bulk solids handling Volume 1, Number 1, February 1981

The Design of Storage Bins for Bulk Solids Handling

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Die Konstruktion von Bunkern für die Schüttgutspeicherung

In den letzten Jahren wurden bei Untersuchungen über Speicherung und Fließeigenschaften von Schüttgütern bedeutsame Fortschritte erzielt. Als Ergebnis liegen nunmehr gut eingeführte Materialprüf- und Konstruktionsverfahren vor, die die Auslegung von Silos und Bunkern und deren Abzugseinrichtungen erlauben und die zu einem zuverlässigen und berechenbaren Materialfluß führen. Ziel dieses Beitrages ist es, die Grundzüge der Bunker-Konstruktion zu umreißen und einige der modernen Entwicklungen in der Theorie von Speicherung und Materialfluß aufzuzeigen.

Es wird ein Überblick gegeben über die Bestimmung der Bunker-Geometrie und es werden für die konstruktions- und bautechnische Auslegung und Analyse Angaben gemacht über Wanddrücke bei Massen- und Kernflußsilos unter statischen und dynamischen Bedingungen.

Die wesentlichen Konstruktionsmerkmale von Bunkeraustragseinrichtungen für gleichmäßige Durchflußregelung werden dargelegt und ein Überblick wird gegeben über das allgemeine Berechnungsverfahren zur Bestimmung der auf Austragseinrichtungen wirkenden Drücke. Die Bestimmung der Durchflußmengen für grobe und feine Massenschüttgüter wird diskutiert.

La construction des silos de stockage

Ces dernières années, des progrès signicatifs ont été réalisés dans l'étude des caractéristiques de stockage et de l'écoulement des solides en vrac. En conséquence, il existe maintenant des procédés bien établis pour tester les matériaux et pour les procédés de construction, permettant de concevoir des silos de stockage et un équipement de déchargement donnant un écoulement fiable et prévisible. Cet exposé a pour but de définir les principes de la conception des silos et de présenter certains des derniers développements concernant la théorie de stockage et de l'écoulement des solides en vrac. Il présente une vue d'ensemble de construction des silos et, pour l'analyse et la conception structurelle, il est donné une indication des charges des parois agissant dans les silos d'écoulement de masse et en entonnoir, dans des conditions statiques et dynamiques. Les caractéristiques essentielles de conception des chargeurs permettant d'obtenir un contrôle uniforme de l'écoulement et le procédé général de calcul des charges des chargeurs sont passés en revue. Il discute aussi la détermination des taux d'écoulement pour les solides en vrac grossiers et fins.

El diseño de tolvas para el almacenamiento de sólidos

En años recientes se han hecho importantes avances en el estudio de las características de almacenamiento y fluidez de materias sólidas a granel. Como resultado existen en el presente procedimientos bien establecidos de pruebas de materiales y métodos de diseño conexos que permiten proyectar tolvas de almacenamiento y aparatos de descarga capaces de proporcionar un flujo seguro y previsible. El propósito de este trabajo es esbozar los principios del diseño de tolvas y poner de relieve algunos de los adelantos modernos relativos a la teoría del almacenamiento y movimiento de productos sólidos a granel. Se da un resumen sobre la determinación de la geometría de tolvas y, para fines de diseño y análisis de estructuras, se da una indicación de las presiones que obran en las paredes de tolvas de flujo másico y flujo en forma de embudo bajo condiciones estáticas y dinámicas. Se presentan las características de diseño esenciales de los alimentadores para obtener un control uniforme del flujo de los materiales y se pasa revista al procedimiento general adoptado para calcular las cargas en los alimentadores. Se discute asimismo la determinación de caudales para sólidos a granel tanto gruesos como finos.

Summary

In recent years significant advances have been made in the study of the storage and flow characteristics of bulk solids. As a result there are now well established materials testing and associated design procedures to enable storage bins and discharge equipment to be designed to provide reliable and predictable flow. The purpose of this paper is to outline the philosophy of bin design and to highlight some of the modern developments concerning the theory of bulk solids storage and flow. An overview is given of the determination of bin geometry and, for the purposes of structural design and analysis, an indication is given of the wall pressures acting in mass and funnel flow bins under static and dynamic conditions. The essential design features of feeders to give uniform flow control are presented and the general procedure for the calculation of feeder loads is reviewed. The determination of flow rates for both coarse and fine bulk solids is discussed.

1. Introduction

The handling of materials in bulk form is a major activity of a vast number and variety of industries throughout the world. In particular, the various mining and associated process industries rely heavily on bulk handling operations. So too do

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the agricultural, food processing, pharmaceutical and manufacturing industries. The costs of handling operations are very substantial indeed and for this reason it is of the utmost importance that all bulk handling and storage facilities be designed and operated with a view to obtaining both maximum reliability and efficiency coupled with maximum economy. In view of the magnitude of the costs involved in handling bulk materials, even small incremental gains in efficiency can lead to substantial cost savings.

In the past the design and operation of handling systems for bulk solids has, all too often, been treated very empirically. This applies particularly to storage bins, silos and surface storage facilities such as stockpiles and gravity fed reclaim systems. There have been many instances of costly flow interruptions such as those caused by the bulk solid forming stable cohesive arches over the openings in the bottoms of storage bins or holding-up against the bin walls without discharge taking place. In most cases such flow interruptions are directly attributable to incorrect design with little or no regard to the flow properties of the material being handled. On other occasions catastrophic structure failures of bins and silos have occurred due to a lack of appreciation, at the design stage, of the magnitudes of the dynamic wall pressures that occur during discharge.

In recent years significant advances have been made in the development of theories and associated design procedures to describe the behaviour of bulk solids under the variety of states that are encountered in bulk solids handling operations. Of particular note is the research associated with storage bin design for which comprehensive mathematical models and design information have been established. This information enables bins to be designed to provide reliable and predictable flow under the influence of gravity. It is important, therefore, that engineers maintain an awareness of the developments that are taking place in order that the design and operational efficiency of handling plant can be improved. It is equally important that plant operators be acquainted with the rudiments of storage system discharge characteristics in order that such handling plant can be operated correctly and potential trouble spots identified. In this way early corrective action, where necessary, can be initiated and the overall maintenance during the life of the plant will be minimized.

The modern theories of storage and flow of bulk solids are largely attributable to the pioneering work of Dr. A.W. Jenike. Jenike and his colleague, Dr. J.R. Johanson, have published many papers and of these the three University of Utah Bulletins [1—3], published in the 1960 s, are of particular note in view of their very comprehensive exposition of the theories of flow and associated design procedures. The work of Jenike has precipitated a great deal of research throughout the world on problems associated with the storage and flow of bulk solids.

The purpose of this paper is to present an overview of the storage bin design concept, highlighting the various phases in the design procedure, including determination of flow properties, bin geometry for reliable and predictable flow, wall pressures for both static and dynamic conditions, and flow rate analysis. In addition some comments are made about the requirements for correct feeder design including the need to determine the actual feeder loads. It is not possible in a paper of this type to cover any aspect in great detail. More specific and detailed information can be obtained from the references listed at the end of the paper.

2. Bin Design Philosophy

2.1 General Remarks

The design of storage bins for bulk solids is basically a four-step process:

1. Determination of the strength and flow properties of the bulk solids for the worst likely conditions expected to occur in practice.
2. Determination of the bin geometry to give the desired capacity, to provide a flow pattern with acceptable characteristics and to ensure that discharge is reliable and predictable.
3. Estimation of loadings exerted on the bin walls and the feeder under operating conditions.
4. Design and detailing of the bin structure.

It is important that all bin design problems follow the above procedures. When investigating the required bin geometry, it should be assumed that gravity will provide a reliable flow from storage. Not until it has been demonstrated that the gravity forces available are insufficient to provide reliable flow should more sophisticated reclaim methods be investigated.

The general theory pertaining to the gravity flow of bulk solids in hoppers and the associated design procedure are fully documented [1—4]. However, for the purpose of the present discussion the salient aspects of the bin design philosophy will be briefly reviewed.

2.2 Bin Flow Patterns

Following the definitions of Jenike, there are two basic modes of flow, *mass-flow* and *funnel-flow*. These are illustrated in Fig. 1.

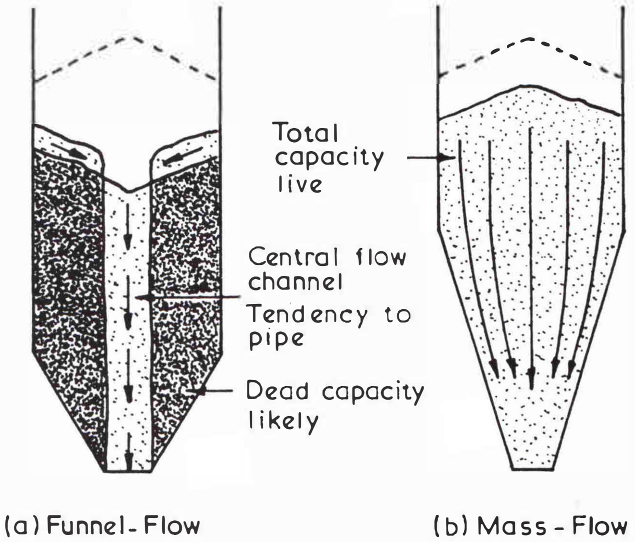


Fig. 1: Bin flow characteristics

In *mass-flow* the bulk material is in motion at substantially every point in the bin whenever material is drawn from the outlet. The material flows along the walls with the bin and hopper (that is, the tapered section of the bin) forming the flow channel. *Mass-flow* is the ideal flow pattern and occurs when the hopper walls are sufficiently steep and smooth and there are no abrupt transitions or inflowing valleys.

Funnel-flow (or *core-flow*), on the other hand, occurs when the bulk solid sloughs off the surface and discharges through a vertical channel which forms within the material in the bin. This mode of flow occurs when the hopper walls are rough and the slope angle α is too large. The flow is erratic with a strong tendency to form stable pipes which obstruct bin discharge. When flow does occur segregation takes place, there being no re-mixing during flow. It is an undesirable flow pattern for many bulk solids.

Mass-flow bins are classified according to the hopper shape and associated flow pattern. The two main types are conical hoppers, which operate with axi-symmetric flow, and wedge-shaped or chisel-shaped in which plane flow occurs. In plane-flow bins the hopper half angle α will usually be, on average, approximately 8° larger than that for the corresponding conical hoppers. Therefore they offer larger storage capacity for the same head room than the conical bin but this advantage is somewhat offset by the long slotted opening which can cause feed problems. The transition hopper, which has plane-flow sides and conical ends, offers a more acceptable opening slot length. Pyramid-shaped hoppers, while simple to manufacture, are undesirable in view of the build-up of material that is likely to occur in the sharp corners of the inflowing valleys.

The limits for mass-flow depend on the hopper half angle α, the wall friction angle ϕ and the effective angle of internal friction δ (see Fig. 3). In the case of conical hoppers the limits for mass-flow are clearly defined and quite severe, as illustrated in Fig. 2. Plane-flow or wedge-shaped hoppers have similar limits for mass-flow but these are much less severe [3—4].

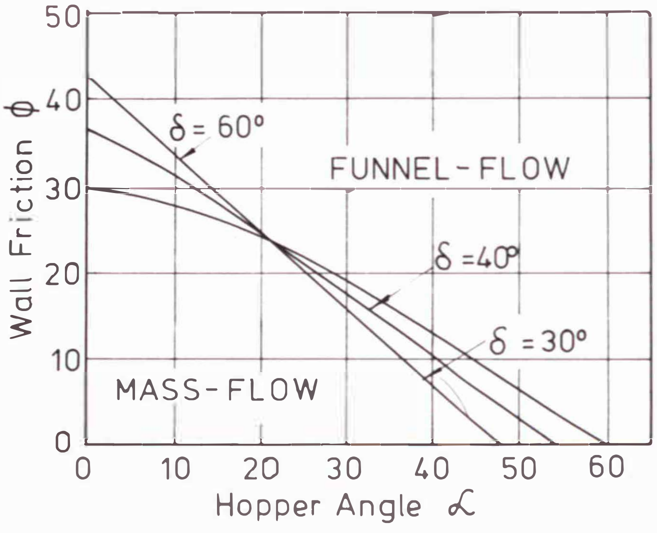


Fig. 2: Limits for *mass-flow* in conical hoppers

Funnel-flow bins are characterised either by their squat hopper proportions or their flat bottoms. For funnel flow bins to operate satisfactorily it is necessary for the opening size to be at least equal to the critical pipe dimension D_f. This will ensure that the material will not form a stable pipe but rather will always collapse and flow. However, for many materials the minimum pipe dimension D_f is too large, rendering funnel-flow bins impracticable. This is certainly the case with most coals which at higher moisture levels are known to have critical pipe dimensions of several metres.

Where large quantities of the bulk solid are to be stored, the expanded-flow bin is often an ideal solution. This bin combines the storage capacity of the funnel-flow bin with the reliable discharge characteristics of the mass-flow hopper. It is necessary for the mass-flow hopper to have a diameter at least equal to the critical pipe dimension D_f at the transition with the funnel-flow section of the bin. This ensures that the flow of material from the funnel-flow or upper section of the bin can be fully expanded into the mass flow hopper. The expanded-flow bin concept may also be used to advantage in the case of bins or bunkers with multiple outlets.

Generally speaking, symmetric bin shapes provide the best performance. Asymmetric shapes often lead to segregation problems with free flowing materials of different particle sizes, and make the prediction of wall loads very much more difficult and uncertain.

2.3 Determination of Flow Properties of Bulk Solids

In order to design storage bins and associated handling systems it is essential that the flow properties be determined by the testing of a representative sample. This testing provides the designer with such parameters as:

- flow functions *FF* for instantaneous and time storage conditions
- effective angle of internal friction δ
- wall friction angles ϕ for different bin wall materials and finishes
- bulk density ϱ as a function of consolidation
- critical pipe or 'rathole' diameter D_f as a function of effective head of solids.

For fine powders, flow rate predictions may be critical. To make flow rate predictions it is necessary to measure:

- solids density
- permeability of the solids as a function of consolidation.

The strength and flow characteristics of a bulk solid are defined by its flow function *FF*, which is normally obtained from tests on a direct shear apparatus. Primarily, the flow function, for a given bulk material, is a plot of the unconfined compressive strength σ_c versus the major consolidating pressure σ_1, these two parameters being obtained from the yield loci, as illustrated in Fig. 3. Typical flow functions are illustrated in Fig. 4.

For the majority of cases, flow functions for cohesive bulk solids will be convex as in curves (a) and (b) or straight lines through the origin as in curve (c). Bulk solids depicting the latter characteristic are referred to as 'simple bulk solids'. Free flowing bulk solids have no cohesion and hence no strength (that is $\sigma_c = 0$); their flow function coincides with the horizontal axis as in the case of curve (d).

The strength of some materials increases more rapidly as the consolidation pressure increases and in this case the flow function will depict a concave upward shape as in curve (e). A typical material exhibiting these characteristics is ammonium nitrate prill [5].

Several factors influence the strength and hence flow function of bulk materials. These include the moisture content, temperature, storage time, particle size distribution, and external factors such as mechanical vibrations. Typically the effect of increase in moisture content is to increase the strength up to a limiting condition beyond which any further increase in moisture content will cause the strength to reduce again. Most bulk solids gain strength with consolidation during prolonged storage. By way of example, typical run-of-mine coals with moisture content in the range 10—15% (dry basis) will show an appreciable, but not unacceptable, increase in strength after two days, that is, storage over a week-end period. However, after one week or longer the strength may increase to such an extent that it is impossible to design a storage bin to discharge the material by gravity after such periods of time; some form of flow promotion will be required. With respect to particle size distribution, as the percentage of fines increases so too will the strength increase.

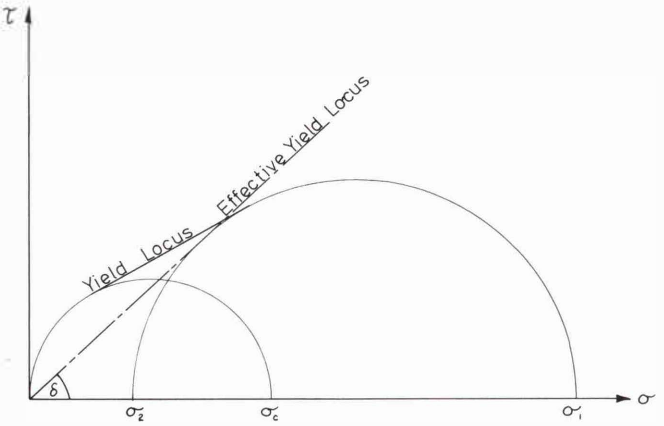


Fig. 3: Yield functions for bulk solids

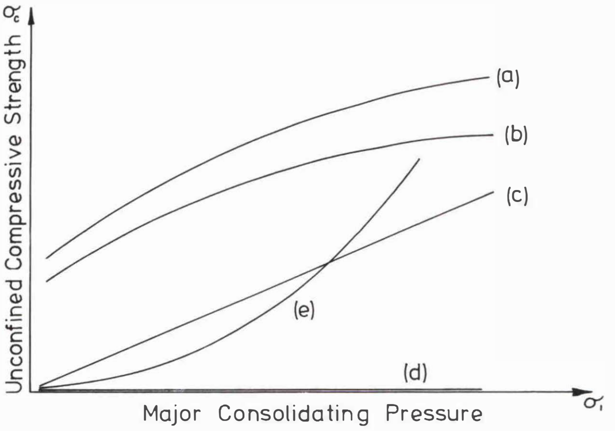


Fig. 4: Typical flow functions for bulk solids

It is interesting to note the effect of various hopper wall materials on the wall friction. Fig. 5 shows a range of possible wall materials on Liddell coal. The advantage of using a low friction material, such as stainless steel, in terms of the gain in hopper half angle α that can be used is readily observed by reference to Fig. 2.

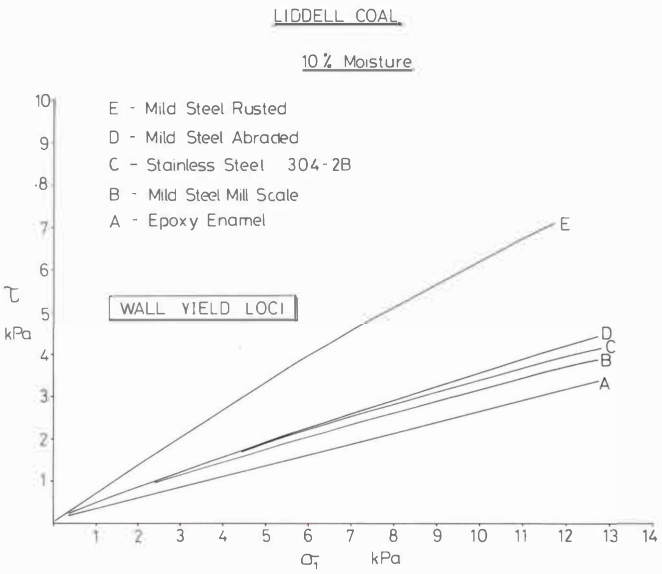


Fig. 5: Wall yield loci for Liddell state coal for a range of wall lining materials

2.4 Determination of Hopper Geometry

Once the relevant flow properties have been obtained it is then possible to determine the required bin shape to provide either mass flow, funnel-flow or expanded flow.

In the case of mass-flow the aim is to determine the hopper geometry, in particular the hopper half angle α and opening size B so that a stable cohesive arch cannot form over the hopper outlet. When determining the opening size the criterion for design is the Jenike 'Flow- No Flow' criterion [3]. Here the stress condition in the arch, as defined by the flow factor ff, must be equal to or greater than the strength of the bulk solid if flow is to occur. This condition must be satisfied for the consolidation condition of the bulk solid at the hopper outlet. Normally the opening dimension is made larger than the minimum value in order to achieve the necessary flow rate.

Whereas in the majority of cases the *mass-flow* design analysis determines the opening dimension at the hopper outlet, in the case of bulk solids with a concave Flow Function as depicted by curve (c) of Fig. 4, a different design criterion is established. Such materials are relatively free flowing at low consolidation conditions and will readily discharge from the lower regions of the hopper. However they are likely to form a cohesive arch high up in the hopper where the consolidation pressures are larger. The design analysis determines a maximum hopper diameter or width for flow to occur and this, in turn, may be used to indicate the maximum diameter or width of the storage bin [5].

In the case of *funnel-flow* and expanded-flow bins, it is necessary to compute the critical or minimum diameter D_f for an unstable pipe or 'rathole', from which the minimum bin opening for funnel-flow or mass-flow hopper dimension at the transition of an expanded flow bin is determined. The value of D_f is a function of the effective consolidation head h_f

which depends on the bin width or diameter and the height to diameter ratio; h_f is determined from the Janssen equation [4].

In general, funnel-flow bins having an opening dimension less than D_f will not empty. They will discharge or draw down for an initial period until the level in the bin drops, theoretically, an amount equal to the effective consolidation head corresponding to the actual bin opening. When flow stops a stable pipe or 'rathole' forms above the bin opening.

It should be noted that the determination of D_f is required in the design of bottom reclaim stockpile systems. In this respect the stockpile behaves in a similar way to a multi-outlet funnel-flow bin.

2.5 Flow Promotion by Vibrations

Ideally, storage bins should be designed so that the contents may be discharged by gravity alone, but occasions often arise in practice where this is not always possible and some form of flow promotion device is necessary. In some situations, due to design constraints such as head room limitations, or due to difficult flow characteristics of a bulk material, a *mass-flow* bin may not be practicable and a funnel-flow bin utilizing flow promotion may be deliberately selected. Where flow promotion is necessary, the use of devices which impart vibrations to the bulk solids are used extensively.

While mechanical vibrations may consolidate a powder or bulk solid, it has been shown that when a bin is in a potential flow mode with the discharge gate or valve open, both the strength of a bulk solid and its wall friction coefficients can be considerably reduced [6—8]. The failure criterion developed in this reported work shows that the vibration velocity on the plane of failure is the significant parameter in causing local dilation and a corresponding reduction in shear strength. The strength decreases exponentially with increase in vibration velocity approaching asymptotically a limiting value.

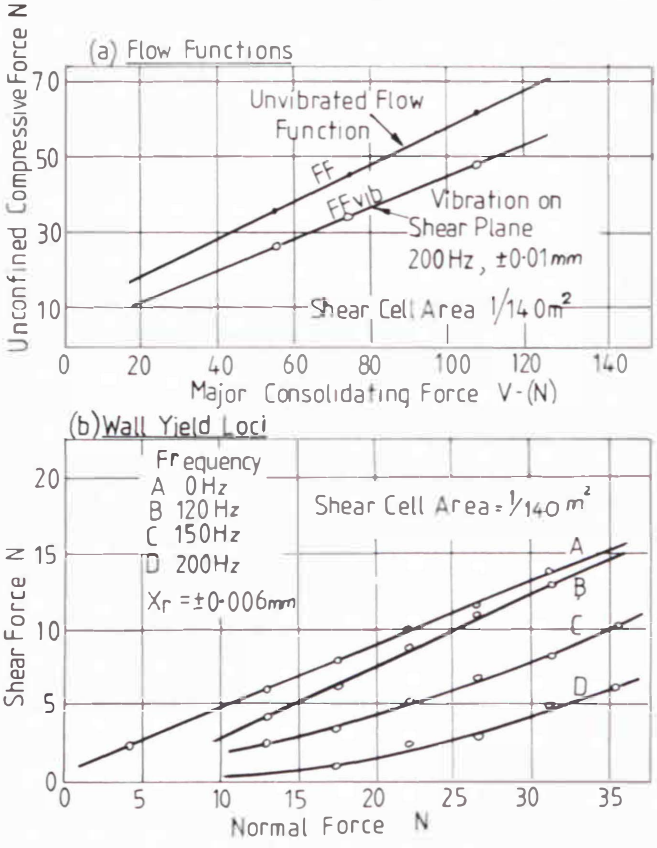


Fig. 6: Flow functions and wall yield loci for vibrated and unvibrated samples, -1 mm pyrophyllite 5% M.C. (d.b.)

The effect of mechanical vibrations in reducing the flow function and wall friction is shown in Fig. 6. These results apply to the bulk solid pyrophyllite, which is used in the manufacture of refractories. Based on these results the application of mechanical vibrations in this case permit the hopper half angle for a conical *mass-flow* hopper to be increased from 19° to 33° and the corresponding opening size to be decreased from 0.9 m to 0.6 m. This provides a ready indication of how a *funnel-flow* bin may operate under *mass-flow* when mechanical vibrations are correctly used.

3. Bin Wall Pressures

The prediction of bin wall pressures continues to be an area of bin design which is the subject of considerable research and conjecture. The latest group of papers on this topic is contained in reference [9]. While there are still widely varying approaches to the problem one thing is clear — the loads exerted on the walls of a bin under operating conditions are directly related to the *flow pattern* which the stored bulk solid exhibits when flowing into and, more importantly, when flowing out of the bin, Fig. 1.

The flow pattern which a *mass-flow* bin exhibits is reasonably easy to predict and is reproduceable. However, in *funnel-flow* bins the flow pattern is more difficult to ascertain, especially if the bin has multiple outlet points, the loading of the bin is not central and/or if the bulk solid is prone to segregation. These factors make the prediction of wall loads in symmetric *mass-flow* bins much easier than the same prediction for non-symmetric *funnel-flow* bins. Unless there are compelling reasons to do otherwise, bin shapes should be kept simple and symmetric.

3.1 Wall Pressures in Mass-Flow Bins

Present Codes of Practice relating to the design of bins do not cover the design of *mass-flow* bins. To predict the wall pressures in mass-flow bins one must refer to the recent literature, notably that due to Walker [10, 11], Walters [12, 13] and Jenike et al. [14—18]. One soon finds, however, that these publications present the designer with certain difficulties when applying the theories to practical design situations. Walters, for example, only deals with conical hoppers with extremely steep walls (the unpublished thesis of Clague [19] must be referred to for wedge hoppers) while the Jenike method relies on the use of graphical information which does not cover a wide range of geometric possibilities. In an attempt to overcome some of these difficulties the present authors have published several works [4, 20—22]; taking into account the current state-of-the-art the suggested procedures for predicting the wall stresses in mass-flow bins are:

For initial filling or static conditions

1. cylinder — Janssen method with $K_j = 0.4$
2. hopper — Jenike method of reference [18] or Walker method with $K = [1 + \frac{\mu}{\tan}\alpha]^{-1}$, or Walters/Clague method with $K_w = 0$ and $D_n = 1$.

For flow or dynamic conditions

1. cylinder — Jenike minimum strain energy method with the modifications as suggested in reference [18].
2. hopper — Jenike method of reference [18] or Walters/Clague method.

It is beyond the scope of this paper to present the detail of any of these theories. Readers interested in such detail are referred to the original papers or to references [4, 22]. To illustrate the variations in the predictions obtained with the suggested methods Fig. 7 is given which shows the theories applied to one of the experimental bins used by Clague. Clague's experimental results are included for comparative purposes.

3.2 Wall Pressures in Funnel-Flow Bins

Two of the most recent and comprehensive methods for predicting the wall loads in funnel-flow bins are due to Jenike et al. [23] and the American Concrete Institute [24]. Both methods make use of the Janssen method (or the Reimbert method in the case of reference [24]) for predicting the static or initial filling loads on the vertical walls and apply overpressure factors to account for the increased wall loads under dynamic or flow conditions. Both theories assume a single symmetric outlet. Such an outlet is the only one which allows the flow pattern in the bin to be predicted with any degree of certainty. It should be appreciated that even with such an arrangement there can be no guarantee that the flow pattern will remain symmetrical. Non-symmetrical flow patterns can result when a segregated stream of material is charged into a bin causing the fines to fall on one side of the bin and the coarse on another side. The difference in flowability between the fine and coarse fractions will result in the flow pattern developing preferentially in the better flowing (coarse) fraction. Fig. 8 gives a comparative example of the loads predicted by the Jenike and ACI methods. More detailed information on these methods can be found in references [14, 15].

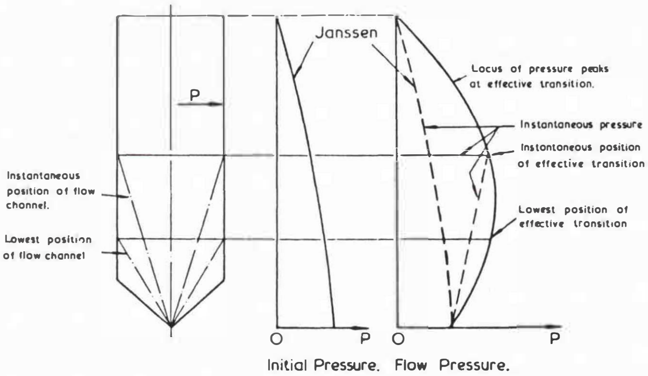


Fig. 8: Wall loads for *funnel-flow* bins

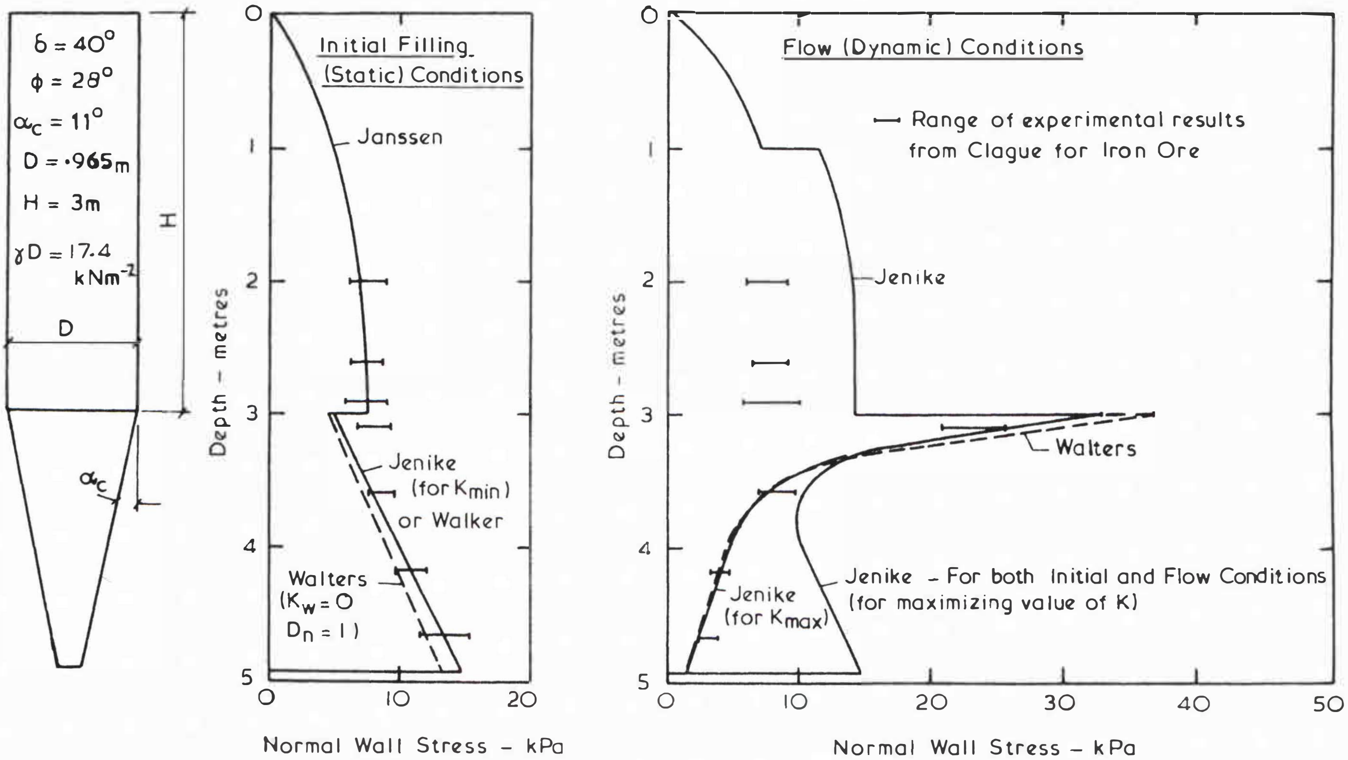


Fig. 7: Comparison of wall stress theories and Clague's experimental results

3.3 Flow of Fine Powders

It should be noted that all the wall pressures determined by the methods mentioned in this paper assume that the stored bulk solids are permeable to air and will immediately deaerate on filling.

For bins filled with fine dry powders, air may be entrained or deliberately injected into the powder causing the powder/air mixture to behave like a fluid. For this situation the possibility of hydrostatic pressures should be considered [22, 24].

3.4 Pressure Increase due to Eccentric Discharge and Filling

Safarian [25] points out that withdrawal of granular material through eccentric openings causes lateral pressure changes considerably different from those caused by withdrawal from a symmetric opening . Tests showing the variation in the pressures are not consistent so it is dangerous to generalise. However, bin walls, including those which are circular, should have adequate bending strength and stiffness to resist the unbalanced loading that can occur during eccentric discharge. Similar unbalanced loading can occur if the filling of the bin is not symmetrical or if the funnel-flow pattern which develops causes a non-symmetrical top surface to develop.

Methods for estimating the increased loads due to eccentric filling and discharge are given in references [24—27].

3.5 Design of the Bin Structure

Once the geometry of the bin has been determined from considerations of the flow of the bulk solid to be used in the bin, and the wall loads that the bulk solid exerts on the bin under operating conditions have been estimated, then the design of a safe, economical bin structure can be undertaken.

It is important that designers keep structural members outside the bin profile so that the flow of the bulk solids within the bin is not hindered. Such items as the fixing of hopper linings, arrangement of feeders, skirts and vents etc. are all integral aspects of the bin design and should not be overlooked; further details on these detailing aspects are provided in reference [28].

4. Estimating Feeder Loads

The design and selection of feeders for removing bulk solids from storage bins is critical. The feeder and the hopper from which it is reclaiming must be treated as an integral unit. A well-designed hopper may be prevented from working properly if the feeder is poorly designed, and vice-versa.

Several authors [29—32] provide an adequate coverage of the principles of feeder design so only brief mention of these principles will be made here. As far as storage bins are concerned a feeder is any device used to control flow of bulk solids from the bin. In selecting a suitable feeder it is necessary to ensure that the device will:

— deliver the range of flow rates required

— be able to handle the range of particle sizes and flow properties expected

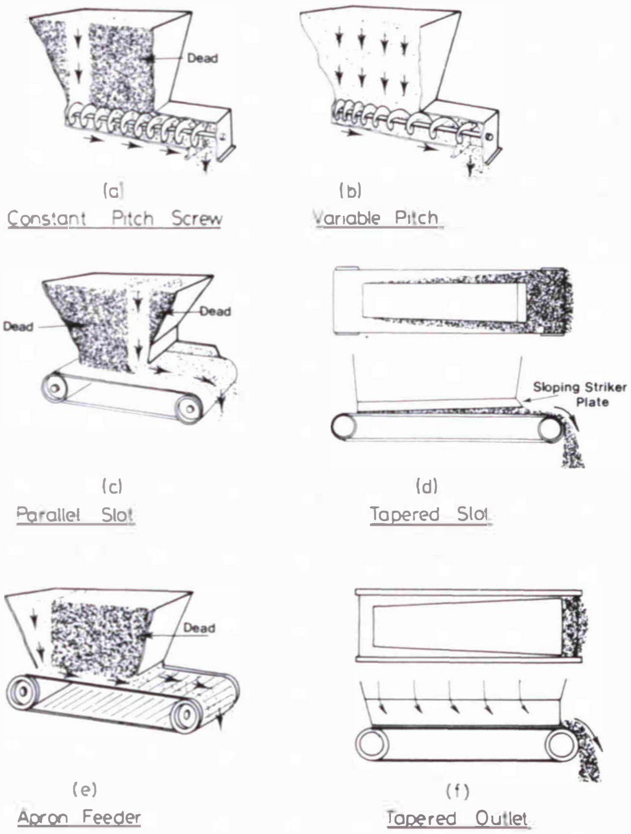
— deliver a stable flow rate for a given equipment setting

— allow flow rate to be varied easily over the required turndown ratio

— fit into the available space.

With small circular or square outlets these requirements can easily be met, for almost any feeder will produce uniform flow if a vertical spout, about one outlet diameter long, connects the bin and feeder.

With rectangular bin outlets, however, the feeder must be designed to have increased capacity in the flow direction. As illustrated in Fig. 9(a), for example, a constant pitch screw feeder will draw only from the rear of the bin. Similarly, the belt feeder in Fig. 9(c), with skirt boards tight against the belt, will draw solids essentially from the front [29]. An apron feeder with parallel sides will often draw from the rear, Fig. 9(e). Even with the best-designed bin, flow may stop because these localised flow patterns cause stable arches and 'ratholes' to develop in non-flowing regions. Examples of feeders that are designed to cause flow across the entire bin outlet [29] are presented in Fig. 9(b), (d) and (f).



(a) Constant Pitch Screw

(b) Variable Pitch

(c) Parallel Slot

(d) Tapered Slot

(e) Apron Feeder

(f) Tapered Outlet

Fig. 9: Feeders for controlling bulk solids discharge

The load which is exerted on a feeder by the bulk solid in a hopper is difficult to predict with any degree of precision. In a recent paper Wright [33] observes that the majority of formulae published for calculating feeder power are inadequate when applied to feeders extracting from mass-flow bins. This problem appears to stem from the fact that most of these formulae are empirical and were derived to accommodate loads for conventional, badly operating, funnel-flow bins. With the advent of mass-flow, which provides a full outlet area of bulk solid to the feeder, many feeders have been found to be seriously lacking in power.

In practice, the loads exerted on feeders vary considerably. The loads exerted under initial filling conditions can be considerably in excess of the loads exerted under emptying or flow conditions. Reisner [30] indicates that the initial loads can be 2 to 4 times the flow loads. Fig. 5 is a typical graph showing feeder load as a function of time during the initial filling and flow stages.

Feeder loads can be predicted from a theoretical [34, 35] or empirical standpoint [30, 31, 35]. Details of the various methods are outside the scope of this paper; interested readers are referred to the original papers or to reference [4] which contains a summary of the various approaches.

5. The Flow Rate of Bulk Solids from Mass Flow Channels

5.1 General Remarks

An important aspect of bin design is the determination of flow rate. More precise predictions of the flow rate are necessary as industry becomes more automated with plant designed on a *matched basis*. In some situations adequate plant performance or in other cases maximum plant capacity may be governed by the discharge rate from a bin. Such situations are demanding increased understanding of the flow of bulk solids from mass flow bins [36, 37, 38].

The prediction of the flow rate of bulk solids requires that the properties of the flowing bulk solid be known. The properties which should be measured include its cohesive and frictional properties, the variation of bulk density and the ease with which interstitial fluid can permeate through the powder as a function of the extent of consolidation of the powder. The determination of the bulk solids permeability indicates whether the material can be regarded as a coarse bulk solid or one in which fluid particle interaction effects will be significant. Such bulk solids are referred to as fine bulk solids. Generally a bulk solid should be considered as a fine bulk solid wherever its mean particle size is less than about 300 micron. However, since fluid particle interaction effects are relative to weight forces, low density powders of a somewhat coarser mean particle size should also be considered as fine bulk solids.

Both coarse and fine bulk solids may be further categorised as either cohesive or simple bulk solids, Fig. 4. In designing bins for cohesive bulk solids, bin outlet dimensions necessary to avoid flow obstructions usually result in flow rates far in excess of plant requirements. In such cases a properly designed feeder is necessary to match the bin discharge capacity to plant requirements. However, in some situations where very large discharge rates are required, the bin outlet dimension may be determined from flow rate considerations.

To date several authors have presented formulae for the flow rate of coarse bulk solids, the most significant of which are presented in references [39—41]. For coarse simple bulk solids the analysis of Williams [39] may be applied successfully. This analysis has been generalised for both plane flow and axisymmetric flow channels by Rennie [43]. These analyses present expressions for the flow rate in terms of a dimensionless parameter, values for which have been presented graphically for a limited range of material properties. The approach which is most consistent for coarse bulk solids is that of Johanson [42]. This analysis, which is most relevant for predicting the flow rate of coarse cohesive bulk solids, is derived by considering the equation, including the inertial forces, for a cohesive arch situated at the outlet of a mass flow channel.

With the handling of finer powders in industry, it became apparent that the flow rate of fine bulk solids was orders of magnitude less than the flow rate predicted by formulae pertaining to the flow of coarse bulk solids. This discrepancy can be accounted for by the formation of adverse interstitial fluid pressure gradients which occur at the outlet during flow, Fig. 10 [36—38]. These gradients occur due to the increasing voidage of the bulk solid as it flows towards the outlet of the channel. Such increasing voidage requires an inflow of interstitial fluid induced by interstitial fluid pressure gradients within the flow channel. It is found that the majority of fluid flows in through the outlet; such a flow results from the formation of an adverse interstitial fluid pressure gradient in the vicinity of the hopper outlet. During the flow of fine bulk solids the presence of these adverse interstitial fluid pressure gradients becomes significant, greatly retarding the flow.

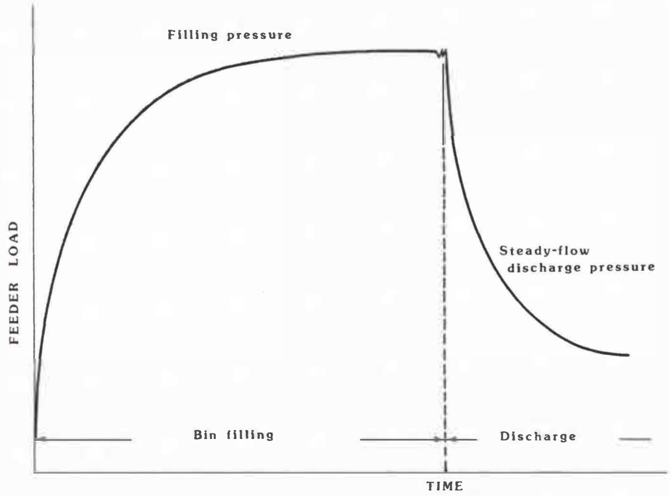


Fig. 10: Typical feeder load variation during bin filling and discharge [Ref. 30]

To prevent the formation of excessive negative void pressure developing in the vicinity of the outlet of the flow channel, interstitial fluid may be injected into the hopper at selected locations, thereby obtaining an increased flow rate. The quantity and pressure of the injected fluid must be determined so that fluidisation and flooding of the bulk solid is avoided and the unfavourable pressure gradients due to the injected fluid have little effect, Fig. 11.

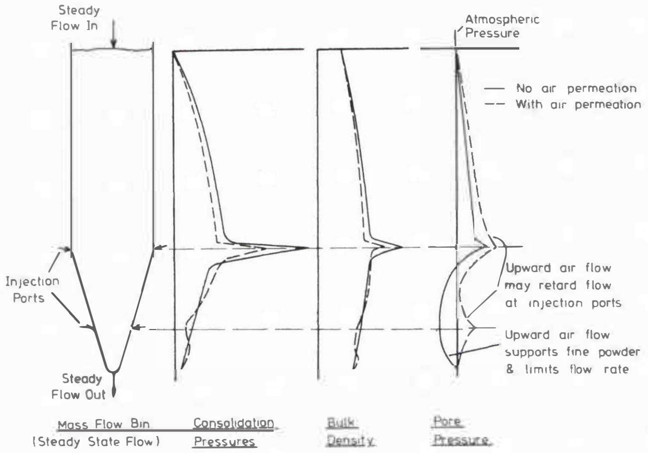


Fig. 11: Air permeation assists the flow of fine powders from *mass-flow* bins (after Reed [37])

Generally the required quantity of interstitial fluid is small and it must be injected at relatively low pressures. Work by various authors to date has indicated that the injection of interstitial fluid into a channel results in considerable improvements in the flow rate [36—38, 44, 45]. The work by Sutton and co-workers [44] indicated that the method of injecting the fluid is of secondary importance and their work also suggests that permeation techniques provide a reliable control method for regulating the flow of fine powders.

For monosize particulate powders, the retarding effects of the counterflow of interstitial fluid is suitably accounted for by fluid drag on individual particles. In this case the flow rate can be predicted by including individual particle fluid drag forces into the equation of motion for an individual particle. Such an analysis has been presented by Carleton [46]. A notable deficiency in the analysis by Carleton is that the individual fluid particle forces are evaluated for an isolated particle. A more appropriate analysis is possible by increasing the fluid drag factor by a multiple which accounts for the fluid drag in a suspension; however the extent by which this factor is increased requires an assumption as to the value of the voidage at the outlet, an appropriate value for which will be in debate for some time. The selection of this constant voidage value is further complicated by noting that voidage variations occur in the hopper during flow [48, 49]. The approach of Carleton cannot be readily extended to predict the interstitial fluid pressure distribution which acts during flow nor account for pressure and additive effects on the flow of bulk solids.

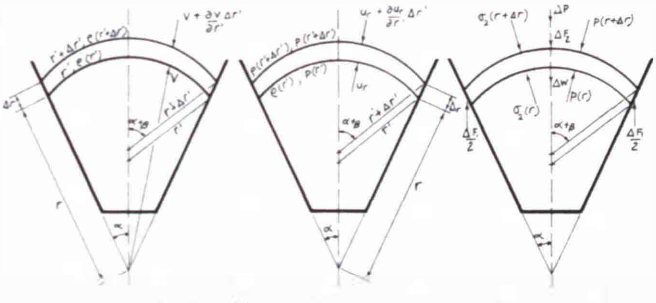
To take account of these pressure and additive effects on the flow of bulk solids, the flow of incompletely deaerated bulk solids and the flow of fluidised bulk solids have been modelled using semiempirical methods based on analogies with fluids [50—54].

Theories which both accounted for and predicted the magnitude of the interstitial fluid pressure distribution during the flow of fine bulk solids were apparent [55—57]. These models could also be readily extended to predict the flow of pressurised bin systems and degenerate to expressions describing the flow of coarse bulk solids by allowing the effects due to the interstitial fluid distributions to become negligible. The analysis of McLean [55] will now be outlined.

5.2 Analysis of the Flow of Fine Bulk Solids from Mass Flow Bins

An approximate prediction of the flow of fine bulk solids from converging channels may be obtained by considering the transportation equations for flow through a suitable element of bulk solid. The analysis is for steady flow from a converging mass flow channel with walls which are both rigid and impermeable. Further, the interstitial fluid flow is assumed to be isothermal and at constant density for the small variations in fluid pressure which occur. Logarithmic variations for both bulk density and permeability with consolidation, as suggested by Johanson [58], will be assumed to apply. The determination of the parameters used in these variations has been outlined in the book by Arnold et al. [4]. This analysis, which assumes that the bulk solid is simple, has been generalised for both plane flow and axisymmetric flow channels.

In this approximate analysis the bulk solid in the channel is considered to be composed of Enstad elements [59] along which the variables acting are assumed to be constant in magnitude and vary only in direction, Fig. 12. Further, the fluid flow is assumed to be perpendicular to the surface of the Enstad element, Fig. 12. The consideration of the continuity of both the interstitial fluid phase and the solid phase, together with the conservation of momentum of the solid phase in which the momentum change of the interstitial fluid is neglected [4, 55], results in three non-linear total differential equations which must be solved for the variables of flow, subject to the boundary conditions relevant to a general channel and subject to the material property variations applying. Since no analytical solutions to these equations exist, numerical procedures are required to solve the unknowns.



(a) Bulk Solid Continuity (b) Interstitial Gas Continuity (c) Equation of Motion

Fig. 12: Flow through an Enstad element in a *mass-flow* hopper

For engineering purposes a sufficiently accurate analytical solution to the flow equations is possible by assuming that the solid phase stress field during flow is adequately described by a power expression for channels with and without surcharge [20]. In this analysis the evaluation of the interstitial fluid pressure distribution requires the use of a step-wise integration technique. To date there are no theoretical procedures to predict values for the parameters used in the power expression for the bulk solid stress distribution. However, a sensititvity analysis [60] usually suggests suitable values for these parameters. The analysis results in a convenient expression for the bulk solid outlet velocity by noting that the equation of motion must be satisfied at the outlet. The actual magnitude of the velocity distribution and the interstitial fluid pressure distribution may then be predicted. The effects of pressurised bin systems can be accounted for by the appropriate inclusion of the imposed boundary conditions. The analysis degenerates to predict the flow of coarse bulk solids by allowing the effects of the adverse interstitial fluid pressure gradients to become negligible [55].

To indicate the applicability of the analysis outlined, the solid phase flow rate and interstitial fluid pressure distribution will now be evaluated, using material properties measured in straightforward laboratory measurements, for an experimental variable geometry plane flow bin in which the interstitial fluid is air. The favourable comparison between the predicted values and the observed values shown in Figs. 13 and 14 for the interstitial fluid distribution and flow rate variation with outlet width, suggests that this initial analysis is valid, although some improvements to the model are necessary.

These improvements include accounting for the extent of surcharge acting on the hopper, the degree of deaeration of the stored powder, and the degree of consolidation due to impact loads. The existing model may be used to predict sufficiently accurate values for air permeation techniques and may also be employed to predict the flow rate and interstitital pressure distribution in pressured bin systems. The work [60] to date utilising the analysis outlined indicates that both the injection of fluid into the channel and subjecting the material in the hopper to positive pressures is favourable. However, extension of this analysis to such bin situations and the modelling of the effects listed above is incomplete; considerable work is still required to model all bin situations.

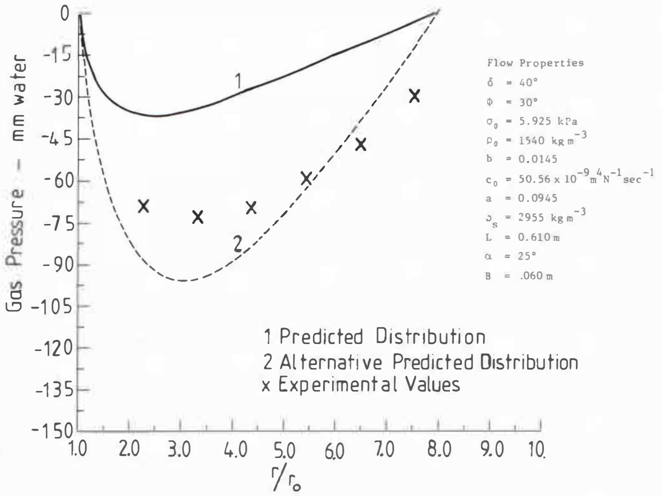


Fig. 13: Comparison of experimental and predicted gas pressure distributions in an experimental plane flow bin

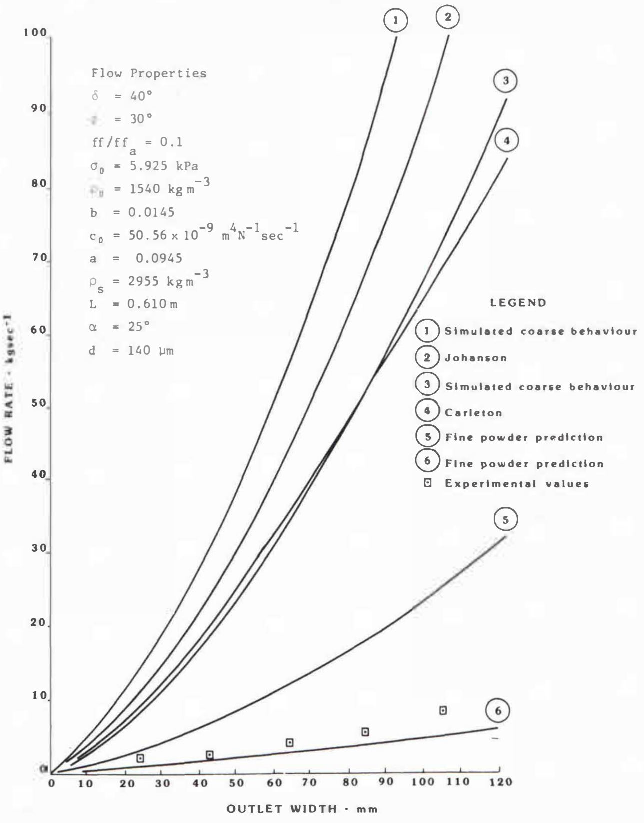


Fig. 14: Comparison of predicted flow rates with experimental values

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