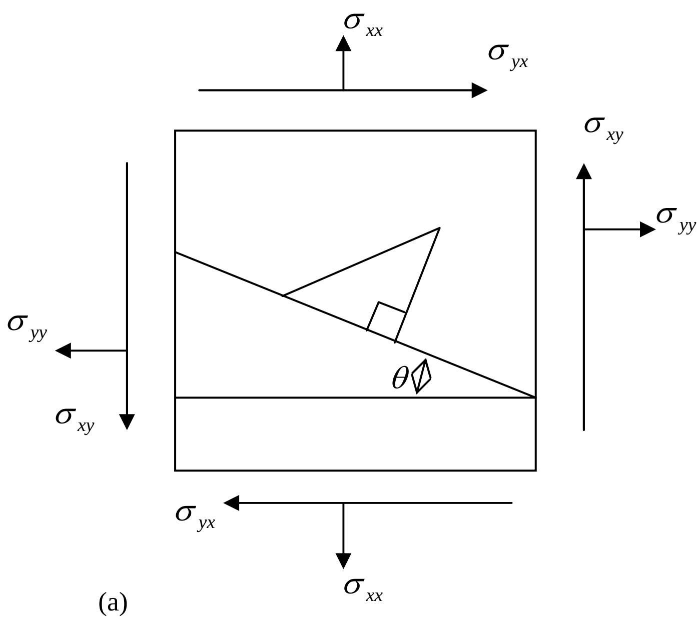
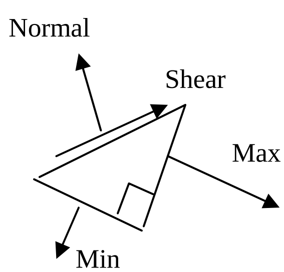
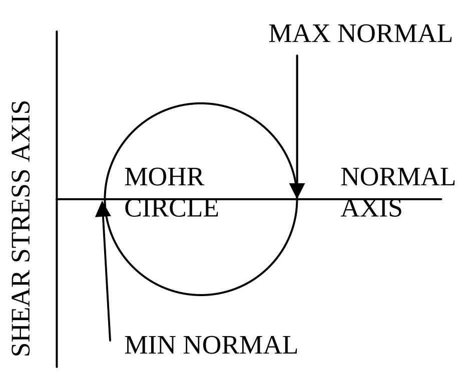
HANDOUT 10-1



(a)

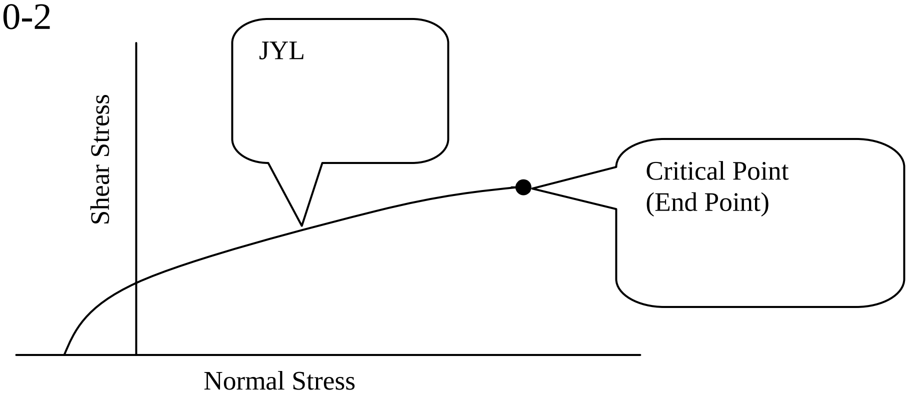
(b)

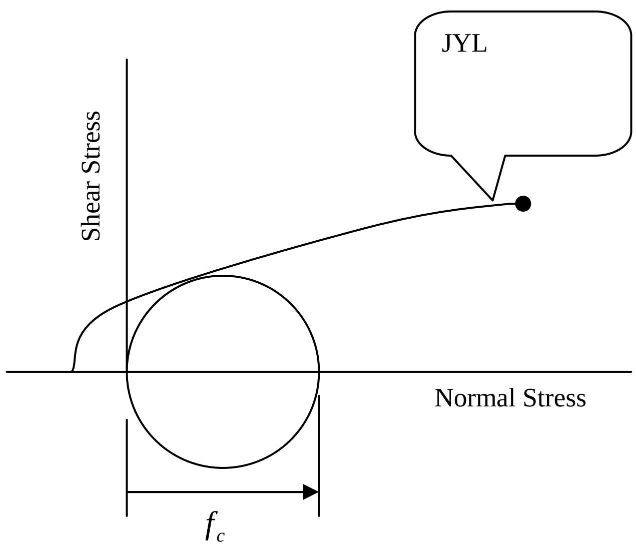


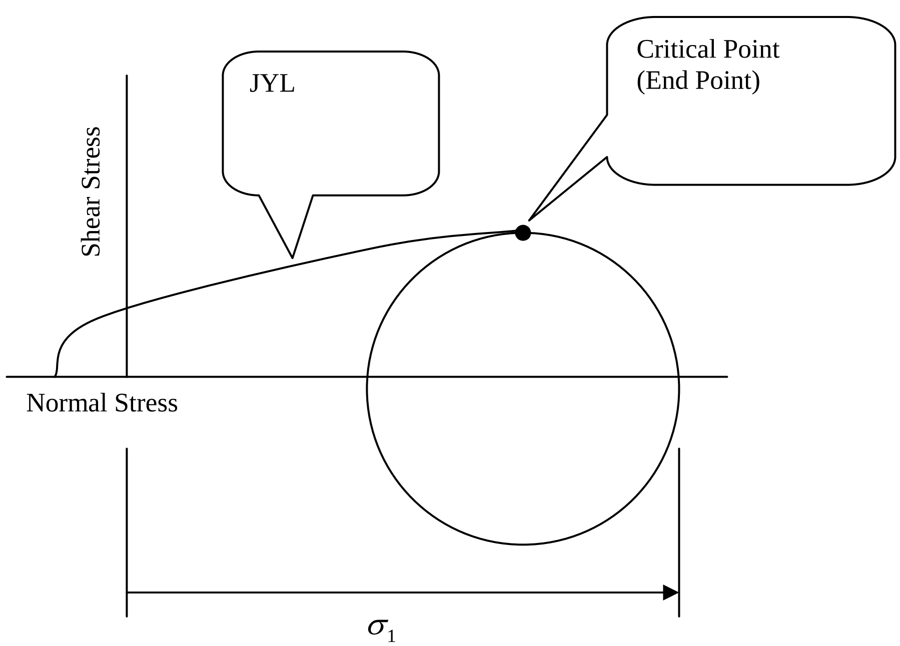


(c)

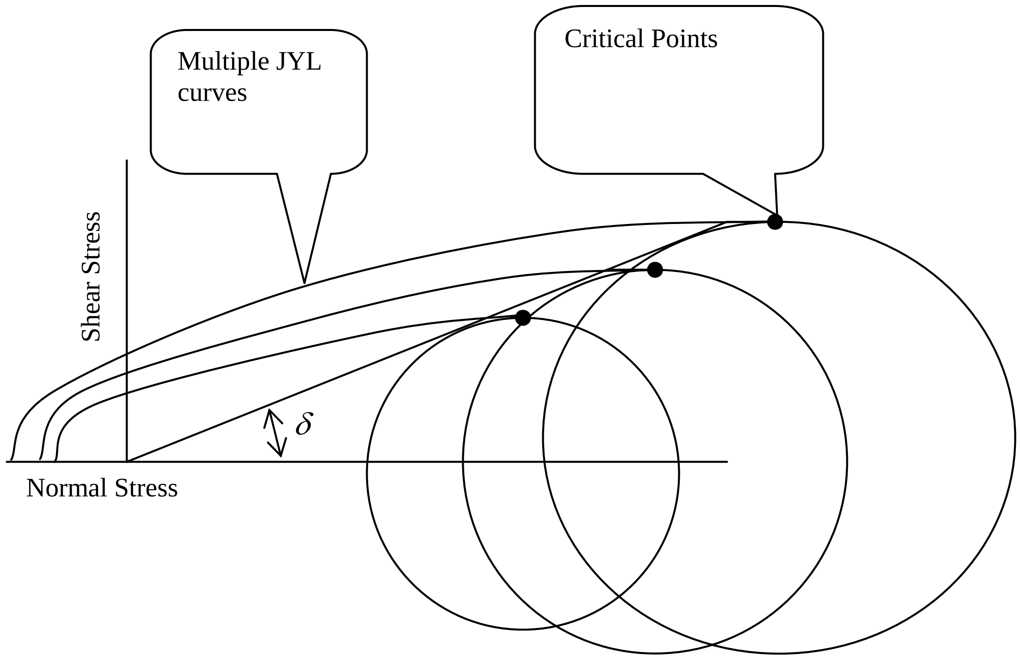
HANDOUT 10-2

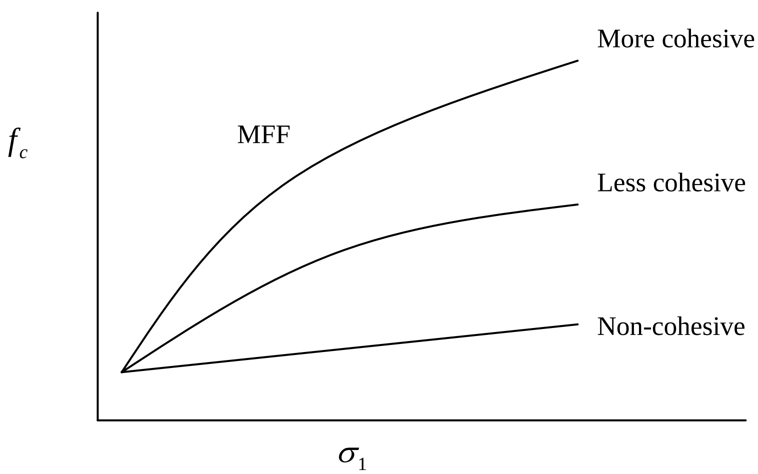

JYL
Critical Point
(End Point)
Shear Stress
Normal Stress


JYL
Shear Stress
Normal Stress
f_c


Critical Point
(End Point)
JYL
Shear Stress
Normal Stress
σ_1

HANDOUT 10-3


Multiple JYL curves
Critical Points
Shear Stress
δ
Normal Stress


More cohesive
MFF
f_c
Less cohesive
Non-cohesive
σ_1

HANDOUT 10-4

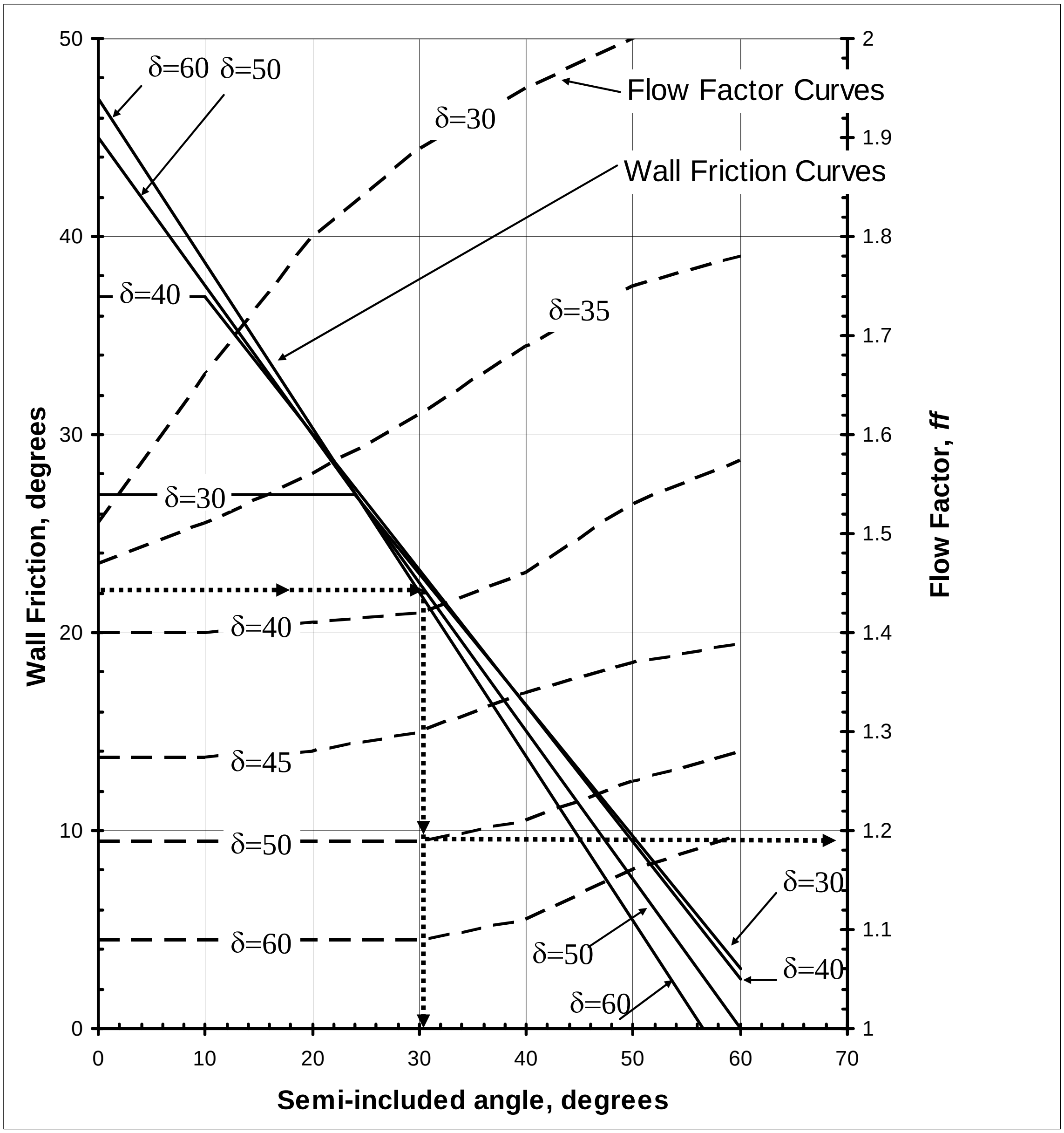


Figure 10-17. Design chart for symmetrical slot outlet hoppers. For example (dashed arrows), $\delta_w = 22^\circ$ and $\delta = 50^\circ$ gives $\theta = 30.5^\circ$ and $ff = 1.19$.

HANDOUT 10-5

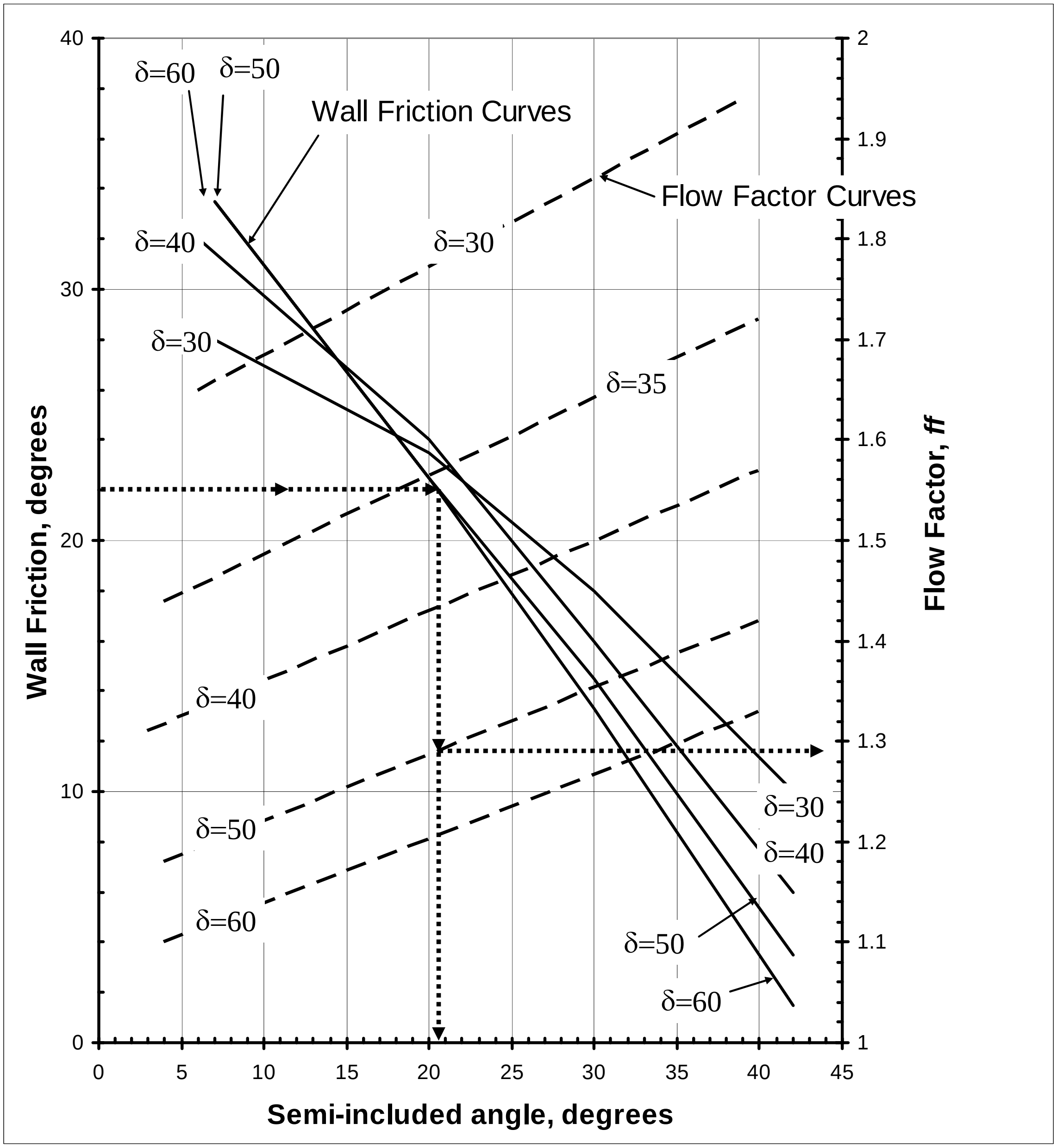


Figure 10-18. Design chart for conical outlet hoppers. For example, $\delta_w = 22^\circ$ and $\delta = 50^\circ$ gives $\theta = 20.5^\circ$ and $ff = 1.29$.

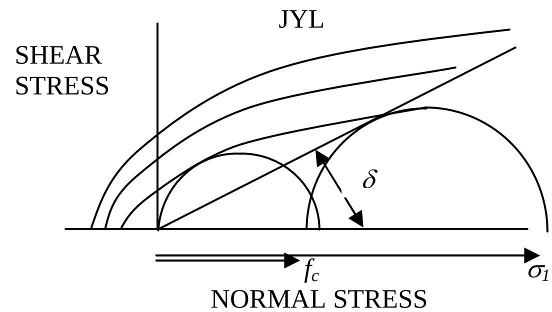
HANDOUT 10-6

Steps on using the shear stress data to design a hopper.

1. Rotating Shear Test

   Plot SHEAR STRESS
   vs
   NORMAL STRESS

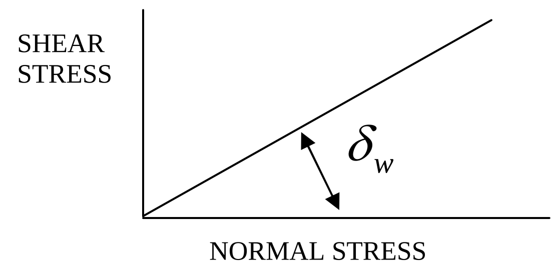
   Internal Friction
   Get f_c vs σ_1
   Get δ



2. Rotating Shear Test

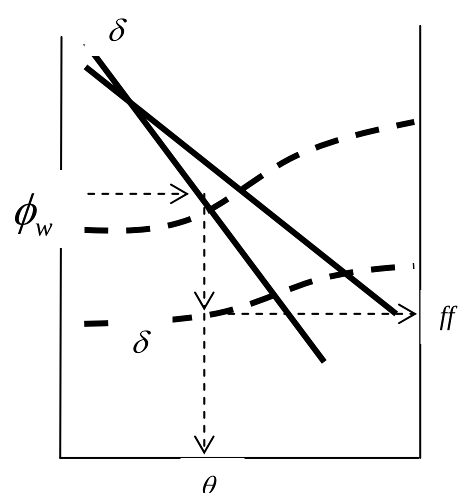
   Wall material

   Get δ_w



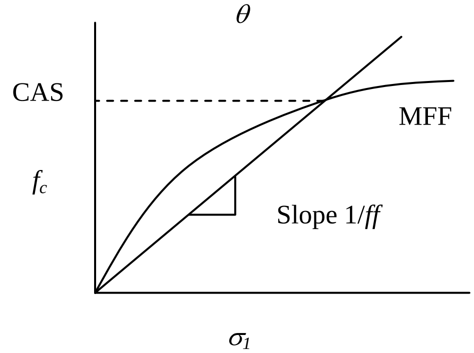
3. Fit ϕ_w and δ to hopper correlation

   Get θ and *ff*.
   (θ is the theoretical angle of the hopper; in final design subtract 3 degrees for margin of safety)



4. Plot 1/*ff* on mff curve (f_c vs σ_1) to get CAS

   Get CAS



5. Use CAS and θ in correlations to select opening size.

HANDOUT 10-7

For conical hoppers, Figure 10-20, the opening diameter, D, is given by

$$D = H(\theta)\frac{CAS}{\rho^{o} g / g_c} \qquad (10\text{-}12)$$

$$H(\theta) = 2 + \frac{\theta}{60} \qquad (10\text{-}13)$$

Where θ is in degrees, from the charts in Figures 10-17 or 10-18. Typical values for H are about 2.4.

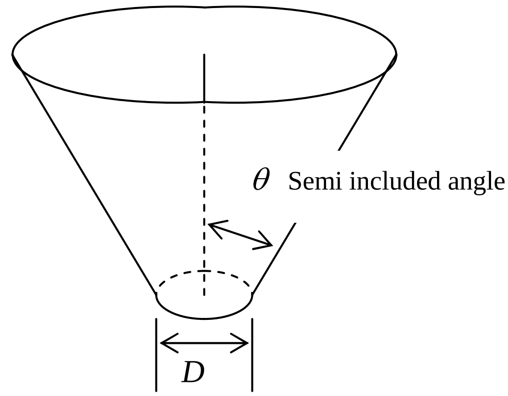


Figure 10-20. Conical Hopper with outlet size *D* and semi included angle θ.

For symmetrical slot outlet hoppers the opening size is determined from

$$W = H(\theta)\frac{CAS}{\rho^{o} g / g_c} \qquad (10\text{-}14)$$

$$H(\theta) = 1 + \frac{\theta}{180} \qquad (10\text{-}15)$$

$$L > 3W \qquad (10\text{-}16)$$

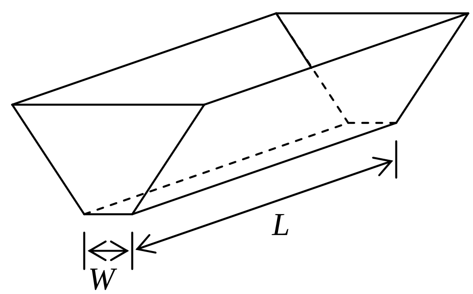


Figure 10-21. Symmetrical slot outlet hopper of opening size *W* x *L*.

HANDOUT 10-8

10.4.1 COARSE PARTICLES (particles > 500 microns in diameter)

MASS FLOW – JOHANSON EQUATION

$$\dot{m} = \rho^o A \sqrt{\frac{Bg}{2(1+m)Tan(\theta)}} \qquad (10\text{-}17)$$

where θ = semi included angle of the hopper

$\dot{m}$ = discharge rate (kg/sec)

ρ^o = bulk density (kg/m^3)

g = gravity acceleration (9.807 m/s^2)

Table 10-3. Parameters in the Johanson Equation, Eq.(10-18)

Parameter	**Conical hopper**	**Symmetric slot hopper**
B	*D*, diameter of outlet	*W*
A	$\frac{\pi}{4}D^2$	*WL*
m	1	0

FUNNEL FLOW – BEVERLOO EQUATION

$$\dot{m} = 0.58\rho^o g^{0.5}(D - kd_p)^{2.5} \qquad (10\text{-}18)$$

where d_p = particle diameter (m)

k = constant, typically 1.3 < *k* < 2.9 with *k* = 1.4 if not discharge rate data are available.

$$D = \frac{4(\text{cross sectional area})}{(\text{outlet perimeter})}$$

10.4.2 FINE PARTICLES (d_p < 500 microns)

CARLETON EQUATION

$$\frac{4V_o^2 \sin\theta}{B} + 15\frac{\rho^{1/3}\mu^{2/3}V_o^{4/3}}{\rho_p d_p^{5/3}} = g \qquad (10\text{-}19)$$

$$\dot{m} = \rho^o A V_o$$

where V_o = average velocity of solids discharging (m/s)

A, *B* = given in Table 10-3

ρ, μ = air density and viscosity

ρ_p = particle density

ρ^o = bulk density of the powder bed