<tr>
<td>445</td>
<td>R</td>
<td>148.3</td>
</tr>
<tr>
<td>453</td>
<td>R</td>
<td>151</td>
</tr>
<tr>
<td>469</td>
<td>L</td>
<td>156.3</td>
</tr>
<tr>
<td>480</td>
<td>L</td>
<td>160</td>
</tr>
<tr>
<td>495</td>
<td>L</td>
<td>165</td>
</tr>
<tr>
<td>511</td>
<td>R</td>
<td>170.3</td>
</tr>
<tr>
<td>520</td>
<td>R</td>
<td>173.3</td>
</tr>
<tr>
<td>530</td>
<td>L</td>
<td>176.7</td>
</tr>
<tr>
<td>536</td>
<td>L</td>
<td>178.7</td>
</tr>
<tr>
<td>550</td>
<td>R</td>
<td>183.3</td>
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TABLE A2.4: MARKER POSITIONS WITH RESPECT TO MIXING CHAMBER FOR EACH REVOLUTION AT 0.7 FILL FACTOR

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$\theta$ = angle of rotation starting from the centre (refer to Fig.4.4.1)

$Z$ = distance along Z axis from the front in mm

R/L = right or left hand side of the lobe
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APPENDIX 3

COMPUTER PROGRAM FOR THE DETERMINATION
OF VELOCITY PROFILES FOR THE ANALYSIS OF
STRESS DISTRIBUTION INSIDE MIXING CHAMBER

A3.1 Programme for computing the data for velocity profiles.

Input variables:

\[ \begin{align*}
AN &= n \text{ (power law index)} \\
p &= \frac{\Delta P}{\mathcal{L}} \text{ (pressure gradient at a point)} \\
H &= \text{gap between rotor and chamber wall} \\
AV &= \eta_0 \text{ (viscosity at 1 sec}^{-1}) \\
S &= \text{rotor speed}
\end{align*} \]

```
00001:  DIMENSION Y(40), D(40), VP(40), V(40), Y1(40),
00002:  IDD(40), ZZ(40), AA(40), BB(40), Z(40), VPI(40)
00003:  READ(5,*) AN, P, H, AV, S
00004:  N=11
00005:  DO 30 I=1,N
00006:  E=H/2
00007:  F=E/(N-1)
00008:  Y(I)=(I-1)*F
00009:  A=AN/(AN+1)
00010:  B=(P/AV)**(1/AN)
00011:  C=(H/2)**(1/A)
00012:  D(I)=((2*Y(I)/H)**(1/A))-1
00013:  VP(I)=-(A*B*C*D(I))
00014:  30 CONTINUE
00015:  K=N-1
00016:  DO 35 I=1,K
00017:  VPI(I)=VP(N-(I-1))
00018:  WRITE(1,11) VPI(I)
00019:  11 FORMAT(15.9)
00020:  35 CONTINUE
```
DO 36 I=1,N
WRITE(1,12) VP(I)
12 FORMAT(F15.9)
36 CONTINUE
N=2*N-1
DO 40 I=1,M
Y1(M)=H
Y1(I)=Y1(M)/(M-1)
Y1(I)=(I-1)*Y1(I)
Z(I)=Y1(I)
OMEGA=2*4.0*ATAN(1.0)*S/60.0
VL=OMEGA*(32.0-H)
V(I)=(H-Y1(I))*VL/H
40 CONTINUE
DO 50 I=1,M
WRITE(1,20) Y1(I)
20 FORMAT(F10.4)
50 CONTINUE
DO 60 I=1,N
WRITE(1,21) V(I)
21 FORMAT(F20.9)
60 CONTINUE
DO 70 I=1,M
WRITE(1,22) Z(I)
22 FORMAT(F10.4)
70 CONTINUE
DO 80 I=1,M
AA(I)=VP(I)
BB(I)=VPI(I)
IF (I.GT.(N-1)) GOTO 7
DD(I)=V(I)+BB(I)
GOTO 80
7 DD(I)=V(I)+AA(I-(N-1))
80 CONTINUE
DO 81 I=1,M
WRITE(1,17) DD(I)
81 CONTINUE
DO 90 I=1,M
ZZ(I)=Z(I)
90 CONTINUE
WRITE(1,18) ZZ(I)
18 FORMAT(F10.5)
CALL EXIT
END
A3.2 Programme for plotting graphs of pressure profiles and velocity profiles

00001:     DIMENSION X(100), Y(100), NA(40), NB(40), NC(40), ND(40),
00002:     INF(50), NG(50), NH(100), NE(40)
00003:     WRITE(1, 190)
00004:     190  FORMAT(4X, '1=T2010 2=T4014 3=PLOTTER 4=SERVOGOR')/
00005:     WRITE(1, 19)
00006:     19   FORMAT(2X, 'PLEASE SUPPLY DEVICE TERMINAL')/
00007:     READ(1, *) IDIV
00008:     IF (IDIV.EQ.1) GOTO 11
00009:     IF (IDIV.EQ.2) GOTO 22
00010:     IF (IDIV.EQ.3) GOTO 33
00011:     IF (IDIV.EQ.4) GOTO 44
00012:     11   CALL T4010
00013:     CALL PICCLE
00014:     GOTO 300
00015:     22   CALL T4014
00016:     GOTO 300
00017:     33   CALL C1051N
00018:     GOTO 300
00019:     44   CALL SE281
00020:     CALL PICCLE
00021:     CALL PICCLE
00022:     CALL DEVPAP(297.0, 210.0, 1)
00023:     CALL WINDO2(0.0, 297.0, 0.0, 210.0)
00024:     CALL ERRMAX(1)
00025:     CALL CHASIZ(2.0, 2.0)
00026:     CALL AXIPOS(1, 40.0, 40.0, 200.0, 1)
CALL AXIPOS(1,40.0,40.0,120.0,2)
CALL AXISCA(3,20.0,0.0,200.0,1)
CALL AXISCA(3,2.0,0.0,20.0,2)
CALL AXIDRA(2,1,1)
CALL AXIDRA(-2,-1,2)

WRITE(1,100)
100 FORMAT(2X,'PLEASE SUPPLY NUMBER OF POINTS'/)
READ(5,*) IGRAPH
DO 20 IZ=1,IGRAPH
READ(5,*) (X(I), I=1,M),(Y(K), K=1,N)
IF(IZ.EQ.1) GOTO 5
IF(IZ.EQ.2) GOTO 6
IF(IZ.EQ.3) GOTO 7
IF(IZ.EQ.4) GOTO 8
IF(IZ.EQ.5) GOTO 9
CALL BROKEN (0)
GOTO 40
CALL BROKEN (1)
GOTO 40
CALL BROKEN (2)
GOTO 40
CALL BROKEN (3)
GOTO 40
CALL BROKEN (4)
CALL PENSEL (1,0.2,3)
CALL GRACUR (X,Y,M)
CONTINUE
READ(5,*) IKEYS
DO 30 J=1,IKEYS
IF(J.EQ.1) GOTO 80
IF(J.EQ.2) GOTO 90
IF(J.EQ.3) GOTO 101
IF(J.EQ.4) GOTO 110
IF(J.EQ.5) GOTO 120
CALL MOVTO2(145.0, 110.0)
CALL LIN702(160.0, 110.0)
297

00076: WRITE(1,303)
00077: 303 FORMAT(2X,'PLEASE INPUT KEY NUMBER ONE'//)
00078: READ(1,202)(NA(I),I=1,15)
00079: 202 FORMAT(15A1)
00080: CALL MOVTO2(170.0,110.0)
00081: CALL CHAA1(NA,15)
00082: CALL BROKEN (1)
00083: GOTO 30
00084: 90 CALL MOVTO2(145.0,120.0)
00085: CALL LINTO2(160.0,120.0)
00086:C
00087:C
00088: WRITE(1,313)
00089: 313 FORMAT(2X,'PLEASE INPUT KEY NUMBER TWO'//)
00090: READ(1,212)(NB(I),I=1,15)
00091: 212 FORMAT(15A1)
00092: CALL MOVTO2(170.0,120.0)
00093: CALL CHAA1(NB,15)
00094: CALL BROKEN (2)
00095: GOTO 30
00096: 101 CALL MOVTO2(145.0,130.0)
00097: CALL LINTO2(160.0,130.0)
00098:C
00099:C
00100: WRITE(1,323)
00101: 323 FORMAT(2X,'PLEASE INPUT KEY NUMBER THREE'//)
00102: READ(1,222)(NC(I),I=1,15)
00103: 222 FORMAT(15A1)
00104: CALL MOVTO2(170.0,130.0)
00105: CALL CHAA1(NC,15)
00106: CALL BROKEN (3)
00107: GOTO 30
00108: 110 CALL MOVTO2(145.0,140.0)
00109: CALL LINTO2(160.0,140.0)
00110:C
00111:C
00112: WRITE(1,333)
00113: 333 FORMAT(2X,'PLEASE INPUT KEY NUMBER FOUR'//)
00114: READ(1,232)(ND(I),I=1,15)
00115: 232 FORMAT(15A1)
00116: CALL MOVTO2(170.0,140.0)
00117: CALL CHAA1(ND,15)
00118: CALL BROKEN (4)
00119: GOTO 30
00120: 120 CALL MOVTO2(145.0,150.0)
CALL LINT02(160.0, 150.0)
CALL LINT02(160.0, 150.0)
WRITE(1,343)
FORMAT(2X,'PLEASE INPUT KEY NUMBER FIVE'//)
READ(1,242)(NE(I),I=1,15)
FORMAT(15A1)
CALL MOVTO2(170.0,150.0)
CALL CHAA1(NE,15)
CONTINUE
CALL CHASIZ(2.5,2.5)
WRITE(1,38)
FORMAT(2X,'PLEASE INPUT TITLE FOR X-AXIS'//)
READ(1,21)(NF(I),I=1,30)
FORMAT(30A1)
CALL MOVTO2(180.0,30.0)
CALL CHAA1(NF,30)
CALL CHASIZ(2.5,2.5)
WRITE(1,32)
FORMAT(2X,'PLEASE INPUT TITLE FOR Y-AXIS'//)
READ(1,23)(NG(I),I=1,30)
FORMAT(30A1)
CALL CHAANG(90.0)
CALL MOVTO2(30.0,120.0)
CALL CHAA1(NG,30)
CALL CHASIZ(3.0,3.0)
WRITE(1,71)
FORMAT(2X,'PLEASE INPUT TITLE FOR THE GRAPH'//)
READ(1,61)(NH(I),I=1,70)
CALL CHAANG(0.0)
FORMAT(70A1)
CALL MOVTO2(70.0,20.0)
CALL CHAA1(NH,70)
CALL DEVEND
CALL EXIT
END