

## CHAPTER 2



### LITERATURE SURVEY

A study on the fundamentals of granulation mechanism is the first of all things, in order to search for or select an appropriate mathematical model for the drum granulator.

This will be followed by a study on the other unit operations which are a part of the granulation process (screen, crusher and mixer) unit by unit.

#### 2.1 Basic Concept of Granulation Mechanism

Before embarking on the work on this thesis, the fertilizer granulation process simulation, it is necessary to understand the basic concept of granulation mechanism.

The following sections will focus on two levels, the intermolecular and the macroscopic level, on which the granulation phenomena occur and the parameters affecting the granulation mechanism.

##### 2.1.1 Intermolecular Level of Granulation

An understanding of the bond strength between agglomerating particles is essential in order to understand the mechanism of granulation. Agglomerated particles are held together by cohesive forces at the particle contact points in the granule.

#### 2.1.1.1 The particle - particle (intermolecular) attractive forces

The overall strength of the granules depends on the magnitude of the cohesive forces and the number of contact points of the particles (Sherrington and Oliver, 1981).

Various contributing forces have been reported in the literature and considerable efforts are made at quantifying them. Rumpf (1962), Cape (1980) and Sehubert (1981) listed various contributing forces to the agglomeration of particles.

Adetayo, (1993) has concluded that, due to the nature of the binder and fertilizer granules, intermolecular attractive forces, electrostatic forces and solid bridges do not play a significant role in the fertilizer agglomeration process. Thus, no further analysis of these forces shall be considered.

Most workers considered that the mobile liquid bridge is the main bridging mechanism in the granulation process (Sherrington and Oliver, 1981 ;Newitt and Conway - Jones ,1958 ; Ennis et al , 1990)

Adetayo (1993) has established from experiments that the granulation mechanism can be explained by the interparticle force on the mobile liquid bridge.

#### 2.1.1.2 Interparticle bridge bonding (Strength of liquid bridges)

Two types of mobile liquid bridges have been identified in the literature; the static and the dynamic pendular bonds.

The static pendular bond is dominant when the particle movement is infinitely slow and the bridge between agglomerating particles can be assumed to

be static. The strength of the resultant static bond strongly depends on the forces due to the surface tension existing along the surface of the liquid and a pressure deficiency force brought about by the curvature of the gas-liquid interface.

Due to the relative motion of the particles in the granulation drum, continuous deformation of the liquid bridge takes place when particles collide. This invalidates the assumption of a static bridge (Mazzone et al., 1987). The resultant bridge between relative mobile particles is no longer static but dynamic. Analysis of the dynamic pendular bond is therefore necessary.

Mazzone et al.(1987) studied the strength and rupture point of the liquid phase between two moving particles in air and concluded that the axisymmetrical bridge (dynamic bridge) formed by the liquid when the particles are close together is orders of magnitude stronger than the geometrically identical static bridge where the attractive force is due to surface tension alone. Particles agglomerate in two stages. The approach stage in which the liquid layer is squeezed between the particles, followed by the disengagement stage where the liquid bridge is elongated and finally ruptures if the force tending to pull them apart is stronger than the corresponding cohesive force.

Surface tension always acts to attract the particles while viscosity resists the particles' motion in any direction. The viscous contribution which has hitherto been neglected should therefore be considered. The dynamic pendular bond depends on the liquid's surface tension, its viscosity as well as the particles' relative movement. The dynamic pendular bond play a significant role in the agglomeration of fertilizer particles.

Ennis et al. (1991) extended the work of Mazzone et al.(1987) by considering the forces involved in the collision of two spherical particles. They assume the binder solution is sufficiently distributed so as to allow for occasional formation of pendular bridges between colliding particles. The detail is given by Ennis et al. (1991).

## 2.1.2 Macroscopic Analysis of Granulation Mechanisms

In the previous section the intermolecular level of granulation bridge bonding has been explained. Growth mechanism of granules will be explained next.

### 2.1.2.1 Granule growth mechanism and proposed growth kinetics

An understanding of granule growth mechanism is necessary in order to understand the granulation mechanism. The dominant mechanism of granule growth should be considered because it is responsible for the rate of growth of the granules. It is also a key factor in determining the final properties and morphology of the product granules and in understanding the controlling mechanisms in any granulation process.

In a typical industrial continuous fertilizer granulation system, fertilizer slurry is pumped into the granulator to mix with recycled granules.

Two phases (solid phase and slurry phase) are therefore present in the granulator; the particulate (recycled granules, fillers, urea, ammonium sulphate, potassium sulphate etc. ) and non-particulate (slurry) phase.

Before going to the macroscopic analysis there are a few technical terms concerning to granulation process to understand.

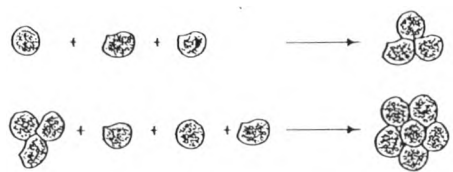
" Layering ", for the purpose of fertilizer granulation , refers to the coating of the non-particulate matter (e.g. fertilizer solution or slurry) on the surface of the particles. Layering increases the mass of particles in the system without affecting their number.

" Coalescence ", otherwise referred to as agglomeration or aggregation by some workers, occurs when two particles successfully collide to form a single granule. When two particles collide, the liquid at their surfaces coalesces resulting in the formation of a dumb-bell shaped intermediate granule . If the forces tending to separate them is higher than their attractive forces, the collision is not successful and the particles simply fall apart. However, if their forces of attraction is stronger than the forces tending to pull them apart, successful collision occurs and the dumbbell intermediate is rolled into a fairly spherical granule by the granulating action of the drum.

Figure 2.1 : shows the various possible mechanisms of granule formation (Sastry and Fuerstenan, 1973). Coalescence (aggregation, agglomeration) occurs when two particles successfully collide to form a single granule. The coalescence mechanism can be further subdivided into random coalescence (coalescence rate is size-independent) and preferential coalescence (coalescence rate is size-dependent).

The addition of fine particles to the outside of well formed granules is sometimes referred to as layering, or snowballing, in the literature.

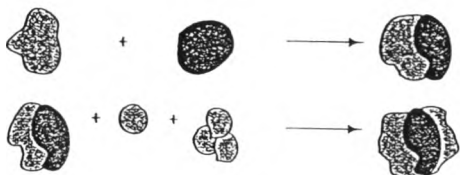
In the study of Adetayo (1993), where the initial (recycle) size distribution is very broad and continuous, it is not appropriate to arbitrarily divide the feed particles into fines and granules. Coalescence affects only the number of particles in the system. The total mass of particles is conserved.



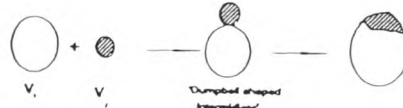
Nucleation



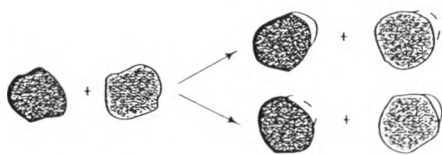
Growth



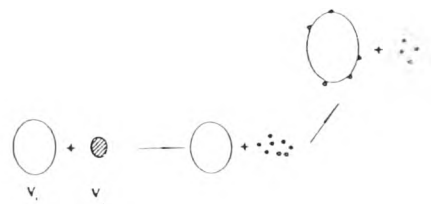
Random Coalescence



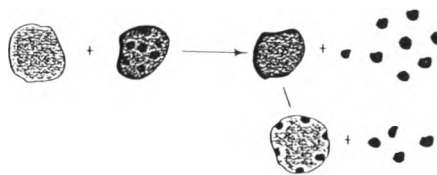
Pseudo-layering  
(preferential coalescence)



Abrasion transfer



Crushing and Layering



Crushing and Layering  
(Preferential Coalescence)

Figure 2.1 : Kinetics of tumble/growth agglomeration involving various phenomena.

If the primary particle size is large, the resulting granules are weaker and less deformable. Weak granules are crushed and redistributed over other granules. The rate of growth at this stage is dependent on the granules surface area. Thus, growth of large granules are favoured. This mechanism is referred to as crushing and layering. The crushing and layering mechanism affects the number of particles in system. The total mass of particles in the system is however conserved.

Capes and Danckwerts (1965) granulate uniformly sized sands with water as binding liquid. They observe that the material initially charged to the drum consists of loose aggregate of sand which are held together by discrete lens-shaped rings of liquid at the points of contact between the sand particles. The tumbling action in the granulation drum squeezes the particles closer together so that the internal pore space in the aggregate is reduced and becomes largely filled with liquid. At the same time, fines stick together (by the coalescence of liquid at the points of contact) to form larger aggregates which then become kneaded into small spherical granules or nuclei of granule.

Kapur and Fuerstenau (1964, 1966) summarize the observed stages of granulation by various workers into three stages. These stages help reconcile the discrepancies observed by different workers. The switch from one stage to another however depends on a combination of factors which have not been properly quantified. As long as the forces of attractions between two coalescing particles exceed the forces tending to separate them, successful collision occurs. This sets cut - off point for each stage, with a different growth mechanism being identified to be the controlling mechanism of granulation in the various stages. A review of the observed stages is given below. More detailed analysis can be found in Kapur and Fuerstenau (1964, 1966).

### Stage 1 : Nucleation growth region

The nuclei growth region involves the initial formation of nuclei through nucleation and subsequent growth of the nuclei or particles by random coalescence. The nuclei growth region is characterized by a three-phase air-water-solid system with the resultant granule size distribution being narrowed.

### Stage 2 : Transition region

As granulation proceeds, granules tend to be compacted by the granulating action of the drum, thereby forcing the particles further into the granules' void space. The result of this is the squeezing of liquid onto the granule surface producing the optimum condition for growth. The growth region is thus switched from the nuclei growth region to the transition region. This is the second stage of growth. Apart from pockets of entrapped air, the transition regime is characterized by a two phase solid-liquid system. The maximum granule growth rate is achieved in the transition regime. The resultant granule size distribution from the transition region is quite broad.

### Stage 3 : Ball growth region

This is the final regime of granulation. In the ball growth region, granules are comprised of a tightly packed interior surrounded by a thin wet shell. Granules are therefore not as deformable. The rate of granulation subsequently diminishes. Very low or near zero growth rate have been identified in this region. Various granulation mechanisms are found to control granulation in this regime. Crushing and layering, abrasion transfer or coalescence has all been identified as the controlling mechanism at this stage (Capes and Danckwerts, 1965; Capes, 1967).



During drum granulation of fertilizer, there will be a small increase in the granule size due to the layering of fertilizer solution onto recycled particles. However, the key mechanism for the increase in granule size is expected to be coalescence (Lister and Liu, 1989)

A typical granulation process starts with the pipe reactor, in which the fertilizer slurry is produced and fed to the granulator. The melting slurry granulation is always wet granulation. When NPK(recycle seed) is produced, the solid phase is the recycled fertilizer along with others such as  $(\text{NH}_4)_2\text{SO}_4$ ,  $\text{K}_2\text{SO}_4$  urea, KCl, fillers, etc. Wang Jin Ming (1996) proposes the following granulation mechanism. At the beginning, the raw materials (recycle seeds, filler, urea, potassium sulphate etc.) fed into granulation are loose fine particles. These particles become the cores of granules as the drum granulator rotates. The driving forces making the fine particles to become the core of granulation are surface tension of the liquid phase, reduction of the total surface free energy of the material system and decrease in the boundary surface between vapor and liquid phase. The particle size changes in many ways after the core is formed. The factors relating to these processes are:

- 1). The particle size and the other properties of added solid materials.
- 2). Surface tension and stickiness, etc. of liquid phase.
- 3). The type of production (continuous or intermittent).

Once the core is formed, the granule for the product grows up in the following ways:

- 1). Adhesion granulation where the melting slurry aggregates small particles into one.

2). Coating granulation : melting slurry is coated evenly on the surface of the solid particles and water vaporizes quickly. After the granule is crystallized, another coating is put on . This process is repeated again and again and granules grow up gradually.

3). Self-granulation : while being sprayed, small slurry drops dry out before touching solid particles and form granules automatically.

In the granulation process, adhesive granulation and coating granulation co-exist and play the leading function. When the range of the particle size distribution of fresh raw materials such as  $K_2SO_4$  , KCl, filler, etc. is narrow, the relative surface area is large. In this case, coating granulation and adhesive granulation occurs easily.

The granules produced are hard and not easy to break. On the contrary, when the range of particle size of solid materials added is wide (bigger portion is in 1 mm. and more), due to less capillary force and smaller relative surface area, there is a lot of opportunities of adhesive and coating granulation. However, as the granulator rotates, the strikes between the granules as well as vaporization of water inside granules cause the loose ones to be broken. As a consequence, granulation efficiency will be low.

#### 2.1.2.2 Effects of some factors on the granulation

##### Granulation kinetics

Previous model studies of fertilizer granulation using sand and fertilizer solution (Sherrington, 1968) showed that granules quickly grew to a stable equilibrium size. Thus, the importance of kinetics in determining fertilizer granule size distributions was studied by Adetayo (1993) using laboratory scale granulation.

Adetayo et al.,(1993) investigate fertilizer granulation at laboratory scale. For all fertilizers (AS, MAP, DAP), at low moisture, an equilibrium size distribution is quickly reached. For DAP and MAP, at higher moistures, granulation kinetics become significant. Granules continue to grow for at least 15 min before an equilibrium size distribution is reached. The granulation kinetics is dependent on both the moisture content and the fertilizer type.

Regarding the effect of granulation time on median granule size for AS, there is no significant difference between the granule size after 5 and 25 min granulation time at all moisture contents (4-8%). For MAP, there is a significant effect of granulation time at or above 6% moisture but not for lower moistures, while, for DAP, granulation time is important at all moisture contents except the lowest (2 %.).

The effect of increased granulation time on the frequency size distribution based on the observed spreading of the granule size distribution suggests that collisions involving large granules are favoured at longer granulation times.

#### Effect of initial particle size distribution

The importance of the initial size distribution on the granulation mechanism is highlighted by the works of Kapur and Fuerstenan (1969), and Sherrington and Oliver (1981). Due to the nature of the packing structure and the large number of contact points associated with a wide distribution of particles, the strength of the resultant granules initially produced by coalescence is appreciable and granules will not break easily. These granules possess an excess amount of liquid on their surface and are thereby more plastic and more deformable than their narrowly sized counterparts at the same moisture content.

The majority of fundamental studies of granulation has used narrow size distributions of primary particles much smaller in size than the granules produced.

Adetayo (1993) has investigated the effect of the initial size distribution on granulation in two ways : changing the shape of the coarse end of the size distribution and increasing the amount of fines.

The results show that the initial size distribution has a strong and complex effect on the granule size distribution. In the operation of a fertilizer granulation circuit the recycle size distribution will be affected by the extent of granulation in the granulation drum and the type and performance of the oversize crusher.

#### Effect of liquid phase content.

For narrow particle size distributions granule growth will broaden the size distribution when the moisture content is near that required to saturate the granule (Newitt and Conwey-Jones, 1985; Capes and Dackwerts, 1965 ). Within a narrow range of moisture , the moisture content has a strong effect on the pelletization kinetics (Kapur and Fuerstenau, 1966; Sastry and Fuerstenau, 1972).

Capes and Danckwerts (1965) observe that liquid content has a strong effect on granulation and they define the "theoretical saturated liquid content" to improve understanding of granulation phenomena. For soluble particles, such as fertilizers the total amount of liquid phase is greater than the moisture content alone.

Sherrington (1968) proposes that the volume of liquid phase present during granulation determines its extent. The concept of the solution phase ratio is

then introduced. The solution phase ratio ( $y$ ) is the ratio of the volume of solution to that of the solid in the granule (Sherrington, 1968; Smith and Nienow, 1983) :

$$y = \frac{g(1+s)\rho_f}{(1-gs)\rho_l} \quad (2.1)$$

$y$	=	Solution phase ratio
$g$	=	Mass fraction of water in the granule
$s$	=	Solubility of fertilizer salt in water (g/g water)
$\rho_f$	=	Density of the fertilizer salt
$\rho_l$	=	Density of the fertilizer solution

For a granule of porosity  $p$  the solution phase ratio  $y$ , is related to its fractional saturation,  $S_{sat}$ , as follows.

$$S_{sat} = \frac{y(1-p)}{p} \quad (2.2)$$

### Effect of binder properties

Cape and Dackwerts (1965) investigate the effect of surface tension on the granulation of material by using different binders to granulate their sand particles. Three different binders are utilized : water, 10% saturated solution of ethanol in water and pure ethanol. The surface tension of these binders at 15 °C are 73, 49 and 23 dyn/cm, respectively. They propose that, for successful granulation of narrowly sized materials, the ratio of the surface tension to that of the mean particle diameter should be greater than 4,600 dyn/cm<sup>2</sup>. They use this to explain the difficulties encountered in granulating sand particles of surface average diameter greater than 165 micrometres with water.

Ennis et al.(1991) show that the pendular bond is dynamic with the viscous contribution being higher than the capillary contribution. Binder viscosity is therefore important.

### Granule deformability and consolidation

Newitt and Convery-Jones (1958) propose that deformability be accepted as essential to granule growth by coalescence. Kristensen and coworkers (1985) show that the deformability of a moist granule comprises its strength as well as its ability to be strained without degradation.

Kristemen et al (1985) show that the strength of moist agglomerates produced by granulation in a high speed mixer influence the granule growth mechanism and growth rate. Growth by coalescence is observed to occur only after a limiting agglomerate strength is achieved.

## 2.2 Prediction of Granulation Regime From the Dynamic Pendular Bond Analysis

In the original work of Mazzone et al. (1987) they studied the strength and magnitude of dynamic pendular bridge. Ennis et al. (1991) has extended the work of Mazzone et al. by considering the forces involved in the collision of two spherical particles.

Adetayo et al. (1993) consider how one could possibly relate the analysis of Ennis (1990, 1991) to the observed granulation regime, They come to the following conclusion.

For relatively high binder viscosity, the dynamic pendular bond formed between two colliding particles will dissipate the relative kinetic energy of the two colliding particles to prevent rebound of the particles on collision. Consider two particles approaching each other with an initial relative velocity  $2u_0$  as shown in Figure 2.2. A force balance on the colliding particles gives

$$m \frac{du}{dt} = F' \quad (2.3)$$

where

$$F' = \pi \tau \bar{r} F \quad (2.4)$$

$F'$  is the strength of the dynamic pendular bond. It is made dimensionless by a capillary scale of  $\pi \tau \bar{r}$  to give the dimensionless dynamic pendular bond strength.  $m$  and  $u$  are the mass and velocity of the granule, respectively.

As a first approximation, by neglecting the capillary contribution to the dynamic pendular bond and retaining only the major contribution to the viscous force, equation (2.4) becomes ;

$$m \frac{du}{dt} = \frac{3\pi\mu r^2}{2x} \frac{dx}{dt} \quad (2.5)$$

where,  $x$  is half the dimensional gap distance between the particles. The solution to equation (2.5) with the boundary conditions  $u = u_0$  at  $x = h$  is shown to be (Ennis et al., 1991) ;

$$u = u_0 \left( 1 - \frac{1}{St_v} \ln \frac{h}{x} \right) \quad (2.6)$$

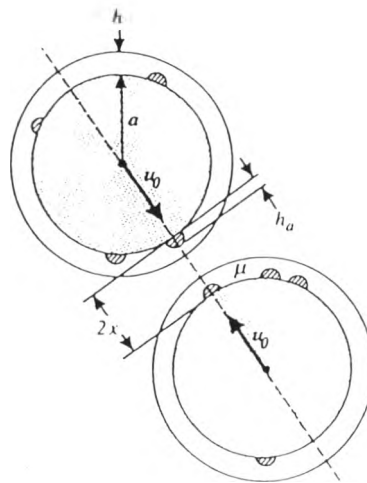


Figure 2.2 : Schematic of two colliding granules each covered by a viscous layer of thickness  $h$ . (Ennis et al., 1991)



Here,  $h$  is the thickness of the binder layer and  $St_v$  is the viscous Stokes number.  $St_v$  is a measure of the level of the relative kinetic energy between two colliding particles in comparison to the viscous dissipation brought about by the pendular bond.

$$St_v = \frac{8\rho_g r u_o}{9\mu} \quad (2.7)$$

Here  $u_o$  is the initial particle velocity,  $\rho_g$  is the density of the particle.

Let the velocity of the colliding granules be  $u_a$  when  $x = h_a$ , where  $h_a$  is the characteristic length scale of the granule's surface asperity (see Figure 2.2). If  $e$  is the granule's coefficient of restitution, then, the granule's initial rebound velocity is  $eu_a$ . Ennis et al. (1991) solve equation (2.5) for the critical Stokes number  $St_v^*$ , at which particle velocity = zero when  $x = h$ ;

$$St_v^* = \left(1 + \frac{1}{e}\right) \ln\left(\frac{h}{h_a}\right) \quad (2.8)$$

$St_v^*$  is the critical viscous Stokes number which must be surpassed for rebound of particles to occur.

Compared to its capillary counterpart, the viscous Stokes number has been shown to be more restrictive, in that more energy is required for rebound (Ennis et al., 1990). For cases where neither contribution is negligible, as a first approximation, the analysis of the order of magnitude increment in the viscous Stokes number should be sufficient to understand the effect of various process variables on the granulation process.

The combination of the resultant and critical Stokes numbers determines the rate and extent of granulation.

Ennis et al. (1991) define three granulation regimes in terms of the magnitude of  $St_v$  in comparison to  $St_v^*$ :

$St_v \leq St_v^*$	Non-inertial regime (all collisions are successful)
$St_v \approx St_v^*$	Inertial regime (some collisions are successful)
$St_v \geq St_v^*$	Coating regime (no collision is successful)

These three regimes are similar to those observed by Kapur and Fuerstenau (1964, 1966). These granulation regimes are also identified by Ennis and coworkers in a laboratory fluid bed granulation of 100 micrometers micro-beads materials. For fine powders, growth typically begins within the non-inertial regime of granulation. As granule size and  $St_v$  increases during granulation, the process may move through the inertial regime and finally end in the coating regime. The exact demarcation between regimes depends on the velocity of collision, the sizes of the colliding particles and the properties of the binder.

Growth in each region is expected to continue as long as the effective granule size is small enough. However, due to the rate of increase of the Stokes number as compared to the critical value, the non-inertial regime is expected to be short. If the rate of increment of the Stokes number is high enough, a quick transition into the coating regime occurs. This will be characterized by a sudden attainment of dynamic equilibrium and the absence of significant kinetic effect.

The extent of granulation will increase with increasing critical Stokes number or decreasing viscous Stokes number. Hence, granulation extent will increase with increasing binder viscosity, increasing granule deformability and moisture content.

### 2.2.1 Limitations of the Ennis analysis as applied to drum granulation.

The above analysis by Ennis uses a number of simplifications when applied to drum granulation of wide size range materials. These include:

1). Collisions are assumed to be between rigid or near rigid particles. This is a reasonable picture in the early stages of granulation where collision takes place between hard recycled seed particles. However, later the collisions may be between very deformable granules. The level of deformation will depend on the amount of fines in the recycled material and the size distribution of these fines. The analysis partly takes the effect of granule deformation into account through the coefficient of restitution,  $e$ , in the critical Stokes number.

2). The liquid phase is assumed to exist as a layer on the surface of a particle. However, once a significant amount of granulation has taken place, most of the liquid is contained within pores in the granule rather than as a layer on the granule surface. On collision with another granule, the granule is deformed forcing some liquid to the granule surface. For qualitative analysis,  $h$  in the critical Stokes number [eq.(2.6)] could be taken as the thickness of the liquid layer forced onto the granule surface.

3). Ennis suggests a characteristic velocity of the order of  $2R\omega$  for drum granulation. A better choice would be the periphery speed of the drum,  $\omega R$ , as the tumbling speed of a particle is related to the speed of the drum, not the size of the particle. this leads to a modified viscous Stokes number:

$$St_v = \frac{8\rho_g r \omega R}{9\mu} \quad (2.9)$$

$R$  = radius of the granulation drum, m  
 $\omega$  = rotational speed,  $s^{-1}$

Despite these limitations, this theoretical analysis can be compared, at least quantitatively, with experimental results for laboratory experiments on fertilizer granulation.

### 2.3 The Proposal of a Two-Stage Granulation Mechanism.

Adetayo (1993) wants to develop a model for use in the simulation of the granulation circuit using a broad initial particle size distribution. So, the fundamental mechanism of fertilizer granulation needs to be established.

In order to develop a granulator model, experiments on laboratory scale granulation are carried out to study the effects of process variables, such as liquid phase ratio, granulation time, binder properties, fertilizer type, etc.

Batch experimental studies are used to investigate the transient distribution of feed particles as they go through the granulation drum in a continuous process.

As recommended by Adetayo (1993), quantitative analysis of the effect of temperature on binder properties should be made before his work is extended to high temperature operation.

On the basis of his experimental results, he proposes that the granulation is occurring via "a two-stage mechanism"

In the first stage of granulation, nearly all collisions are successful and granulation proceeds by random coalescence. This stage is similar to the nucleation stage of the granulation of fine powders. This stage mechanism narrows the granule size distribution. For the very broad size distributions considered in his work, this stage is very fast (5 minutes). Fine particles disappear quickly because of their higher number density. This mechanism narrows the granule size distribution. At low moisture contents, this is the only stage of granulation and an equilibrium granule size distribution is quickly reached once the smallest granules in the size distribution reach some critical size.

The second stage of granulation occurs at higher moisture contents. In this stage, the granules may grow significantly larger than the largest particles in the initial size distribution and the granule size distribution is broadened. Growth is by preferential coalescence. Not all collisions are successful. Successful collisions rely on granule compaction to squeeze additional liquid to the granule surface and on deformation of the granules on collision to increase the contact area of the colliding granules. This stage of granulation is slow and granulation kinetics are important.

The two-stage mechanism helps explain the change in shape of the granule size distribution with time especially for DAP (Fig. 2.3), and the varying extent of granulation for the different fertilizers (Fig. 2.4).

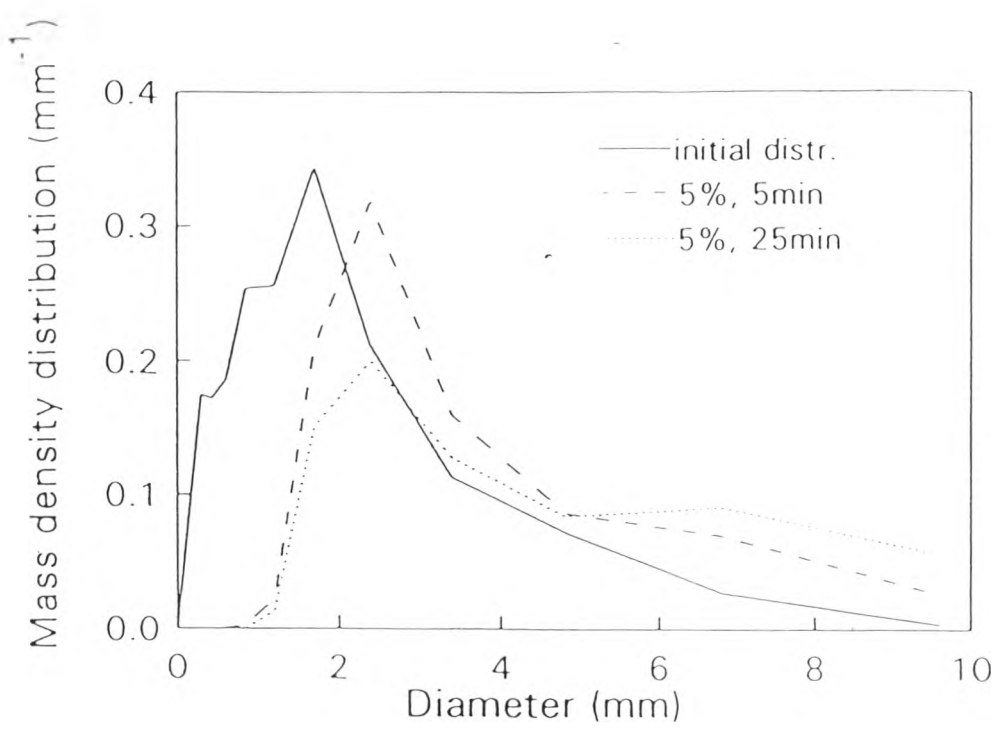


Figure 2.3 : Effect of granulation time on the mass frequency distribution for DAP fertilizer.

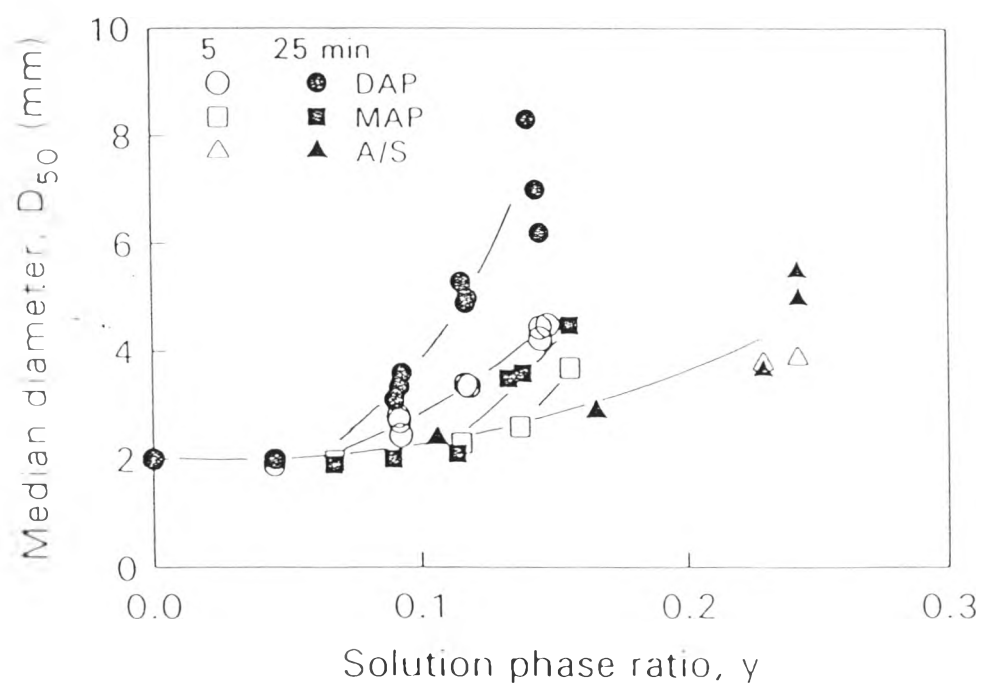


Figure 2.4 : Variation of the median granule diameter, D50 with the solution phase ratio for A/S, DAP, MAP

Table 2.1 : A summary of the two-stage mechanism

	First Stage	Second Stage
Regime type	All collisions successful (independent of granule size)	Some collision successful
Mechanism	Random coalescence	Preferential coalescence
Timing	Fast (<5 minutes)	Slow
At low moisture contents	Able to occur	Able to occur
Granule size distribution after granulation	Narrows	Broadens
Obvious point	Fine particles disappear quickly because of their higher number density	Successful collisions rely on granule compaction to squeeze additional liquid to the granule surface and on deformation of the granules on collisions to increase the contact area of the colliding granules.
Granulation kinetic	Not important	Important

In short, Adetayo (1993) has established the pioneering work and made a significant contribution to the existing knowledge on the granulation process.

### 2.3.1 Explanation in terms of Ennis's theory.

This two-stage mechanism can be viewed in terms of the granulation regimes described by Ennis and co-workers (Ennis et al., 1991). The first stage of granulation corresponds to the non-inertial regime. The viscous Stokes number ( $St_v$ ) is less than the critical stokes number ( $St_v^*$ ) for all collisions involving small particles, and all collision are successful. The small particles are quickly used up. The viscous Stokes number then increases until it is equal to or greater than the critical Stokes number for all collisions. No collisions are successful and an equilibrium size distribution is reached (coating regime).

The second stage of granulation corresponds to the Ennis inertial regime. Granule compacting and deformation will increase the critical Stokes number in some collisions, and therefore these collisions may be successful where collisions between non-deformable particles of the same size would not be. This process is relatively slow and granulation kinetics are important, but an equilibrium size distribution is still eventually reached. Adetayo(1993) shows that the proposed mechanism can explain the effect of the process parameters on the granule size distribution. The two-stage granulation mechanism, based on the Ennis granulation regimes, is consistent with the experimental observations.