The application of granulation to fine coal preparation

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Noting granulation constitutes a process in an extensive process chain, refer to Figure VII-1, optimization of the overall system depends on optimization of all individual process stages and optimization of the granulation process itself. Other subsequent processes after fine coal granulation including drying, oil recovery, treatment of waste products, also determine, in part, the efficiency of the total process. Because of this interdependence discussion of post granulation treatment is essential. This discussion is now presented.

VI.1 Drying and Oil Recovery

It is possible to recover oil during mechanical dewatering and thermal drying of granules. Oil used in coal agglomeration can be recovered during dewatering by recycling the filtrate containing excess oil. In thermal drying recovery of oil is also possible. Water and oil evaporations occurring during thermal drying, for instance, will lead to the collection of water and oil after condensation or distillation, respectively. The technique of oil recovery and drying will be further evaluated.

VI.1.1 Agglomerate and Granule Drying.

In certain circumstances agglomerates or granules have to be further dried to fulfil handling or consumer requirements. To do this, various drying methods can be adopted depending upon their suitability, effectiveness and costs. The need for thermal drying is caused by the inability of mechanical dewatering devices to further
depress the residual moisture content to an acceptable level. In general, drying is done for one of the following reasons [82].

1. To prevent freezing problems during winter and to facilitate handling during shipment, storage and transfer.

2. To maintain high pulverizer capacity.

3. To improve coal quality for the production of coke, granules or briquettes.

4. To minimize handling and freight costs.

5. Increase calorific value or heating efficiency by reducing heat loss due to evaporation during coal burning.

6. Reduce energy consumption during carbonization.

7. To optimize moisture content for subsequent process stages.

From the evidence above, the benefits of drying in coal utilization are obvious. However, thermal drying lowers coal and coke qualities as a result of the partial oxidation during drying. Also, safety and environmental hazards may be experienced in thermal drying of coal fines.

In addition, drying of agglomerates or granules may be required since granulation of coal fines is possible only within a narrow range of water addition [75]. In granule or granule production, curing or drying is usually conducted in order to increase either the strength or handling characteristics of the granules. However, the removal of moisture from granules or agglomerates may result in physical and chemical changes which are probably undesirable in regard to fine coal utilization. The positive side effect occurs when moisture removal causes an increase in bulk density. This bulk density increase results in freight cost savings and increased storage, transportation and production capacities. Also, in certain circumstances where the moisture requirement in the granule is optimal, granule strength is enhanced.
In regard to granule volume, moisture reduction usually implies a reduction in granule volume. Unfortunately the expected change in the granule volume may not be forthcoming because granule degradation may occur. This rapid degradation occurs due to the induction of cracks on the surface. Further detrimental drying effects include the fact that heating may cause oxidation or pyrolysis [50, 76] as well as spontaneous combustion or explosions. For example, washed lignite can partially lose its heating value when dried in hot air. Furthermore the similar negative effects of deterioration in coking properties due to drying coal in hot air should not be overlooked.

VI.1.1.1 Convection Drying

Convection is used as the major conventional drying technique in the coal industry [50]. In convection drying hot gas containing oxygen, nitrogen, water vapour and a small amount of carbon dioxide produced from combustion may be applied. Such a hot combustion stream can be made to contact the wet granules by cocurrent, counter-current or cross-current flows. The granules can be situated on fixed, fluidized, vibrated or moving beds. The drying gas passes around the granules which may be stacked in a bin, spread over grates or over a moving perforated belt. If the gas velocity is sufficient, fluidized or pneumatic-conveying drying conditions may occur.

Obviously, granules being dried need heat from the gas stream to evaporate the moisture. The gas stream loses heat and the granules gain the heat. The transfer flux of heat losses is proportional to the change of the gas temperature [76].

\[ q = h(T_a - T_g) \]  \hspace{1cm} (VI-1)

where \( T_a \) and \( T_g \) are the temperature of air/gas and granules respectively, and \( h \) is the coefficient of heat transfer.
In convection heating without considering other heat effects, the temperature of saturated surfaces, $T_s$, remains constant approaching the wet bulb temperature of the gas stream, $T_b$. The pressure gradient, $\Delta p$, between the vapour pressure at the temperature surface and the partial pressure of the water vapour in the gas stream drives the moisture from the granule surfaces. At this condition a dynamic equilibrium is developed between the rate of heat transfer to the granules and the rate of vapour removal from the surfaces. This equilibrium is given \[124\] by

$$
\frac{d\upsilon}{dt} = h_l A \frac{\Delta T}{\lambda} = k A \Delta p
$$

where $\frac{d\upsilon}{dt}$ is the drying rate (kg. water/hr.), $h_l$ is the total heat transfer coefficient (kJ/hr.m$^2$.K), $A$ is the area for heat transfer and evaporation ($m^2$), $\lambda$ is the latent heat of evaporation at $T_s$ (kJ/kg.), $\Delta T$ is the difference between $T_s$ and $T_b$ (K), $k$ is mass transfer coefficient (kg/hr.m$^2$.kPa) and $\Delta p$ is the pressure gradient (kPa).

When the effective heat is provided by radiation and convection, the heat transfer coefficient is the sum of the radiation and the convection coefficient \[124\]. In this case, $T_s$ exceeds the wet bulb temperature. Similar results are experienced when the heat is supplied by convection and conduction. It is obvious, however, that the drying rate is affected by the external factors such as the heat and mass transfer coefficient, the exposed area and the difference in temperatures or humidity between the gas stream and the wet surface of the granules. It is found \[76\] that the internal mechanism of mass flow on the other hand does not influence the drying rate.

Granules are porous bodies in which four stages of moisture movement occur during drying \[76\]. It should be noted that the moisture movement involves evaporation-condensation and vapour flows. In the first stage, the moisture flows as a liquid due to the existence of the hydraulic gradients. This movement may cause the generation of air pockets. In the second stage, moisture is withdrawn deeper from the pores by evaporation and condensation between liquid bridges. In the next stage
liquid bridges evaporate leaving absorbed moisture behind which has moved due to vapour diffusion. The final stage involves desorption-adsorption. Hence any moisture that vaporizes is condensed and the body is in hydrothermal equilibrium with its environment.

One of the paramount factors in drying is temperature which should be maintained at a safe level. Unfortunately lower temperatures are not suitable because extensive gas flows are required. These high gas flows result in considerable sensible heat losses. In addition, low temperature causes low thermal efficiency, higher fuel and power requirements and increased dust emissions. However, the application of very high temperature is restricted due to the fact that spontaneous combustion may occur. The actual incidence of spontaneous combustion is related to the ignition temperature of the coal. The latter is significantly governed by particle size, volatility or rank of coal, mineral matter and moisture content. By consideration of these variables the temperature can be controlled to prevent ignition.

VI.1.1.2 Conduction Drying

Another way to minimize moisture is drying by conduction. Granules in contact with hot materials will conductively receive the heat necessary to evaporate the moisture. The rate of evaporation will be affected by the characteristics of granules, the temperature difference between the granule surfaces and the hot material, conductivity of the granules and material and the area for heat transfer and evaporation. In general, equation (VI-2) may be applied for calculation of the drying rate by considering the granules to be porous bodies.

The extent of thermal conduction through porous bodies is a strong function of the porosity [76]. The heat flow may be either parallel or transverse to the axes of
the pores. For conduction along the axes the equivalent resistance \( (R_c) \) of the system is

\[
\frac{1}{R_c} = \frac{A}{Z} (\varepsilon \lambda_{G/L} + (1-\varepsilon) \lambda_s) \text{ and} \quad (VI-3)
\]

the equivalent thermal conductivity is

\[
\lambda_e = \varepsilon \lambda_{G/L} + (1-\varepsilon) \lambda_s \quad (VI-4)
\]

In comparison the equivalent resistance for conduction across the axes of the uniform capillaries is

\[
R_e = \frac{Z}{A} \left( \frac{\varepsilon}{\lambda_{G/L}} + \frac{(1-\varepsilon)}{\lambda_s} \right) \text{ and} \quad (VI-5)
\]

\[
\lambda_e = \frac{1}{\left( \frac{\varepsilon}{\lambda_{G/L}} + \frac{1-\varepsilon}{\lambda_s} \right)} \quad (VI-6)
\]

where \( A \) is the cross section or transfer area, \( Z \) is the total distance, \( \varepsilon \) is the porosity, \( \lambda_{G/L} \) is the thermal conductivity of the gas/liquid of \( \lambda_s \) is the thermal conductivity of the solid.

For a real porous body where \( f \) is a function of the pores oriented at right angles to the heat flow direction, the equivalent conductivity is

\[
\frac{1}{\lambda_e} = \frac{(1 - f)}{(1-\varepsilon) \lambda_s + \varepsilon \lambda_{G/L}} + f \left( \frac{(1-\varepsilon)}{\lambda_s} + \frac{\varepsilon}{\lambda_{G/L}} \right) \quad (VI-7)
\]

VI.1.1.3 Radiation Drying

Energy is emitted from hot materials through thermal radiation with a wavelength range between 0.2 \( \mu \)m and 800 \( \mu \)m. The shorter wavelengths radiate from hotter surfaces. When the energy reaches a material surface, it may be fully or partly absorbed, reflected or transmitted. In particular the sum of the absorptivity (\( \alpha \)), the reflectivity (\( \beta \)) and the transmissivity (\( \gamma \)) receivable on a material surface are equal to
\[ \alpha + \beta + \gamma = 1 \]

Most solid bodies are opaque to thermal radiation. One form of radiation drying is solar drying. Basically, solar drying involves a solar radiation level which affects the drying rate \[124\]. The use of solar radiation is appropriate to improve the economics of drying based on the suggestion that the unlimited solar energy can freely be utilized. To increase the drying rate, solar radiation is often combined with convectional heating. Hence the air velocity should be maintained at a reasonable level to prevent air pollution and coal dust losses.

The use of heat radiation for drying moist material such as coal cakes or granules is limited due to the fact that the heat only penetrates to a shallow depth resulting in non-uniform heating. To avoid this problem one has to vibrate or shake the coal bed. Effective radiation drying is obtained when using infra red radiation which is useful for a specific application such as drying paint films \[76\].

VI.1.1.4 Dielectric Drying

Moist materials can usually be classified as poor electrical conductors when subject to 50Hz electric field. When the frequency is increased to the radio frequency \((13.56 - 27.12 \text{ MHz})\), the technique becomes a feasible heating method because in this frequency range the impedance of the drying load falls almost inversely. The heat is generated due to the water molecular dipole reorientation following the alternating field. At frequencies lower than this range the polarization easily follows the electric field. The displacement current has a full value with the phase equal to the applied current. At this moment there is no energy loss. At a very high frequency, however, the polarization cannot follow the applied field, so neither a displacement current nor an energy loss occurs. Under the proper range the current lags the applied field causing a large energy loss which is dissipated as heat.
A dielectric material, such as coal, existing between the electrodes may experience dielectric heating. A full analysis of dielectric heating is conducted in [76]. Due to economic and practical reasons widespread dielectric drying of coal is not expected.

VI.1.1.5 Fine Coal Drying by Microwaves

Recently, advanced drying has been conducted in order to improve drying efficiency and product quality. One such technique is volumetric drying wherein a wet material is dried by means of electromagnetic energy generated at microwave frequencies. In this technique, the energy is transmitted immediately to the bulk wet fine coal without conduction of heat from the surface. At these frequencies electromagnetic energy is absorbed due to the receptivity of polar liquids, particularly water. The benefit of this energy transfer is the increased efficiency resulting in accelerated drying. Increased drying tonnages, therefore, compensate for the higher initial capital cost associated with this technique. Microwaves offer many advantages, particularly in regard to the improved product quality and the faster processing rate. In addition many problems associated with conventional methods, for instance environmental and safety problems, are minimized.

The application of microwave drying is suggested by the following advantages of this form of drying [77].

1. Improved product quality resulting in reduced wastage.
2. Faster processing leading to increased drying tonnages.
3. Smaller and more compact equipment causing reduced maintenance and overhaul costs.
4. Reduced environmental and safety problems.
5. Reduced drying costs as a result of improved efficiency and quality.
6. Increased equipment reliability.

7. The process is capable of being automated.

Particularly in regard to coal drying, the improved product quality can be seen in some of the following results.

1. Reduced residual moisture level in the product.

2. Product shrinkage can be avoided due to internal evaporation leading to improved rehydration.

3. Product deterioration, such as oxidation, can be prevented.

4. Uniform product moisture distribution results.

Fundamental aspects in microwave drying can be described as follows. Heat generated within dielectric materials, such as coal, on exposure to microwave fields is given by

\[ q = 2\pi e_0 f P_f^4 E^2 \text{ W/m}^3 \quad \text{(VI-8)} \]

where \( f \) is the microwave frequency, \( e_0 \) is the permittivity of the free space, \( P_f \) is the loss factor and \( E \) is the electric field strength in the material. Permitted microwave frequencies have been determined; notably 896, 915, and 2450 MHz [77]. The extent of energy absorbed by the coal is dependent upon the loss factor which is determined by the electrical properties of the medium. For wet coal, \( P_f \) is a function of moisture content, temperature and frequency. Another factor influencing energy adsorption is the dielectric field strength which depends on the configuration of the electric circuit producing the electric field and the dielectric constant of the coal.

The effective loss factor is made up of three components; notably solid coal, the bound and the free water. The loss factor of the free water is

\[ P_f = \frac{\tau}{2\pi e_f} + P_f(\text{dipole}) \quad \text{(VI-9)} \]

where \( \tau \) is the ionic conductivity of free water due to a dissolved salt, \( P_f(\text{dipole}) \) is the loss factor caused by the rotation of the dipolar water molecules in the applied
electric field. Both $\tau$ and $P_f$ (dipole) depend on temperature. As temperature increases, $\tau$ increases and hence $P_f$ (dipole) decreases. The loss factor associated with the bound water is dependent upon the temperature change and can be calculated from the intermediate value of the loss factors between ice and free water. The solid coal loss factor can be found using a mixture theory in so far as its loss factor corresponds to the solid volume fraction of the mixture. In comparison the free water loss factor is determined by equation (VI-9) [77].

Research on fine coal drying using microwaves to eliminate the drawbacks experienced in conventional drying been conducted in U.S. Bureau of Mines [78]. The research using the microwave drying system employed a standard industrial 2450 MHz magnetron microwave generator. Using this drying system a maximum efficiency of 97% or 1.54 kg. water per kWh for bituminous and subbituminous coals was obtained. It differed from lignite drying which indicated a lower efficiency due to the dielectric property of the lignite being greater than that of bituminous coal. The loss factor of the lignite was 0.21 compared with 0.10 for bituminous coal resulting in the lignite absorbing twice as much microwave energy as the bituminous coal. In addition, the experiment indicated that microwave energy gave a selective drying to affect efficient fine coal drying.

Microwave drying of coal is based on the fact that coal is a poor absorber and water is a good absorber of microwave energy. At the resonant frequency of 2450 MHz at which a water molecular dipole rotates, the electric field changes direction at the rate of 4.9 billion times per second. This is approximately the same rate as molecular rotation. This generates a force on the molecules which produces a violent motion which, in turn, results in instant heating. Heat generated is directly proportional to the square of the electric field strength, $E$, the frequency, $f$, and the loss factor, $P_f$. The amount of heat is calculated by the equation (VI-8), quoted as the energy absorbed per unit volume of material exposed to the microwave energy.
Chapter VI

The heating rate depends on the energy absorbed, specific heat, $C$, and density, $\rho$ [78].

$$\frac{dT}{dt} = \frac{5.71 \times 10^{-11} P}{C \rho} \quad \text{Kelvin/s} \quad (VI-10)$$

At a given frequency and electric field strength, the dielectric loss factor constitutes the main variable. It is 0.1 for coal and 12.0 for water. Therefore water heats 120 times quicker than coal does. In other words, the heat concentrates on the wet area only. When drying approaches near completion, the energy required is less, limiting the tendency of overheating. On the other hand, coal essentially does not absorb microwave energy. Heat is not generated to a great extent, allowing production of coal which is not deteriorated by oxidation or degradation. One of the advantages of microwave heating is selective heating where water exists to affect efficient drying.

VI.1.1.6 Coal Drying with Ultrasonic Aids

Low temperature drying can be effected using ultrasonic aids to promote moisture removal directly or in combination with convectional techniques or another drying aid, such as vibration. When applying the ultrasound technique two things result; an increase in drying rate and an extension of the constant drying curve to a lower moisture content. The increased drying rate may be attributed to the operating conditions and irreversible dispersion of the water vapour during each vibration cycle. In particular water vapour is carried away from the drying area during the ultrasonic compression and expansion cycles which produce various pressure changes at the applied ultrasound intensity [80, 81]. A minimum frequency of ultrasound gives a poly type flow of the fluid between the particles. This flow allows
the water to move easily to the evaporation surface. The required minimum frequency is a function of the particle size,

\[ f_{\text{min}} = \frac{\pi \mu}{4 \delta^2} \]  

\[ \text{(VI-11)} \]

in which \( \mu \) is the kinematic viscosity in cm\(^2\).s\(^{-1}\) and \( \delta \) is the channel diameter of water flows in cm.

The constant drying rate in this technique is also controlled by other factors such as air temperature, air velocity and bed depth [80]. Coal drying at higher temperatures using a certain intensity of ultrasound gives a higher drying rate. However, the addition of ultrasounds at higher temperatures affects a lesser degree of improvement compared to that at lower temperature. The drying can further be enhanced by increasing the velocity of the air stream. It is known that increased air velocity promotes evaporation. It is also gives additive effects when it is used in combination with ultrasonic drying. Experiments [80] show that ultrasound significantly increases the drying rate and drying efficiency when suitable conditions are applied. It is also found that ultrasound is very effective for temperature-sensitive materials such as coal. That is, the deterioration of coal is greatly reduced by low air temperature drying [80].

VI.1.2 Oil Recovery

The use of oil as a binding agent in granulation for finely washed coal decreases the economic means of the product due to the high cost of oil used. Oil recovery can be effected by evaporating and condensing the oil by which double benefits can be obtained; to reduce moisture content and to recover oil. In particular the various drying techniques previously discussed can produce a vapour mixture of water and oil. Distillation and condensation can then be used to separate the mixture
so obtained. Hence oil recovery is a decisive factor in the application of granulation to fine coal preparation.

Some previous attempts have been made to recover the oil used in agglomeration and granulation. Using either reduced pressure at 250° C or superheated steam at 350° C, between 40 and 50% oil recovery has been obtained from agglomerates by thermal treatment [82]. An additional advantage of this technique is that the agglomerate strength increases. Fortunately this increase is not associated with a decrease in calorific value. This maintenance of the caloric value is due to the enhancement of the hydrophobic property [82]. It should be noted that during this heating the moisture content significantly reduces.

A particular previous investigation of oil recovery using thermal treatment [83] found that

- the drying medium should have limited oxygen content and temperature to avoid oxidation and fire hazards associated with the flammable oil and coal products,
- drying medium must be condensible and capable of carrying a high concentration of oil vapour,
- granule breakages should be prevented by selecting a suitable drying technique.

An oil recovery of 95% was achieved when using superheated steam to remove oil from granules dried within a turbo dryer [83]. The main factors governing oil recovery in this technique were drying time, steam temperature and velocity. In this investigation flue gas was found to be inferior as a drying medium compared to superheated steam because it was incapable of bearing oil vapour and uncondensible oils. This investigation also identified that oil recovery reduced agglomeration and granulation costs. The investigation also found that the product quality was much better compared to that of granules without oil recovery. In particular the product had
extremely uniform moisture content, 0.7 - 0.8 kg/litre in bulk density, and was strong enough (± 20 N per granule) to withstand handling [83].

Further experiments on an oil recovery plant, which processed agglomerates using terminol 66 as a heat transfer medium, showed that oil recovery depended on the medium temperature and residence time. For 96% oil recovery the medium temperature needed to be about 300° C and the residence time at least 50 minutes [125].

VI.2 The Agglomeration/Granulation Benefits to Fine Coal Utilization

Technical aspects of fine coal granulation have been presented in the previous sections. In this section the benefits on fine coal utilization including material handling are described to justify the application of granulation to fine coal preparation. In addition, some features of fine coal granulation will indicate the potential of the product.

VI.2.1 Granulation Improves Fine Coal Handleability

Two aspects of fine coal handling which should receive proper attention are dust suppression and flow enhancement in order to avoid the serious problem which may otherwise appear in downstream handling and processing. Obviously, there are many ways to overcome the problems arising due to these aspects. These include the use of properly designed handling facilities and appropriate transportation methods, such as trains, slurry pipelines or conveyors. In this section the benefit of agglomeration and/or granulation will be discussed. This discussion will emphasize the problems normally associated with fine coal handling.
The benefits of agglomeration/granulation to avoid dust generation and flow problems should commence with the identification of fine coal handling characteristics. The related characteristics are

- particle sizes and specific area,
- hardness, friability and particle shape,
- solid density and bulk density,
- permeability and compressibility,
- cohesiveness and flow function,
- angle of repose, wall friction and internal friction and
- moisture content.

These characteristics cause adverse effects during subsequent fine coal handling. Agglomeration and granulation are expected to reduce these adverse effects. The effects include

- the effect of segregation and undesirable agglomeration,
- abrasion and corrosion,
- dust emission and pollution,
- oxidation and possible dust explosion,
- coal handling and transportation obstruction,
- and blockages and hang ups at transfer points.

VI.2.1.1 Dust Emission and Suppression

Based on Stokes' Law the settling velocity of a small particle is \( v_s = 3.0 \times 10^{-5} \rho \delta^2 \) m\(^2\)s\(^{-1}\), where \( \rho \) and \( \delta \) are the density and the diameter (in microns) of the dust particles. Hence dust emissions are caused by a very low settling rate \( (v_s) \) associated with fine particles [84]. Generally dust sizes, ranging between 0.1 \( \mu \) to 150 \( \mu \), are carried away by air which result in air pollution and fine coal losses.
This suggests that dust emissions are a challenge in fine coal handling processes and conflict with environmental clean air requirements.

It is obvious that the settling velocity is greatly affected by the density or the weight per unit surface area and the size of particles. Since increased weight and particle size of particles are affected by granulation, fine coal granulation is an appropriate method for reducing dust emission. In addition, granulation can eliminate the need for the purchase and operation of dust collectors or other methods to prevent dust generation.

Although a mechanical conveyor is the cheapest and simplest way for fine coal handling, dust emission still exists and is difficult to control, especially at loading and transfer points. This transport method, hence more or less, demands the transport of granulated products. Otherwise alternate forms of transport such as slurry pipelines must be used.

VI.2.1.2 Flow Enhancement

Coal size and specific area of coal particles greatly affect the flow ability of coal fines. In particular as the coal size decreases the flow problems increase. This decreasing flowability is due to the fact that size reduces and cohesion increases. In addition the permeability of fine coal beds decreases with decreasing particle size. Furthermore, the surface friction tends to increase with decreasing coal size. Another notable feature is that wide differences between coarse and fine particle size promotes segregation which influences the operation of all subsequent downstream solids handling and processing [85, 86].
When coal with a wide range of size distribution is poured to form a conical pile, the coarse size tends to concentrate at the periphery of the pile. If a subsequent feed of coal fines is presented to the pile, the coal fines can percolate through the voids existing between the larger particles as illustrated in Figure VI-1 [126]. In funnel flow channels the percolation will increase due to the presence of a horizontal shear movement which enhances segregation over the cross section of the channel [126]. Segregation also occurs due to the fact the individual particle size components have different angles of repose. In particular smaller particles usually exhibit a larger angle than do coarser particles. Hence the particle size with a larger angle of repose, notably the fines, will concentrate in the centre of the pile with the coarser one collecting at the periphery.

On the other hand, when a bulk solid is comprised of a size range of particles, each constituent size range will display a particular wall friction value. The differing wall friction values promotes segregation. This segregation is apparent when particles of differing size slide down a chute. Here the velocity of each particle size will be different due to the difference in wall friction. Subsequently their paths and subsequent trajectories will differ. Noting the finer particles usually have a larger
friction angle than that exhibited by the coarse particles, the fine coal will slide down the chute with slower velocity than that for the coarser particles. As a result the fine material will collect close to the tip of the chute relative to the coarser material. As the fines concentrate near the chute surface the cohesiveness increases due to the build up on the chute surface. This build up causes hang ups or blockages in the chute. A similar phenomenon occurs in the burden on conveyor belts, wherein the percolation of fines through the burden causes the fine coal to deposit and stick to the belt.

An attempt had been made to study segregation during filling of hoppers [85, 86]. These investigations indicate that during filling small particles collect in the centre, while large particles segregate towards the wall. The concentration, \( C_1 \), of both sizes is dependent on their composition, \( C_0 \), in the feed, the characteristics of material used and the position in the hopper or \( C = C_0^k \), where \( k \) is segregation constant for certain material. Medium size particles characterized by close size distribution remain unsegregated resulting in uniform concentration throughout the hopper.

In view of this phenomena it is obvious that coal size plays a significant role in segregation. Reduced coal size increases cohesion, wall and internal friction angle, angle of repose, holding moisture and decreases permeability. Hence it is difficult to achieve reliable flow of fine coal without using flow promotion devices, alternate transport mode such as slurry pipeline transport or alter the size of the coal, e.g. by granulation. In regard to the latter granulation will eliminate a large percentage of fine coal flow problems. This suggests that segregation will be reduced due to both size enlargement and the close size distribution of the granules.

Other phenomena associated with coal flows are abrasion and corrosion. Coal is considered to be an abrasive material. High contact stresses, high wall friction and high velocity, such as in pneumatic conveying, result in serious abrasion during coal handling, especially at changes of direction such as bends. The abrasiveness of coal
particles is not only affected by those factors listed above but also by the hardness and the shape of coal particles. Corrosion caused by coal bearing corrosive mineral matter, such as sulphur, increases abrasion which may occur along steel wall bins. Granules, on the other hand, which are commonly round in shapes are expected to reduce the extent of abrasion due to low friction. Likewise the extent of corrosion will be less because oil coating the granules reduces the extent of corrosion.

![Graph showing the effect of free moisture on coal handleability.](image)

**Figure VI-2.** The effect of free moisture on coal handleability [133]

Other factors affecting fine coal handleability are moisture and ash content. The effect of moisture content is well known. In particular increasing moisture content causes great difficulty in fine coal flows as indicated in Figure VI-2. Also, similar problems are experienced when fine coal contains high ash level, particularly if the impurity consists of clay materials. In such coals it is usual for the moisture to
associate with mineral matter. Both moisture and ash can be diminished in oil agglomeration before granulation. Experience has shown that the handleability of coal and its flow function can be improved from 2.2 to 3.2 by spraying the coal with oil [133]. This reinforces the advantage of granulation wherein the oil used in the granulation feed preparation will enhance the flowability of fine coal.

VI.2.2 Agglomerated/Granulated Coal Product Utilization

Although spherical agglomeration has not been considered as an economical method for refining coal fines on a large scale, it has good prospects in certain utilization areas. The discussion of these utilization areas will show that spherical agglomeration, including granulation, will hold an important role in coal utilization and energy conversion in the future. This prospect results from the improved yield, quality and handling characteristics of fine coal. In fact it will be shown that coal agglomeration greatly enhances the utilization potential of fine coal. The characteristics increasing this utilization potential will now be discussed.

Agglomeration converts dusty coal fines into near dustless granules with improved handling and storage properties. In regard to power generation, agglomerates provide consistent and free flowing feed for subsequent continuous combustion. These free flowing characteristics are maintained provided the granules do not shatter due to imposed handling stresses. Since agglomerates are characterized by lower moisture and ash content, improved combustion, lessened boiler erosion and reduced environmental impact occur. Furthermore, higher calorific values may be obtained by the use of oil or organic binders and the tendency for agglomerates to exhibit lower moisture and ash contents. When a power generation facility uses COM (coal-oil mixture) or COW (coal-oil-water) mixture, coal agglomeration is obviously a suitable method for preparing these fuels.
In regard to coke production, the elimination of fines in the coke-coal feed by using agglomeration/granulation diminishes the generation of coke breeze. In addition, the binding oil tends to increase the fixed carbon in the product which, in turn, improves the density and stability of the product [60].

VI.2.2.1 Agglomerated Coal in Cleaning and Transport

Typical fine coal produced from the coal cleaning process is commonly difficult to handle either in wet or dry form. Particle shape, size distribution and surface properties have great effect on the bulk flow properties of fine coal as briefly discussed in Section VI.2.1.2. Other factors influencing the flow properties include bulk density, permeability, compressibility, packing properties and moisture content.

Likewise, the recognized problems associated with dry fine coal in handling and transporting, including dust emission and losses, explosion and spontaneous combustion and natural oxidation require considerations. To overcome these problems wet methods for transporting fine coal are preferred. The wet methods include coal water or oil pipeline techniques. These slurry pipe line techniques are the cheapest method for large quantity and long distance transportation. Unfortunately intensive capital is required.

The advantageous production of coal beneficiated by agglomeration whilst simultaneously transporting fine coal has been perfected in Australia [139, 140]. In this process coal slurry which has undergone shear mixing with oil is pumped through a pipeline. During transportation agglomeration and cleaning processes occur. On arriving at the terminal, coal agglomerates are separated by means of a sieve bend or the like from an impurity suspension which still contains excess oil. Water and oil are then recovered and recycled by a suitable process. If the handled coal is coking coal, another advantage is obtained by transporting back the by-
product oil produced in the coking plant together with the recycled water and excess oil to the fine coal preparation plant.

VI.2.2.2 Coal Oil Mixture from Agglomerated Coal

The utilization of granulated coal was exhibited successfully at Port Kembla Steelworks where the open-hearth was fired with COM produced from agglomerated coal [88]. The reason for the adoption of an agglomerated coal process was that it overcame the main drawbacks of COM technology which included slurry stability, fly ash erosion and removal. The fineness of the coal particles in the agglomerated coal and the addition of oil to form COM resulted in significant stability compared to the COM produced from pulverized coal. Fly ash erosion and removal problems were reduced by using COM generated from agglomerated coal because the ash level was significantly less. Moreover, several other advantages of this technique were identified including improved moisture content, elimination of the need for grinding and possible oil recovery. Figure VI-3 shows the related schematic process for the use of agglomerates as an intermediate process in COM production [88]. Additional benefits are gained if a parallel combination of the flotation and granulation processes are included after classification. By introducing this process drying may be eliminated and enhanced handling characteristics may be obtained.

A further valuable observation noted during the COM preparation was that adequate agglomerate stability was gained by using an appropriate oil. In particular a waxy residual oil produced from crude oil distillation was found to be optimum because it was semi solid at ambient temperature producing adequate agglomerate strength for conventional transportation. However, it softened and melted as the temperature increased beyond 40° C at which agglomerates dispersed readily in COM before combustion. The agglomerated coal produced using such oil exhibited
suitable characteristics for both storage and transportation. This suitability was assessed by conducting drop, abrasion and crushing tests on the agglomerates.

![Diagram](image)

**Figure VI-3.** Agglomeration fine coal utilization in COM production [88]

The storage characteristics also were investigated by shipping a limited quantity of agglomerates for seven days. On completion of the tests, it was found that the settling of the agglomerates was less than that predicted from laboratory observation and that the agglomerates flowed freely from their container. This suggests that the agglomerated fine coal has better handling properties than coal fines. Considering COM is one of the main techniques in energy conservation which is currently being highly developed on large scales in both Japan and USA, agglomerated coal will play a significant role in COM production and utilization.
VI.2.3 Coal Granulation/Agglomeration Utilization in the Future.

The improvements to fine coal characteristics by granulation/agglomeration will, in turn, enhance wider application of coal granulation. This implies that granulation will not simply be coal cleaning, but will be extensively used in many applications such as the production of metallurgical cokes, electric power, domestic smokeless fuels etc. For instance, it is reported [89] that waste from a coal preparation plant makes up about 28% ROM feed and represents a 16% loss of the energy value of the coal mined. This loss can be recovered by means of agglomeration which produces agglomerates having higher calorific values. The agglomerates, in turn, can be directly employed in a fluidized combustion to generate electric power. This is possible because a fluidized bed needs a coarser feed to prevent fines filling the voids and restricting the gas flowing up through the bed. It also can be used in a fixed bed wherein fine coal is usually removed through the exhausted gas. Another possible use is as a gasifier feedstock.

The economic loss associated with adding oil as a binder during granulation can be recovered somewhat during combustion. This economic gain results from the fact that the heating value of granules is higher than that of the untreated coal. A second advantage is obtained from the fact that the ash content is significantly reduced, hence fouling and environmental waste disposal problems are eased.

The application of coal granules to smokeless fuel production for domestic needs is very interesting, especially for developing countries. This fuel may be produced by carbonization of a specific size to form coke pellets which can be used either as metallurgical coke or smokeless fuel.
VI.3 Reject Material Beneficiation

As seen in the flowsheet (Figure VII-1) waste solid discharge from the agglomeration chamber is a fine refuse slurry consisting of about -500 μm particle at low solid concentration. In general, after thickening this finely wasted slurry is pumped to a disposal area such as settling ponds, long lagoons or impoundment. Because the waste solid particles are very fine, the settling process is very slow which implies that considerable land area is required for disposal. This system, therefore, is undesirable since many constraints appear including unavailability of land and environmental hazards. Although significant research has been conducted to improve the settling rate such as the use of flocculants, dewatering ponds by electro-osmosis and agglomeration for fine coal beneficiation, the demand for extensive nonproductive land areas for the thickened slurry disposal still exists. Hence a method or process is required by which the land requirement could be reduced greatly. Such processes include pretreatment and beneficiation of the rejected material.

An ideal solution to satisfy the above requirements includes slurry thickening, mechanical dewatering and size enlargement. The latter is applied to enhance handleability and improve its utilization. In this process waste slurry from the agglomeration chamber flows down to a holding tank where lime is added to get an appropriate pH for flocculation. By stirring for sufficient retention time strong agglomerates are produced. Further flocculation occurs in the next holding tank wherein the lime treated slurry is mixed with flocculants such as the high molecular weight polyethylene oxide (PEO) [90]. At this stage +0.25 mm flocculated material can be separated from the suspension using a screen or a basket centrifuge. This dewatering results in a material containing approximately 60% solid. The suspension may be collected in a thickener which clarifies the suspension into process water and a sludge. The process water is recycled back to the first holding tank. On placing the
dewatered material in a stock pile, dewatering continues until about 70% solid is reached. At this moisture level the refuse material can be treated for land fill or other purposes.

After centrifuging, other processes such as granulation or briquetting may be applied to enhance the properties of the dewatered material and to suit its utilization other than as land fill. A common typical waste solid material produced from coal preparation plants contains shale, kaolin, sulfide, carbonate, chloride, oxides and accessory minerals such as feldspar, gypsum, pyrophylite etc.[91]. Washery shales comprise of between 4 and 10% carbon which is useful for making aggregates, light granulates, bricks and blocks. Light aggregates are used for making light weight concrete which offers the advantage of being heat insulating and nonflammable. By their small size the light granulates are indispensable in attaining the bulk density reduction. Also, by its lightness, thermal insulation and ease of handling, concrete made with light granulates can compete with air foamed concrete [92].

The coal refuse has also shown potential as a raw material for production of light weight bricks. Here the dewatered material can be shaped in brick or block forms using pressing machines. After curing the green bricks are fired at elevated temperatures. When firing no shrinkage is observed [93] and the colour changes from grey-black to tan-red due to the presence of iron oxides. It has been found that the compressive strength of the bricks is dependent upon firing temperature and the pressure applied during green brick pressing. Also, the carbon content affects the compressive strength. The lesser the carbon present in the coal refuse, the stronger the product bricks.
VI.4 Environmental Consideration

Coal refuse consists of coal waste, slates, carbonaceous pyrite slate and other inorganic materials. Weathering and leaching of coal refuse produce water pollution including silt, acid and other dissolved mineral matter. Siltation is caused by finely divided coal, minerals and discarded soil. Acid drainage is produced when iron sulphide is exposed to air and water. The sulphur is oxidized to sulphuric acid and the iron becomes iron sulphate. The effluent streams from coal preparation contain suspended materials and dissolved substances which change the chemical characteristics of the waste stream. Infiltration of contaminated water from tailing ponds containing fine solid waste deteriorates the environment.

The characteristics of the waste from a physical coal preparation plant are highly dependent on the raw coal utilized and the process system used. The quantity and volume of the waste slurry are also dependent on those factors. An agglomeration-granulation system process in particular, gives not only additional recovery and quality of coal products but also reduces the amount of waste slurry. Consequently this decreases the land requirements for slurry ponds. Furthermore, the tailings have excellent settling behaviour which is affected by the trace of oils absorbed by rejected inorganic materials [37, 59] and by the reduction in slurry concentration [8, 60]. These factors assist with water clarification prior to delivering into the environment or recycling.

As seen in Figure VI-4. the settling rate of the slurries may be expressed by [60],
\[
\frac{U}{U_i} = (1 - QC)^n
\]  \hspace{1cm} (VI-12)

where \(C\) is the particle concentration,
\(U\) is the particle settling rate velocity,
\(U_i\) is the particle settling rate velocity at \(C \rightarrow 0\),
Q and \( n \) are parameters.

It is apparent from equation (VI-12) and Figure VI-4 that the overall reduction in the concentration \( C \) of the slurry by agglomeration and carbonaceous removal results in a considerable increase in the settling rate of the waste slurry after agglomeration. A further increase in the settling rate can be assisted by the use of flocculants.

![Figure VI-4](image)

Figure VI-4. Settling rate of waste slurry before and after oil agglomeration [60]

Waste tailings rejected in the coal-oil agglomeration-granulation system process have excellent settling characteristics. Reduced waste fines loading resulting from this technique extends tailing pond life and reduces water addition requirements. The black water stream problem may be eliminated, not only by recovering organic material, but also due to the rapid settling of inorganic material. The treatment of waste fine coal slurries and recovery of coal from tailing ponds are probably the most attractive applications for the proposed system process.

It is obvious that dust emission is caused by the low settling rate of air bourne particles, the settling rate of which is affected by the particle mass and ambient air flow rate. Generally dust sizes ranging between 0.1 to 150 \( \mu \text{m} \) can be carried away by air resulting in air pollution and nuisance. As the mass of the particle increase, dust emissions decrease. Since increased particle size and weight is the objective of
granulation, fine coal granulation is an appropriate method to suppress dust emissions.

**NOMENCLATURE**

A  - area (cross section) for heat transfer and evaporation  
C  - specific heat  
\( \frac{dT}{dt} \)  - particle concentration  
\( \frac{dv}{dt} \)  - heating rate, equation (VI-10)  
\( \frac{du}{dt} \)  - drying rate  
E  - electric field strength  
\( e_0 \)  - permitivity of the free space  
f  - a function of the pores oriented at right angles to the heat flow direction,  
\( f_{min} \)  - microwave frequency, equation (VI-8)  
h  - minimum frequency  
h  - coefficient of heat transfer  
h_t  - total heat transfer coefficient  
k  - mass transfer coefficient  
n  - a parameter  
P_f  - loss factor  
\( \Delta p \)  - pressure gradient between vapour pressure at the temperature surface and the partial pressure of the water vapour in the gas stream  
Q  - a parameter  
q  - heat generated within electric materials,  
\( q \)  - transfer flux of the heat losses  
\( R_c \)  - equivalent resistance along the axis  
\( R_e \)  - equivalent resistance across the axis  
\( T_b \)  - wet bulb temperature of gas stream  
\( T_s \)  - temperature of the saturated surface  
\( \Delta T_s \)  - difference between \( T_s \) and \( T_b \) (K)  
\( t_a, t_g \)  - temperatures of air/gas and granules  
U  - particle settling rate velocity  
\( U_i \)  - particle settling rate velocity at \( C \) \( \rightarrow \) 0
\( z \) - total distance  
\( \alpha \) - energy absorptivity  
\( \beta \) - energy reflectivity  
\( \delta \) - channel diameter of water flows; diameter of the dust particles  
\( \gamma \) - energy transmissivity  
\( \lambda \) - thermal conductivity, equation (VI-3), latent heat of evaporation at \( T_s \)  
\( \lambda_e \) - equivalent thermal conductivity  
\( \lambda_{G/L} \) - thermal conductivity of liquid/gas  
\( \lambda_s \) - thermal conductivity of solids  
\( \rho \) - density  
\( \tau \) - ionic conductivity of free water due to dissolved salt, equation (VI-9)  
\( \mu \) - kinematic viscosity  
\( \nu_s \) - settling rate velocity of small particles