Wall Pressure-Feeder Load Interactions in Mass Flow Hopper/Feeder Combinations

Part II

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Abstract

The interactive roles of mass flow bins and feeders are discussed. The effect of feeder speed, gate height, clearance between the hopper outlet and the feeder surface, method of filling, rate of filling on wall pressures in mass flow bins and feeder load and power requirements of the feeders are highlighted. Measurement of wall pressures suggests that initial pressures during filling are less than hydrostatic, hence initial loads on feeders are less than theoretically predicted. The higher experimental flow loads on the feeders are due to the fact that the measured values of wall pressures towards the vicinity of the outlet of the hopper diverge from the radial stress field theory of Jenike. On the basis of the above measurements, the values of K and n are computed and the bounds for initial filling are suggested. The flow loads are based on the major consolidating stress σ_1, which compares satisfactorily with the measured values. Finally, methods to control overloading of the feeders are discussed.

Nomenclature

a	—	gate height
A	—	area
B	—	hopper opening dimension and width between skirtplates
B_b	—	belt width
c	—	clearance between hopper and feeder
D	—	bin diameter or width
ff	—	flow factor
F_a	—	force to accelerate material onto belt
F_b	—	empty belt resistance
F_{be}	—	belt load resistance, extended section beyond hopper
F_{bh}	—	belt load resistance, hopper section
F_f	—	tangential force, flow condition
F_i	—	tangential force, initial condition
F_s	—	skirtplate friction
F_{spe}	—	skirtplate resistance, extended section beyond hopper
F_{sph}	—	skirtplate resistance, hopper section
g	—	acceleration due to gravity
h_c	—	surcharge head acting at transition of cylinder and hopper
h_o	—	distance from apex to transition of hopper
h_s	—	bin surcharge head
H	—	head of bulk solid in cylinder
H_h	—	height of hopper
H_s	—	actual bin surcharge
K	—	ratio of p_n/p_v for hopper
K_j	—	pressure ratio in Janssen equation
K_v	—	ratio of lateral to vertical pressure in skirtplate zone
L	—	length of slotted hopper opening in plane flow bin
L_c	—	length of conveyor
L_s	—	length of skirtplates
m	—	hopper shape factor; $m = 1$ for axisymmetric hopper, $m = 0$ for plane flow hopper
m_c	—	cylinder shape factor; $m_c = 1$ for square or circular cylinder, $m_c = 0$ for rectangular cylinder
m_s	—	surcharge factor; $m_s = 1$ for conical surcharge, $m_s = 0$ for triangular surcharge
n	—	factor of index in bin pressure distribution equation
p_n	—	normal wall pressure
p_v	—	average vertical pressure
P	—	power
q	—	nondimensional surcharge factor
q_f	—	nondimensional surcharge factor, flow condition
$q_{f\sigma_1}$	—	nondimensional flow surcharge factor based on σ_1
q_i	—	nondimensional surcharge factor, initial condition
Q	—	feeder load
Q_f	—	feeder load, flow condition
$Q_{f\sigma_1}$	—	feeder load based on σ_1
Q_i	—	feeder load, initial condition
R	—	hydraulic radius
v	—	belt velocity
w_b	—	belt weight per unit length
X, Y	—	factors in feeder load equations, flow condition
y_e	—	depth of bulk solid in skirtplate zone, extended section
y_h	—	depth of bulk solid in skirtplate zone, hopper section

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z — depth coordinates in hopper
α — hopper half-angle
β — angle in Eq. (17)
γ — bulk specific weight
δ — effective angle of internal friction
η — drive efficiency
μ — coefficient of friction
μ_2 — skirtplate friction coefficient
μ_b — belt idler friction
μ_i — coefficient of friction for bulk solid at feeder outlet
ξ — release angle
ϱ — bulk density
σ_1 — major consolidating pressure
σ_w — normal wall pressure
ϕ — wall friction angle.

Fig. 9: Comparison of theoretical and experimental feeder loads in plane flow bin and belt feeder test rig — material: plastic pellets

7. Experimental Results and Discussion

Experiments were conducted using the model perspex plane flow bin and flat bed belt feeder, as shown in Fig. 3, to examine the reliability of feeder load equations. Two bulk materials were handled, plastic pellets and white sand with different moisture contents. The effect of the filling rate, method of filling, feeder speed, gate height a and clearance c between the hopper outlet and the feeder surface on the feeder load, power requirements and wall pressures in the hopper have been investigated.

7.1 Initial Filling Conditions

In Fig. 9, the theoretical feeder loads as a function of the head H for the initial filling case have been plotted using Eq. (21) in conjunction with the nondimensional surcharge factor Eqs. (24), (25) and (26). In the case of Eq. (24), eight curves have been drawn for $n = 0$, 0.1, 0.2, 0.3, 0.4, 0.5, 1.5 and 3.0; the curve based on $n = 0$ is identical to that given by Eq. (25). The experimental results indicate that the initial feeder loads increase as the clearance between the hopper outlet and the feeder decreases; the larger clearance no doubt permits some redistribution of the pressure conditions at the outlet to provide a degree of cushioning. The influence of the rate of filling of the bin is quite significant; at the faster rate, the impact effect of the bulk solid discharging into the bin causes a greater degree of compaction.

Fig. 10 shows the theoretical feeder loads as a function of h_c for two types of filling: one filling directly from a chute and in the other case the chute feeding onto a distributer which evenly distributes the bulk solid along the length of the bin, as shown in Fig. 3. The hopper outlet was supported at two points which act as local stiffeners. The deflection of the skirt zone was recorded using linear voltage displacement transducers (LVDT).

Eqs. (24) to (27) and (29) have been plotted as shown. In the case of Eq. (24), curves have been drawn for the values of $n = 0$, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0 and 2.0.

The experimental results indicate that the initial feeder loads decrease as the bulk solid is evenly distributed using a distributer. This is due to the impact effects being absorbed in the distributer and the flow being uniform along the slot. Comparison of the experimental results with those based on
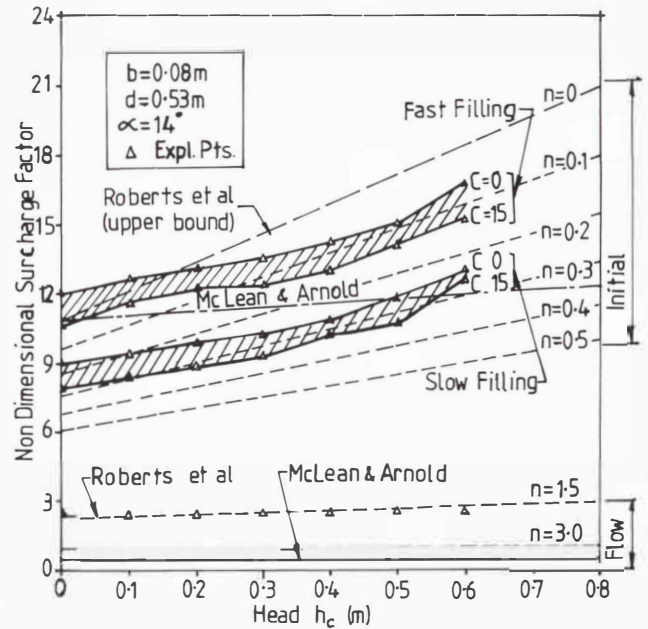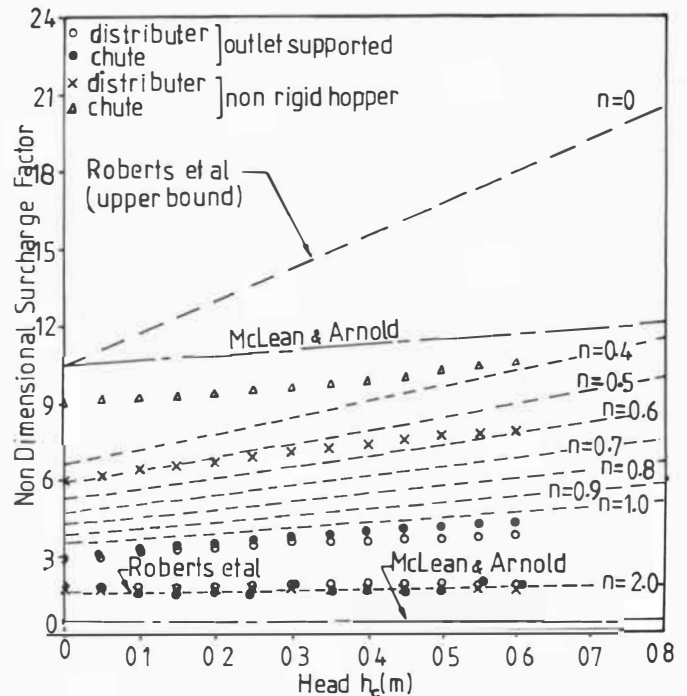

Fig. 10: Comparison of theoretical and experimental feeder loads in plane flow bin and belt feeder test rig — material: white sand

theory would indicate that feeder loads computed on the basis of Eqs. (24) or (25) with $n = 0$ be regarded as a possible upper bound. A satisfactory prediction of initial loads can be made by using Eq. (24) with appropriate values of n from Table 1.

Table 1: Initial filling conditions

Clearance C mm	Method of Filling	Rate of Filling	Hopper Wall Type	n	$K = K_{min}$
0	chute	fast	nonrigid	0.1—0.2	0.456—0.498
15	chute	fast	nonrigid	0.2—0.3	0.498—0.54
0	chute	slow	nonrigid	0.2—0.3	0.498—0.54
15	chute	slow	nonrigid	0.3—0.5	0.54 —0.623
15	chute + dist.	slow	nonrigid	0.7—0.9	0.69 —1.16
15	chute + dist.	fast	nonrigid	0.5—0.6	0.623—0.664

7.2 Flow Conditions

The theoretical predictions given by Eq. (27) underestimate the feeder loads. The comparison between the measured and predicted values based on the major consolidating pressure σ_1 for which Eq. (29) applies is quite satisfactory (Figs. 9 and 10).

8. Power to Shear Bulk Solid in Hopper

The total load on the feeder is computed from Eq. (21) using the appropriate value of the surcharge factor q from Eq. (24).

For a belt or apron feeder, the force to shear the material is given by:

$$F = \mu_i Q \tag{30}$$

The value of μ_i is given in Table 2.

Table 2: Values of μ_i

Researcher	μ_i
Reisner [3], Bruff [4]	0.4
Johanson [5], McLean and Arnold [10]	$\sin\delta$
Rademacher [13]	$0.8 \sin\delta$

Following Rademacher [12] and considering the quasi-static equilibrium of the bulk solid at the interfacial zone, the following expression for μ_i can be deduced:

$$\mu_i = \tan\left[\xi + \tan^{-1}\left(\frac{T-F_s}{Q-w}\right)\right] \tag{31}$$

where:

ξ — release angle
T — tangential load
F_s — skirt friction
Q — initial load
w — weight of the interfacial material.

Table 3 presents experimental values of μ_1 obtained using Eq. (31).

Table 3: Experimental values of μ_i obtained using Eq. (31)

Bulk Solid	Gate Height m	$\mu = \sin\delta$	Q_i kN	Q_{si} kN	μ_i	μ_i/μ %
Plastic pellets	0.02	0.6691	0.2524	0.1372	0.5433	81.15
	0.042	0.6691	0.2646	0.1176	0.461	69.02
	0.062	0.6691	0.2892	0.1367	0.514	76.8
	0.108	0.6691	0.2744	0.118	0.486	72.63

Current experimental investigations suggest that $\mu = \sin\delta$ overestimates and $\mu = 0.4$ underestimates the power requirements. Based on model analysis, $\mu = \mu_i$ is calculated from Eq. (31). It is noticed from Table 3 that $\mu_i = 0.7$ to 0.8 times $\sin\delta$ is a reasonable prediction.

The power to shear bulk solid at the hopper outlet is given by:

$$P = Fv \tag{32}$$

In addition to this power, component resistances and corresponding powers due to such factors as belts, skirtplates and gates must also be taken into account; they are discussed in Section 12.

9. Influence of Hopper Geometry on Feeder Loads — Effect of Varying α and B

For reliable and uninterrupted flow, it is recommended that a mass flow hopper be employed. The flow rate from mass flow hoppers depends on the hopper geometry, the wall lining material and the flow properties of the bulk solid. As commonly occurs in practice, the wall friction angle ϕ decreases with increase in the major consolidating pressure σ_1; a decrease in ϕ permits α to increase. At the same time, an increase in σ_1 in the flow stress field is accompanied by an increase in B. The net result is that the half-angle α will normally increase with the opening dimension B, the rate of increase being more pronounced at low values of B, with α approaching a constant value as B becomes larger, as shown in Fig. 11. For a plane flow hopper α is about $12°$ larger than for a conical hopper for the same value of B. The potential flow rate is quite significant, and while in some operations there is a need for high discharge rates, for the majority of cases the potential flow rate may be excessive, rendering the need to employ feeders as flow controlling devices.
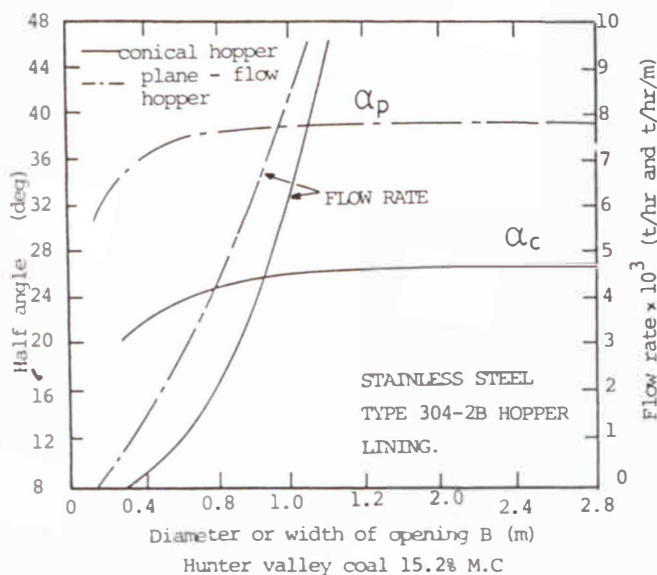

Fig. 11: Mass flow hopper geometries and flow rates for typical coal

By way of example, consider the wedge-shaped plane flow bin and belt feeder of Fig. 12. The bin, which is to handle
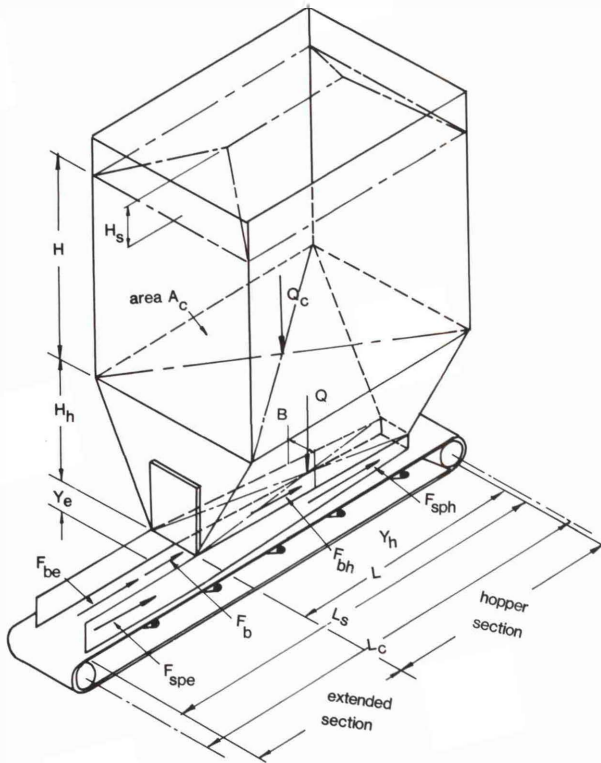
Fig. 12: Schematic arrangement of wedge-shaped bin and belt feeder

Fig. 13: Feeder load variations with hopper geometry for plane flow bin example

coal, is of mild steel, with the hopper being lined with stainless steel type 304 with 2B finish. The relevant details are:

1. *Bin*

Height H	8.0 m
Width D	5.0 m
Length L	5.0 m
Surcharge H_s	1.5 m

The hopper height H_h, half-angle α and opening dimension B are to be varied in accordance with the flow properties of the coal.

2. *Coal*

Effective angle of internal friction δ	50°
Angle of friction between coal and mild steel ϕ	30°
Angle of friction between coal and stainless steel ϕ	18°
Bulk density ϱ	0.95 t/m³

The coal flow properties permit α and B to be varied in accordance with Fig. 13. The changes in surcharge factors q_i and $q_{f\sigma_1}$ are also shown in Fig. 13; q_i has been determined using Eq. (25). The feeder loads Q_i and $Q_{f\sigma_1}$ determined in accordance with the methods outlined are shown plotted in Fig. 13. The decrease in Q_i and $Q_{f\sigma_1}$ with increase in α and B to maintain mas flow is clearly evident. However, the ratio $Q_i/Q_{f\sigma_1}$ increases with decrease in B.

10. Controlling the Feeder Loads

Once the flow has been initiated and the feeder stopped, the load on the feeder does not revert to the original initial load, but remains almost equal to the flow load during which an arched stress field exists. This concept leads to the genera-
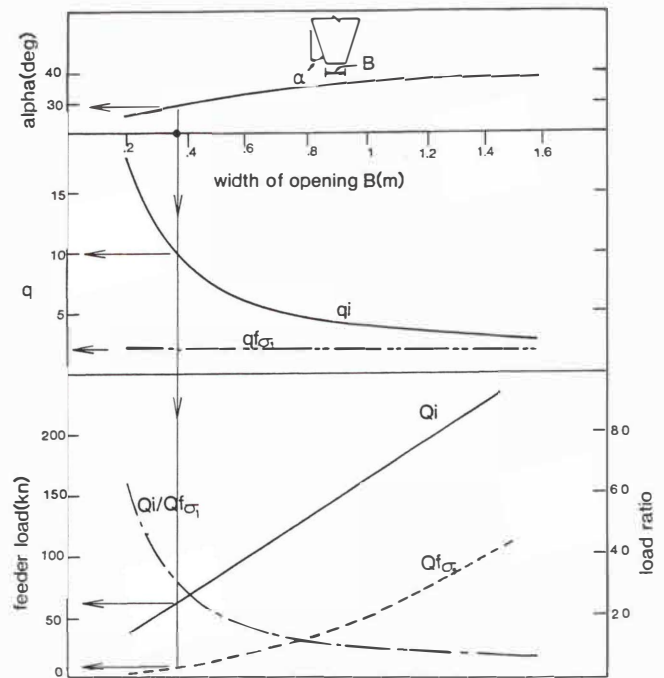
tion and maintenance of an arched stress field in the hopper during filling. The methods proposed to control the feeder loads, with each method having been thoroughly investigated, are:

1. Slow feeder motion during filling
2. Feeder flexibility
3. Retaining a cushion of material.

10.1 Slow Feeder Motion during Filling

Slow motion of the feeder is possible in all the feeders with stepped speed control, and it is a simple means of controlling the feeder loads. Fig. 14 shows that the loads generated during filling are almost equivalent to the loads during flow. Even a slight motion of the material is enough to create an arched stress field in the hopper section.
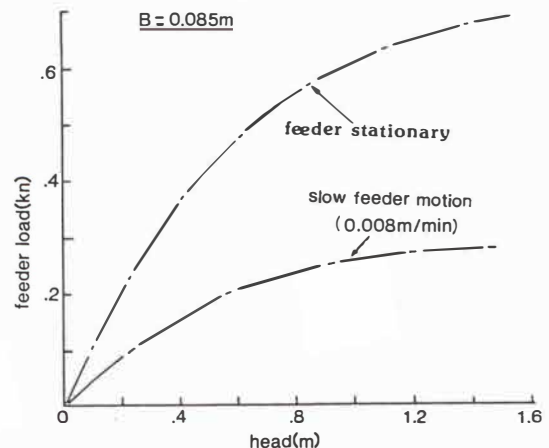

Fig. 14: Reduction of initial feeder load due to very slow running of the feeder during filling for the model test rig

10.2 Feeder Flexibility

The loads which act on the feeders are very much dependent on the clearance between the hopper outlet and the feeder and the flexibility of the feeder supports. If the feeder is firmly attached to the hopper and the bulk solid within the feeder is contained by closely fitted skirts, the load is close to the hydrostatic value. If the feeder supports are flexible and deflect more than the hopper as the bin is filled, the loading on the feeder is significantly reduced, as shown in Fig. 15. The slight movement of the material when the feeder is displaced is equivalent to some of the material being withdrawn from the hopper, and the loading shifts partly towards dynamic values.
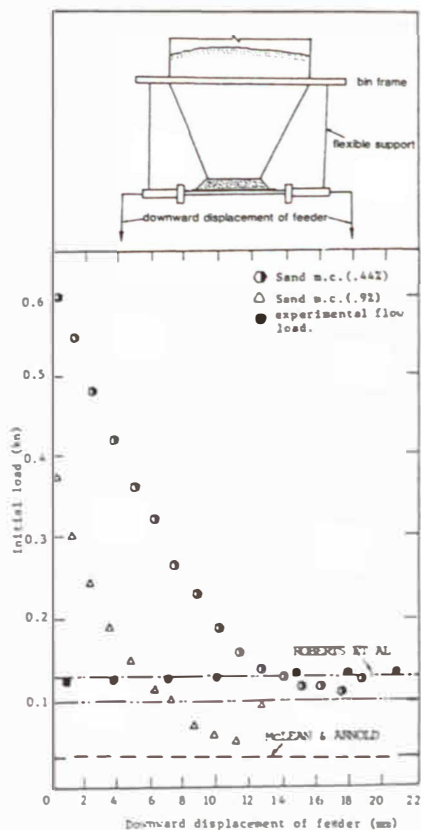

Fig. 15: Reduction of initial feeder load due to downward displacement of the feeder

10.3 Effects of Cushioning

The high initial loads which act on feeders are a matter of some concern, and possible steps should be taken to reduce the magnitude of these loads, which has been demonstrated by Roberts et al. [26]. Fig. 16 presents experimental results for the model plane flow bin and belt feeder using sand. Computed nondimensional surcharge factors are compared with the theoretical results. The reduction of the initial loads due to cushioning is quite significant. This is because the material left in the hopper, having previously been in motion, will preserve an arched stress field. The new material being deposited will have a peaked stress field. This will provide a surcharge load on the arched stress field, but the magnitude of the load at the outlet will be of a lower order than if the bin is totally filled from empty condition. It is noticed that the experimental values are higher than the theoretical curve as
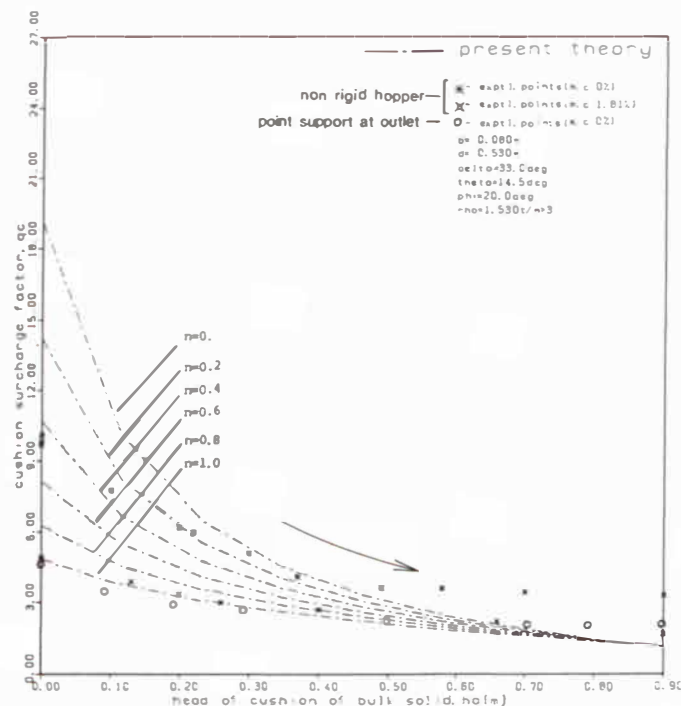

Fig. 16: Influence of "cushioning" on initial feeder loads

the head h_a of the cushion of bulk solid is increased. This is certainly due to the redistribution of the stress field at the interfacial zone of the hopper and feeder. Further, the theoretical analysis does not take into account the acceleration of the layer [15]; the increase in the bulk density of the flowing bed due to sudden stoppage of the feeder results in higher loads than the fully developed dynamic values. In the theoretical analysis, the material is assumed to be fully plastic, which gives rise to lower bound values. The other reason being the clearance between the feeder and the hopper outlet, the material weight in this interfacial zone and on the feeder has to be considered. Hence a correction factor is introduced which takes account of the weight of the material in the interfacial zone and on the feeder and the rate of change of the momentum during filling the bin.

The condition for the minimum height of cushion is given by:

$$\frac{dp_v}{dz} = 0 \qquad (33)$$

Based on this, it is possible to derive an expression for the minimum height of the cushion to achieve almost flow loading conditions:

$$z \leqslant h_0 - n\, q_{f\sigma_1} (4/\pi)^m B \qquad (34)$$

where the value of n is to be computed from $K = K_{max}$ and $q_{f\sigma_1}$ is given by Eq. (24).

11. Effect of Hopper Wall Rigidity on Feeder Design

The hopper wall deflection is proportional to the head of the bulk solid contained within. Accordingly, the hopper walls are classified into rigid and nonrigid types, based on the magnitude of the normal wall stress p_n exerted on them

being hydrostatic or less. Static stresses more than hydrostatic are physically not possible. Based on the experimental investigations, it is found that the feeder load and power requirements reduce significantly as the hopper wall becomes nonrigid, forcing the channel boundary to be flexible. This results in economical and less troublesome feeder design and performance requirements. Further, any deflection of the hopper wall before start-up to relieve the arches at the outlet has a detrimental effect on the operation and maintenance of the feeder, and the initial load and power requirement to shear the bulk solid at least doubles. This is due to sudden slippage of bulk solids at the walls, which acts as shock loading on the feeder. Fig. 17 shows the effects of rigidity on wall pressures and feeder loads.
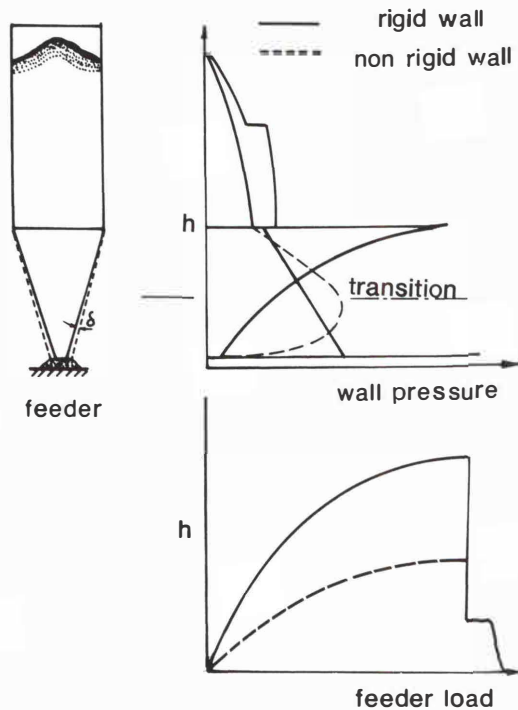

Fig. 17: Effect of rigidity of the hopper wall on wall pressures and feeder loads

By way of illustration, Fig. 18 shows the predicted wall pressures, based on a rigid hopper, and the corresponding measured values for the model plane flow bin and feeder of Fig. 3. Despite the fact that the hopper walls of the model were well supported, a small amount of movement did occur. This explains why the initial pressures in the hopper vary from the hydrostatic based values, particularly towards the hopper outlet where the measured values are significantly lower. The measured flow pressures also show a departure from the predicted values, being lower towards the transition and higher towards the outlet. Other tests using the model bin in which the walls had greater flexibility have indicated a more pronounced "bulge" in the initial pressure curve of the type illustrated in Fig. 17.

12. Total Power Requirements for Belt Feeders

For a complete feeder design, the total power for the initial and flow cases needs to be determined. In addition to the
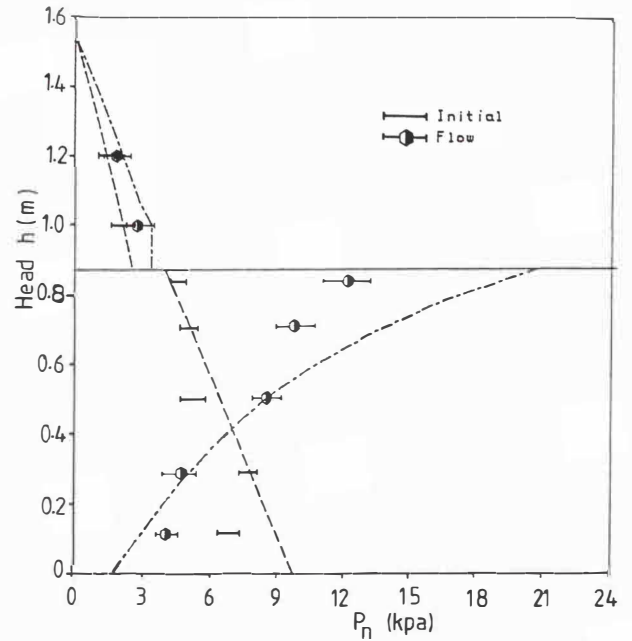

Fig. 18: Normal wall pressure measurement, initially and during flow —
bin: $D = 0.53$ m, $B = 0.08$ m, $H = 0.63$ m;
material: $\delta = 33°$, $\phi = 20°$, $\varrho = 1.52$ t/m³

feeder loads and the corresponding power to "shear" the bulk solid, consideration will need to be given to the other resistances to be overcome in order to operate the feeder. In the case of belt feeders, for example, the influence of skirt-plates and belt resistances must be taken into account, and this is illustrated by a design example in Section 12.2.

12.1 Design Equations for Belt Feeders

By way of illustration, the power requirements for a dump hopper and belt feeder of the type illustrated in Fig. 12 are now considered. The design equations are summarised in the following [26].

12.1.1 Bin and Hopper Surcharge and Corresponding Power

These are determined in accordance with the methods described in Section 6.

12.1.2 Skirtplate Resistance

Assuming steady flow, the skirtplate resistance is determined for the hopper section and for the extended section (see Fig. 12). The pressure distributions for the skirtplate sections are illustrated in Fig. 19.

Neglecting the vertical supports y_h and y_e due to the skirt-plates, the skirtplate resistance is given by:

— for the hopper section:

$$F_{sph} = \mu_2 K_v (2Q + \varrho g B L y_h) y/B \qquad (35)$$

— for the extended section (section beyond hopper):

$$F_{spe} = \mu_2 K_v \varrho g (L_s - L) y_e^2 \qquad (36)$$

where:

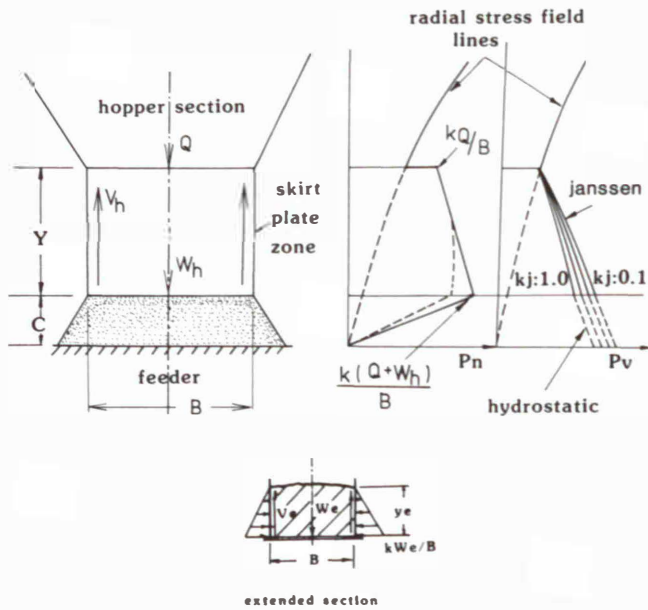Q — feeder loads as determined by Eq. (21)
ϱ — bulk density

Fig. 19: Skirt zone pressure distributions

y_h — average height of material against skirtplates for hopper section

y_e — average height of material against skirtplates for extended section

K_v — ratio of lateral to vertical pressure at skirtplates

g — acceleration due to gravity; $g = 9.81$ m/s²

B — width between skirtplates

μ_2 — skirtplate friction coefficient

L_s — total length of skirtplates.

The pressure ratio K_v is such that $0.4 \leqslant K_v \leqslant 1.0$. The lower limit may be approached for the static case and the upper limit for steady flow.

12.1.3 Belt Load Resistance

The belt load resistance is given by:

— for the hopper section:

$$F_{bh} = (Q + \varrho \, g \, B \, L \, y) \, \mu_b \tag{37}$$

— for the extended section:

$$F_{be} = \varrho \, g \, B \, (L_s - L) \, y \, \mu_b \tag{38}$$

where:

μ_b — idler friction; $\mu_b \approx 0.02$.

12.1.4 Empty Belt Resistance

$$F_b = w_b \, L_b \, \mu_b \tag{39}$$

where:

w_b — belt weight per unit length

L_b — total length of belt.

12.1.5 Force to Accelerate Material onto Belt

$$F_A = Q_m \, v \tag{40}$$

where:

Q_m — mass flow rate

v — belt speed.

It is assumed that:

$$Q_m = \varrho \, B \, y \, v \tag{41}$$

Usually, the force F_A is negligible.

12.1.6 Initial and Flow Loads and Powers

The foregoing loads and resistances are determined for the initial and flow conditions using the appropriate values of the variables involved.

The power is computed from:

$$P = (\textstyle\sum Resistances) \, \frac{v}{\eta} \tag{42}$$

where:

η — efficiency

v — belt speed.

The condition for non-slip between the belt and the bulk solid under steady motion can be determined as follows:

$$\mu_3 \, (Q_f + W) \geqslant F_f + F_{sp} \tag{43}$$

where:

μ_3 — coefficient of friction between belt and bulk solid

Q_f — flow surcharge at hopper outlet

W — weight of bulk material between skirtplates in hopper section of conveyor

F_f — force to shear material at hopper outlet

F_{sp} — skirtplate resistance.

A design example is presented in the next section, taking into account the above design equations.

12.2 Design Example — Feeder Loads and Power Determination [26]

12.2.1 Design Data

Bin Details:

Type of hopper	plane flow
Hopper opening dimension B	1.50 m
Bin diameter or width D	5.00 m
Height of cylinder H	8.00 m
Cylinder surcharge H_s	1.50 m
Height of hopper H_h	2.50 m
Hopper half-angle α	35°
Length of outlet slot L	5.00 m

Belt Feeder Details:

Feeder speed v	0.50 m/s
Length of skirtplate L_s	20.00 m
Average height of skirtplate z	0.50 m
Pressure ratio K for initial case	0.40
Pressure ratio K for flow, hopper section	1.00
Pressure ratio K for flow, belt section	1.00
Length of feeder L_b	20.00 m
Belt width B_b	2.00 m
Drive efficiency E_{ta}	90 %
Skirtplate friction angle ϕ_s	30°
Belt idler friction coefficient U_b	0.03

Bulk Solid Flow Properties:

Effective angle of internal friction δ	50°
Wall friction angle for cylinder ϕ_c	30°
Wall friction angle for hopper ϕ_h	18°
Bulk density ϱ	0.95 t/m³

12.2.2 Feeder Loads and Power Requirements

Hopper Surcharge, Loads and Power:

Bin surcharge Q_c/A_c	40.53 kPa
Initial surcharge factor q_i	2.54
Flow surcharge factor q_f	1.05
Feeder load, initial condition, Q_i	265.89 kN
Tangential load, initial condition, F_i	162.94 kN
Feeder load, flow condition, Q_f	109.84 kN
Tangential load, flow condition, F_f	67.31 kN
Feeder power, initial condition, P_i	81.47 kW
Feeder power, flow condition, P_f	33.66 kW

Skirtplate and Belt Resistances:

Skirtplate resistance, initial condition:	
— hopper section, $F_{sph,i}$	43.63 kN
— extended section, $F_{spe,i}$	8.07 kN
Belt load resistance, initial condition:	
— hopper section, $F_{bh,i}$	9.03 kN
— extended section, $F_{be,i}$	3.15 kN
Skirtplate resistance, flow condition:	
— hopper section, $F_{sph,f}$	49.00 kN
— extended section, $F_{spe,f}$	20.18 kN
Belt load resistance, flow condition:	
— hopper section, $F_{bh,f}$	4.34 kN
— extended section, $F_{be,f}$	3.15 kN
Empty belt resistance F_b	1.41 kN
Force to accelerate material F_a	0.09 kN

Total Resistance and Power for Belt Feeder:

Total resistance, initial, $F_{tot,i}$	229.73 kN
Total resistance, flow, $F_{tot,f}$	146.90 kN
Total power, initial, $P_{tot,i}$	127.63 kW
Total power, flow, $P_{tot,f}$	81.61 kW

13. Summary of Conclusions

Based on the work reported in this paper, the following conclusions may be stated:

1. To achieve the most reliable feeding of bulk solids, mass flow hoppers should be used in conjunction with feeders. This will ensure reliable flow, provided the feeder geometry is such that uniform draw of material is achieved with a fully active hopper outlet.
2. Eq. (24) is recommended for determining the initial loads on feeders, provided an appropriate value of n is used. However, for simplicity, Eq. (26) may also be used.
3. Eq. (29) is recommended to compute the loads on feeders under flow conditions.
4. In order to reduce feeder loads and the corresponding power requirements during start-up, some form of cushioning in the hopper is recommended. Also, nonrigid skirt zones may be employed in order to reduce feeder loads. Methods of controlling feeder loads are discussed in Section 10.

5. The value of $\mu_i = 0.8 \sin\delta$ is recommended to calculate the force to shear the bulk solid in the hopper.

Acknowledgements

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