HYPERBOLIC HOPPER OUTLET MEANS

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This invention relates to devices normally utilized in conjunction with bunkers, bins or silos holding bulk materials and, more specifically, the instant invention pertains to hopper outlet devices especially designed for use with coal bunkers located in electric power stations.

To those skilled in this art it is well known that the discharge of coal or other bulk materials from conventional bunkers, bins or silos and other similar devices frequently develop chokes at their outlet ends which impedes the free flow of the material therefrom and forms what is known as a "rathol." On still other occasions, the materials form, adjacent the discharge end of the hopper, an "arch" or "bridge" which effectually plugs the discharge end and completely stops the material flow. This is particularly true in the handling of bulk materials such as, for example, fine coal when wet or compacted. Again, the same difficulty is encountered with the discharge of fine coal mixed with clay making the same sticky or adherent to further impede the free flow thereof. Then too, in large sized bunkers, the vertical height of the coal column tends to, and often does, compact itself at the discharge end thereof and choke off the material flow. These are serious problems to steam engineers and the same has moved more prominently into the forefront in recent years since coal has become finer and is mixed with greater proportions of clay and other materials than heretofore.

In conventional steam power plants, it has been found that the enlargement of the discharge opening does, to some extent, relieve the tendency of the coal to choke. However, in conventional installations, the optimum dimension of the opening is determined by the inlet size of the coal receiving apparatus disposed thereof. And other approaches to the solution of this problem has been made with but little success in practical application, the same comprising the increase in the slope of the hopper walls to an angle of 75 degrees (or more) from the horizontal.

The prior art teaches other proposed methods and apparatus for solution of this vexing engineering problem to no practical avail. For example, it has been proposed to attach mechanically, electrically or pneumatically operated vibrators to the hopper walls at points thereon where the choke is frequently engaged. Still another proposed solution contemplates the vibration of a flexibly mounted hopper, per se. All of these attempted resolutions of the problem immediately at hand are, for the most part, impositive in operation, require power to operate, and, of course, are subject to considerable maintenance work which adds to the overall operational costs. For example, should the vibrator or agitating device be located within the hopper and require repair, it is first necessary to remove all of the coal from the bunker before initiating any repairs on the vibratory apparatus.

There are two other flow promoting devices presently available on the open market, one of which is a pneumatically operated slide gate. Briefly, this device consists of a flexible panel bonded to the back of a steel plate forming a part of the undersides of the bunker and hopper. Compressed air is alternately admitted and exhausted between the plate and the panel causing the latter to pulsate. Several of such units are installed on the inside walls of the hopper and operate to push the coal in order to prevent bridging or funneling from forming. In actual tests, the device proved that the coal flow stoppage was reduced but not eliminated; the other of the last mentioned devices employs a capped cone suspended above the discharge opening to retard the center core of coal flow. These two devices have not been widely accepted by industry inasmuch as they too are mechanically inefficient and inept for achieving the desired free flow of coal through the discharge opening.

Accordingly, one of the primary objects of this invention is to provide a hopper outlet device for a conventional bunker which will obviate the above objectional features of existing known prior art devices.

Another object of this invention is to provide a hopper outlet device for a conventional bunker or bin for coal and other bulk materials such as grain, sand, gravel, crushed rock, and pulverulent materials like powdered cement, fly-ash, flour, and powdered plastics, the improved hopper outlet being readily secured to or substituted for present existing conventional hopper outlets.

A further object of this invention is to provide a generally hyperbolically shaped hopper outlet device for insuring the free flow of coal or other bulk material therefrom, the improved hopper outlet device being simple in construction and involving no moving parts thereby reducing wear and maintenance of the hopper.

Still another object of this invention is to provide a hyperbolically shaped hopper outlet device which requires no power consumption to maintain a free flow of bulk materials therefrom.

This invention contemplates, as a still further object thereof, the provision of a hyperbolically shaped hopper outlet device for coal bunkers or bins for other bulk material, the hopper outlet device being simple in construction and assembly, inexpensive to manufacture and maintain, and durable in use.

A further object of the invention is to provide a hopper outlet device for a conventional bunker or bin for bulk materials which will provide an increased rate of flow of materials therefrom as contrasted to the rate of flow of materials through a conventional hopper having straight side walls.

It is a further object of the invention to provide a hopper design wherein the pressure of the material at the hopper outlet is substantially constant regardless of the height of the material above the hopper, resulting in more uniform density and flow of material.

Other and further objects and advantages of the instant invention will become more evident from a consideration of the following specification when read in conjunction with the annexed drawings, in which:

FIGURE 1 is a side elevational view of a conventional coal bunker or bin for other bulk material having connected thereto a hyperbolic hopper outlet device constructed in accordance with the teachings of this invention, FIGURE 1 being partially in cross-section;

FIGURE 2 is a bottom plan view of the coal bunker or bin for other bulk material and hyperbolic hopper discharge device shown in FIGURE 1;

FIGURE 3 is a graphic presentation illustrating the structural differences in shape between hopper outlet devices constructed in accordance with the invention and the conventional hopper outlet;

FIGURE 4 is a graphic presentation illustrating the rate of contraction of area in percent per foot of descent for conventional hopper outlet devices as contrasted to hopper outlet devices constructed in accordance with the invention;

FIGURE 5 is a graphic presentation of the involved wall friction factors as determined per foot of descent; and

FIGURE 6 is a graphic presentation illustrating the rate of coal flow, in percent per foot of descent for conventional hopper outlet devices as contrasted to hopper outlet devices constructed in accordance with the invention.

FIGURE 7 is a graphic presentation illustrating the rate of airflow, in percent per foot of descent for conventional hopper outlet devices as contrasted to hopper outlet devices constructed in accordance with the invention;
FIGURE 6 shows the curve for an equilateral hyperbola; and FIGURE 7 is a graphical presentation illustrating the differences in length and shape between hopper outlet devices constructed in accordance with the invention.

Referring now more specifically to the drawing, reference numeral 10 designates, in general, a conventional bunker, bin or silo having a substantially rectangular configuration and including a first pair of oppositely disposed substantially rectangular side walls 12, 14 extending in spaced parallel and confronting relation, and a second pair of oppositely disposed substantially rectangular side walls 16, 18 also extending in spaced parallel and confronting relation. To each of the exterior sides of the side walls 12, 14, 16 and 18 are fixed the bodies, in vertically spaced relation, a pair of reinforcing channel members 20, 22 having their respective opposed ends rigidly connected, by conventional means, to vertical supports 24.

Normally, the lower ends of the side walls 12, 14, 16 and 18 are integrally connected with the upper ends of the downwardly converging conventional hopper walls 26, 28, 30 and 32, respectively. To the lower ends of the hopper outlet walls 34, 36, 38, and 40, respectively, the particular shape of the outlet walls forming the gist of the invention.

If desired, reinforcing strings 42 may be utilized to strengthen the bunker 10, the strings extending transversely between and connected to the channel members 20, 22 in longitudinally spaced and substantially parallel relation, and the hopper and hopper outlet walls may also be reinforced, at desired points, by continuous reinforcing channel members 44 and a continuous peripheral substantially rectangular brace or flange 46 at or near the discharge ends of the hopper outlet walls. The brace or flange 46 affords means for connection to a bulk material handling device such as a coal gate, coal scale, coal chute, coal feeder or other coal handling device of conventional design and construction not illustrated herein since the same form no part of the instant invention.

The above described bunker 10, the hopper side walls 12, 14, 16 and 18 as well as the hopper outlet walls 34, 36, 38 and 40 may be formed of metal, cement or other desirable materials and the configuration of the device may be square, rectangular, circular, symmetrical or asymmetrical. In the illustrated embodiment of this invention, the bunker 10 is substantially square or rectangular in transverse cross-sectional configuration, and the vessel may be lined if so desired.

To fully understand and appreciate the importance of the frictional resistance referred to herein, it should be noted that when coal or other bulk material flows in a hopper, two components of resistance thereto are encountered. The first of these is the friction generated or encountered between the surface of the hopper walls and the coal or other bulk material in contact therewith. For the same pressure and the same slope, wall friction is proportional to the ratio of the circumference or periphery to the area at that horizontal section. For a square hopper, such as is illustrated herein, at a given or certain cross-section through the hopper walls, each side thereof will have a span or width which may be denoted as "b." Thus "b" equals the width of the hopper or the horizontal distance between the opposite walls of the hopper. The circumference or periphery of the hopper consequently becomes 4b and the cross-sectional area of the hopper at any horizontal section is b². The ratio referred to above is therefore

\[ \frac{4}{b} \]

which is proportional to \( f_1 \). Now as the circumference or periphery is reduced as the coal or other bulk material approaches the discharge end of the hopper, the value of the ratio

\[ \frac{4}{b} \]

increases as does \( f_1 \). \( f_1 \) is the frictional resistance due to particles rubbing or abrading against the hopper wall and may be called "wall friction."

The second important component involved herein is the resistance offered to the free flow of coal or other bulk material through the hopper due to area contraction of the hopper in the direction of the coal or other bulk material flow. As the coal or other bulk material descends in the hopper walls, that is into more constricted areas, the mass of coal or other bulk material must be constantly deformed and reduced in cross-sectional area and increased in depth as the coal or other bulk material occupies descending sections of the hopper and offers frictional resistance which may be designated as \( f_2 \). \( f_2 \) is the frictional resistance to relative motion between particles and may be called "particle friction."

This reduction in area and resultant increase in depth of the body of coal or other bulk material involves relative movement of the particles of the mass thereof and also requires the expenditure of energy to accomplish the same. Obviously, the greater the reduction in area of mass per foot of descent through the hopper, the greater amount of energy will be required. The energy necessary to overcome these two components of resistance is the gravity force of the coal within the hopper walls. Of course, referring to coal by way of example, the fineness of the coal, its moisture content, the foreign matter mixed therewith and the compactness of the coal increases both resistance components. It naturally follows that if the available energy is not enough or sufficient to overcome the sum \( f_1 \) plus \( f_2 \) the flow of coal or other bulk material through the hopper is choked or completely cut off.

The hopper outlet walls 34, 36, 38 and 40 take these factors into consideration and the proper curvature therefor of may be easily ascertained to obtain the optimum coal flow conditions from the following equations.

The rate of area contraction is an important factor concerning the flow characteristics of the hopper. It may be defined as the ratio of area reduction of a certain section of the hopper per unit distance of descent with respect to the original area. It may be restated as comprising the percent change of volume for unit weight of material flowing from one section to a second section a unit distance therebelow. Thus, let \( A \) represent the original cross-sectional area of a certain section of the hopper and \( A' \) the cross-sectional area of the hopper one unit distance (that is, one foot) below \( A \), then the average rate of contraction of area \( c \) may be expressed in percent or decimally as follows:

\[ c = \frac{A - A'}{A} \times 100\% \text{ in percent} \quad (1) \]

or

\[ c = \frac{A - A'}{A} \text{ in decimal} \quad (2) \]

\( c \) equals the average rate of area contraction of the hopper per unit distance of descent.

Referring to FIGURE 3, reference numerals 48, 50 designate in phantom lines the profiles of a pair of opposed hopper walls of a conventional square hopper wall having a slope or inclination of substantially 60 degrees with respect to a horizontal plane passing therethrough. Now, from an elevation designated at 55 to the elevation designated 56, the span \( b \) is reduced from 8.5 feet to 7.4 feet and the contraction of area is seen to comprise approximately 28% per foot of descent. From elevation 60 to 61, the average contraction of area for the conventional hopper becomes 68%. As is seen in FIGURE 4, the contraction of the area defined by walls 48, 50 at differ-
ent elevations of outlet increases rapidly towards the outlet opening as is indicated by the dotted curve 102 which comprises an extension of the full line curve 101. This is a general characteristic of conventional heretofore know hoppers having straight side walls. The high rate of contraction of area of the hopper outlet causes increasing reduction in area and increase in depth of the body of coal and other bulk material, increasing particle friction, as well as greater restriction to flow of the material. The resistance or wall friction $f_w$ is inversely proportional to the hydraulic radius which is equal to the area divided by the perimeter or

$$\frac{A}{U}$$

$U$ represents the circumference of a certain section of the hopper. In other words, $f_w$ is directly proportional to the ratio of the perimeter to the area of the passage or

$$\frac{U}{A}$$

For a square cross-section hopper this ratio is

$$\frac{4b}{b^2} = \frac{4}{b}$$

where $b$ represents the length or span at any section of the hopper. It is obvious that the ratio increases rapidly as the material approaches the opening 104 of FIGURE 3.

As stated above, both particle friction and wall friction of conventional hoppers increase in the direction of the material flow and reach a maximum at the discharge opening 104. If the total resistance at a certain hopper section exceeds the gravity force of the material, the flow will be interrupted. In commercial installations, most stoppages do occur at or near the opening 104. Pounding, poling and vibrating the hopper has the effect of supplying extra energy to the coal or material being handled to overcome the resistance, but such practices are very inefficient. It has been found that the most positive, efficient and effective way to promote the coal flow is to limit the increase of both rate of area contraction and wall friction. This is accomplished by adopting the outlet defined by the curved inwardly concave hopper outlet walls 34, 36, 38 and 40. In the instant invention, the gradual increase of the steepness of the outlet walls 34, 36, 38 and 40 has the effect of limiting the increase in the rate of area contraction and the effect of reducing wall friction. The walls 34, 36, 38 and 40 are so shaped that the rate of area contraction of the hopper outlet is constant or decreases in a downward direction toward the discharge opening.

Curve 108 of FIGURE 4 depicts the rate of area contraction in percent per foot of descent at different horizontal sections of a hopper outlet made in accordance with the invention as presently described and it is seen that the same is far less than that of the conventional hopper outlet as is demonstrated by the curve 100, especially at the outlet opening 110. As has been stated above, the resistance due to wall friction is proportional to the ratio of

$$\frac{U}{A}$$

and the pressure normal to the walls. The ratio of

$$\frac{U}{A}$$

for the hopper outlet of FIGURE 4 is designated by the curve line 112 of FIGURE 5. It has been found that the ratio of coal pressure at the direction of 60 degrees from the vertical is 55% of that in the vertical direction. It becomes 40% in 70 degrees, 30% in 80 degrees and 21% in 90 degrees to the horizontal. This ratio, denoted by $n$, decreases as the wall steepness increases. $n$ equals the ratio of pressure of bulk material at a certain point in a certain direction or angle with respect to the pressure at the same point in a vertically downward direction. This may be called the "inclination factor." Therefore, the wall friction factor

$$n = \frac{U}{A}$$

for the hopper outlet is not proportional to the curve 112 but instead follows the curve 114 which is less than that for conventional hopper outlets as shown by the dotted line curve 116 (see FIGURE 5). If the curve 114 increases slightly near the plane of the discharge opening, it is preferred to have the hopper outlet as defined above so designed that the rate of area contraction decreases slightly toward the opening 110 as represented by the curve 108 (FIG. 4). In this case, the combined maximum resistance of the hyperbolic hopper outlet is far less than that of the conventional hopper outlet. For a hopper outlet delineated by the outlet walls 34, 36, 38 and 40, and making reference to the curvature thereof, the maximum resistance is only 40% of that of a conventional hopper outlet having a 60 degree slope and only 66% of a conventional hopper outlet having a 75 degree slope. This reduction in maximum resistance is sufficient to eliminate all coal stoppage.

While the above discussion has been directed to substantially square hopper outlets, the principles expressed herein are also applicable to hopper outlets having rectangular or circular cross-sectional configurations and/or of symmetrical or asymmetrical design.

It is important here to note that it has been found that for a certain height of column of coal or other bulk material the pressure normal to the wall reduces as the steepness of the wall increases. The following is a set of pressure measurements for coal taken in different directions together with the calculated inclination factors.

<table>
<thead>
<tr>
<th>Angle from Vertical</th>
<th>Relative Pressure</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>150</td>
<td>1.00</td>
</tr>
<tr>
<td>10</td>
<td>148</td>
<td>0.98</td>
</tr>
<tr>
<td>20</td>
<td>144</td>
<td>0.94</td>
</tr>
<tr>
<td>30</td>
<td>141</td>
<td>0.90</td>
</tr>
<tr>
<td>40</td>
<td>139</td>
<td>0.88</td>
</tr>
<tr>
<td>50</td>
<td>137</td>
<td>0.85</td>
</tr>
<tr>
<td>60</td>
<td>136</td>
<td>0.81</td>
</tr>
<tr>
<td>70</td>
<td>133</td>
<td>0.77</td>
</tr>
<tr>
<td>80</td>
<td>129</td>
<td>0.73</td>
</tr>
<tr>
<td>90</td>
<td>125</td>
<td>0.69</td>
</tr>
<tr>
<td>100</td>
<td>121</td>
<td>0.65</td>
</tr>
<tr>
<td>110</td>
<td>118</td>
<td>0.61</td>
</tr>
<tr>
<td>120</td>
<td>114</td>
<td>0.57</td>
</tr>
<tr>
<td>130</td>
<td>110</td>
<td>0.53</td>
</tr>
<tr>
<td>140</td>
<td>106</td>
<td>0.49</td>
</tr>
<tr>
<td>150</td>
<td>102</td>
<td>0.45</td>
</tr>
<tr>
<td>160</td>
<td>98</td>
<td>0.41</td>
</tr>
</tbody>
</table>

The rapid decrease of pressure from an inclination of 60 degrees to 90 degrees is utilized in the design of the hopper outlet. The gradual increase of steepness reduces the normal pressure against the wall so as to compensate for the increase of wall friction due to the reduced passage area as the material moves toward the discharge opening.

Thus, in the instant invention, the curvature of the wall is intended to limit the particle friction by controlling the contraction of area and at the same time to reduce the wall friction by gradually lessening the normal pressure of the material thereafter.

Reference is now made to FIGURE 3 of the drawing wherein the abscissa and ordinate lines are designated X—X axis and Y—Y axis, respectively. As represented therein, the abscissa line passes through the plane of junction or junction point of the upper end of the hopper outlet with the lower end of the constantly sloped upper hopper. In this figure let A represent the cross-sectional area at any horizontal transverse section, $dA$ represent the contraction or reduction of area, and $dy$ represent the
3,071,397

7 descent. \( dA \) equals the differential of A and is a small change of A, that is, A plus or minus an infinitesimal change in A as commonly used in calculus. \( dy \) equals the differential of y and is a small change of y, that is, y plus or minus an infinitesimal change in y or amount as commonly used in calculus. Then

\[
\frac{dA}{A} = \frac{dy}{y} 
\]

or

\[
\frac{dA}{Ady} 
\]

will represent the rate of area contraction per unit of descent. This is a negative value since A decreases while y increases. \( A \) equals the vertical distance from the curve to the X–X axis as illustrated in FIGURE 3.

In certain hopper outlet designs, where the material being handled is dry and the hopper is relatively large, the decrease in inclination factor \( n \) can be assumed to compensate for the increase of the factor

\[
\frac{U}{A} 
\]

In this case the change in the wall friction factor

\[
n\left(\frac{U}{A}\right) 
\]

is negligible in comparison to the rate of area contraction. Therefore we may design the hopper outlet by assuming that

\[
\frac{dA}{Ady} 
\]

is a constant. This design will result in an outlet whose walls will follow the shape of an exponential curve. Then:

\[
\frac{-dA}{Ady} = \text{constant} = c 
\]

\[
\frac{dA}{A} = -cdy 
\]

\[
\log A = -cy + K_1 
\]

(1)

\( (K_1 \) equals a constant used only temporarily during the mathematical operation which is accepted mathematical procedure and it does not appear in the final equation.)

\[
A = (e^{K_1})(e^{-cy}) 
\]

(2)

where \( e \) equals the natural logarithm or 2.71828.

At the juncture of the hopper outlet with the upper hopper:

\[
y = 0 
\]

therefore

\[
(e^{-cy}) = 1 
\]

\[
A = (e^{K_1}) = A_0 
\]

Here \( A_0 \) represents the area of the hopper at the juncture of the hopper outlet with the conventional upper hopper and the equation thus becomes

\[
A = A_0(e^{-cy}) 
\]

(3)

This is the general equation for any sectional shape of hopper outlet based upon the above assumption that the value of

\[
\frac{dA}{Ady} 
\]

is set at a constant. In the particular case of square type hopper outlets having symmetrical walls, \( A = b^2 \) where

\[
\frac{b}{2} 
\]

equals the horizontal distance from the Y–Y axis to the curve as illustrated in FIGURE 3. Let this relation be substituted into the general equation, then:

\[
b^2 = A_0(e^{-cy}) 
\]

\[
\begin{align*}
\frac{b^2}{2} &= \pm \left(\sqrt{\frac{A_0}{2}}\right) (e^{-cy} - y) \\
\frac{b^2}{2} &= \pm b_0 (e^{-cy}) 
\end{align*} 
\]

(4)

c equals the rate of area contraction between certain cross-sectional areas of the hopper outlet taken at different levels. If \( b_0 \) equals the horizontal distance between the opposite hopper walls at the junction of the outlet walls with the upper conventional hopper, for a square cross section then

\[
\frac{b^2}{2} = b_0 
\]

if we let

\[
\frac{e^{-cy}}{2} = e_1 
\]

(5)

Then the above equation becomes

\[
\frac{b^2}{2} = \pm b_0 (e_1) 
\]

(6)

for a square cross sectional shape of hopper.

In the above equations, \( b \) may equal the diameter of a circular hopper outlet. Therefore, the equations apply to both square and circular hoppers.

In actual practice it has been found that the hopper outlet wall friction sometimes increases slightly near the discharge opening. It is therefore preferable to have the rate of contraction of area reduced slightly toward the opening so as to keep the resistance to flow constant. When this is done, the equation for the curvature of the walls of the hopper outlet approach the equation for a hyperbola, as presently described. The change in rate of contraction of area toward the opening may be represented mathematically by the expression:

\[
\frac{c}{K_1 + y} 
\]

where \( a \) is a constant depending upon the character of the bulk material being handled, \( K_2 \) is the distance from the point on the mathematical curve corresponding to the junction point of the upper end of the hopper outlet to the horizontal axis of the mathematical curve of the hopper outlet and \( y \) is the distance of any point on the curve of the hopper outlet below the junction point. Based on experiments with coal, it was found that \( a = 2 \), therefore:

\[
\frac{c}{K_1 + y} = \frac{a}{K_1 + y} 
\]

(7)

Since

\[
\frac{c}{K_1 + y} = \frac{dA}{Ady} 
\]

and \( y \) increases downwardly:

\[
\frac{-dA}{Ady} = \frac{2}{K_1 + y} 
\]

\[
\frac{dA}{A} - \frac{2}{K_1 + y} 
\]

\[
\log A = -2 \log (K_1 + y) + K' 
\]

\[
A = K'(K_1 + y)^{-2} 
\]

(8)

when \( y = 0 \) then

\[
K' = A_0 K_2^2 
\]

\[
A = A_0 K_2^2 (K_1 + y)^2 
\]

This is the general equation for any hopper outlet.
3,071,297 regardless of its cross-sectional shape, i.e., square, rectangular, round, etc.

For square and symmetrical hoppers:

\[ A = b^2 \]

\[ \frac{b}{2} = \pm \sqrt{\frac{K_2}{K_1 + \gamma}} \]

\[ \frac{b}{2} = \pm \frac{b_2}{2} \left( \frac{K_2}{K_1 + \gamma} \right) \]

\[ \frac{b}{2} = \frac{b_2}{2} \left( \frac{K_2}{K_1 + \gamma} \right) \]

\[ \frac{b}{2} = \frac{b_2}{2} \left( \frac{K_1}{K_1 + \gamma} \right) \]

Let

\[ m = \pm \frac{b_2}{2} (K_2) \]

\[ x = \frac{b}{2} \]

and

\[ \gamma' = K_1 + \gamma \] (transformation of ordinate)

Then the equation becomes

\[ x = \frac{y}{\gamma'} \]

or

\[ xy' = m \]

The last two equations coincide with standard equations for an equilateral hyperbola. The curve of the equilateral hyperbola defined by Equation 9 is shown in FIG. 6. It may be noted that \( K_2 \) is the distance between the horizontal directrix \((X-X' axis)\) and the upper end of the hopper outlet or junction point of the hopper outlet with the remainder of the hopper. The distance \( y \) is measured from the upper end of the hopper outlet and the distance \( y' \) is measured from the horizontal directrix of the hyperbola. It can, of course, be understood that the opposite wall of the hopper outlet has an identical curvature below the \(X-x' \) axis but is the mirror image of the curve shown in FIG. 6.

It should be noted at this point that the exponential Equation 4 and the hyperbolic Equation 9 are intended for symmetrical square or circular hoppers. Since many of the more recent hoppers are rectangular and asymmetrical, and in order to have the hopper outlet conform to the configuration of the upper hopper, each side wall of the hopper outlet may follow the above equations but with a different constant for each wall, while the area, that is the cross-sectional area is still governed by the general Equations 3 or 8. These equations also apply to a circular outlet.

As has been defined above, the average rate of area contraction per foot of descent may be expressed as:

\[ c = \frac{A - A'}{A} \times 100\% \]

in percentages, or

\[ c = \frac{A - A'}{A} \]

in decimal representation.

It will be recognized that this average contraction of area \( c \) is slightly different from the real contraction of area as expressed by the factor

\[ \frac{dA}{Ady} = c \]

However, \( c \) will equal \( c \) when the distance of descent considered is very small.

In addition to utilization of the exponential Equation 4 and the hyperbolic Equation 9 to design hopper outlets, the desired configuration of hopper outlets may be obtained by mathematical trial and error as follows: In actual design, the actual area or width for each foot of descent is calculated as follows:

\[ A' = A(1 - c) \]

for rectangular hoppers having a width \( b_1 \) and \( b_2 \), \( b_1' \) and \( b_2' \) are the horizontal distances between opposite hopper walls of a rectangular section one foot below the aforementioned section respectively where \( b = b_1 \) and \( b_2 \):

\[ A = b_1(2b) \]

\[ b_1' = b_1 \sqrt{1 - c} \]

\[ b_2' = b_2 \sqrt{1 - c} \]

The points calculated from the above equations are connected to form smooth curves, and the slope of the curve at each point is measured to determine the corresponding \( n \). The value of

\[ n = \left( \frac{U}{A} \right) \]

is then calculated and if it exceeds that at the top of the hopper outlet, the value of \( c \) is reduced for the given point and the calculations of \( b_1' \) and \( b_2' \) are recalculated. The resultant curves plotted in this manner will lie between the exponential curve and the hyperbolic curve.

The value of \( c \) depends upon the character of the material being handled, the compacting pressure, the moisture content of the material, and other miscellaneous factors. From actual experience with coal, it has been found that this value should not be more than 0.3. In the event the hopper is asymmetrical or rectangular, the rate of area contraction should be a little less than this value. It has been found that a hopper outlet with \( c = 0.22 \) at the upper top and \( c = 0.17 \) at the discharge opening gives very satisfactory results for coal.

Therefore, the hopper outlet should satisfy the fundamental equation

\[ A - A' = c \]

For coal \( c \) should not have a value of more than 0.3 and should be either held as a constant or reduced slightly toward the discharge opening.

The walls of the hopper outlet may be designed by utilization of any of the three aforementioned methods, namely, the use of the exponential equation, the use of the hyperbolic equation, or mathematically by trial and error. In each case it is desired to obtain a hopper outlet which will have the rate of area of contraction remain substantially constant or decrease slightly downwardly toward the discharge opening. If the exponential equation is used, the rate of area of contraction will be substantially constant downwardly toward the discharge opening whereas if the hyperbolic equation or the trial and error method are used the rate of area of contraction will decrease in a direction downwardly toward the discharge opening.

FIG. 4 depicts the rate of area of contraction in percent per foot of descent at different horizontal sections of the hopper outlet. The conventional hopper outlet as demonstrated by the curve 100 has an increasing rate of area of contraction toward the discharge opening. The rate of area of contraction of a hopper outlet defined by the inwardly curved outlet walls 34, 36, 38, 40 is represented by the substantially similarly shaped curves 108a and 108b. Curve 108a is a curve of the hopper outlet made by the trial and error method, curve 108a is the curve of the hopper outlet having hyperbolic curved walls and curve 108b is the curve of the outlet having exponential curved walls. It is apparent that the rates of area of contraction of the hopper outlet having curved walls as
represented by curves 108, 108a and 108b are substantially less than the rate of area of contraction of the conventional hopper as represented by the curve 100. FIG. 5 which represents the rate of change of the ratio

\[ \frac{U}{A} \]

and wall friction factor

\[ n\left(\frac{U}{A}\right) \]

per foot of descent at different horizontal sections of the hopper outlet. For conventional outlets the ratio

\[ \frac{U}{A} \]

as shown in curve 106 and the wall friction factor as shown in curve 116 increase substantially. On the other hand, a hopper outlet having inwardly curved walls in accordance with the invention has corresponding curves 112, 112a, 112b for the ratio

\[ \frac{U}{A} \]

and 114, 114a and 114b for the wall friction factor

\[ n\left(\frac{U}{A}\right) \]

Curves 112, 114 are for a hopper outlet made by the trial and error method, curves 112a and 114a are for hopper outlets made by using the hyperbolic equation and curves 112b and 114b are for hopper outlets made by using the exponential equations.

It can be seen by reference to FIG. 4 that the rate of area of contraction for an exponentially curved hopper outlet wall, as represented by the curve 108b, is substantially constant while the rate of area of contraction of a hyperbolically shaped outlet wall, as represented by the curve 108c, decreases slightly in a direction downwardly toward the discharge opening. On the other hand, a hopper outlet having a hopper outlet wall made by the trial and error method, as represented by the curve 108, has a rate of area of contraction decreasing downwardly toward the discharge opening but not to the degree that the hyperbolic outlet decreases.

It should be understood that the hopper outlet having a particular configuration formed in accordance with the three methods, namely, the use of the exponential equation, the use of the hyperbolic equation, or the compound curve obtained mathematically by trial and error should have its upper end begin and connect with a conventional hopper in a smooth joint in the vicinity where the flow of material begins to be unduly affected by the wall friction and the particle friction. The rate of area contraction for the curved hopper outlet should not exceed that at the junction. In order to have proper slope to keep material flowing, only the portion of the exponential curve, hyperbolic curve or compound curve, as the case may be, will be used which has a slope equal to or steeper than that of conventional upper hoppers. The junction point will be at a point where the rate of area contraction becomes critical and would adversely affect the flow. In the case of most hoppers, the side walls are sloped at 60 to 70 degrees with the horizontal. In the case of coal, the junction point is where \( e = 0.3 \). For other materials, this point must be determined by experiment and will depend on the character of the material. In most materials similar to coal, this point will be where \( e \) is approximately 0.3. For materials which are dry, \( e \) can be greater, e.g. 0.5.

As shown in FIG. 7, for proper connection to a hopper of predetermined construction, a greater height or vertical distance is required for a hopper outlet made in accordance with the invention than is required for a conventional hopper outlet. A greater height is required for a hopper outlet made by using hyperbolic equations than for a hopper outlet having walls made by the trial and error method or by using the exponential equation.

Where head room is critical and limited, it may be necessary to utilize either the exponential equation or the trial and error method rather than the preferred hyperbolic shape thereby reducing the vertical length of the hopper outlet which is required to produce the desired results. In addition, the hopper outlet walls may be formed with a combination of curves. For example, the upper portion of the outlet walls may have an exponential shape which merges with a hyperbolic shape at the lower portion of the outlet.

Although it is preferred that all the walls of the hopper outlet be curved and inwardly concave in order to produce best results, one or more of the walls of the hopper outlet may be straight, while the others are curved and inwardly concave in accordance with the invention and improved results can be thereby obtained over the conventional hopper outlet 48 (FIG. 3).

The invention eliminates the choking and clogging of the flow of bulk materials. It is also found that the rate of discharge is also much faster than in a conventional hopper. In addition, the pressure of material at the discharge outlet is practically constant regardless of the height of material in the hopper. The tendency to maintain constant discharge pressure will keep density of material constant and enable the volumetric feeder to give better quantity control of feeding.

Having described and illustrated one embodiment of this invention in detail, it is to be understood that the same is offered merely by way of example, and that the instant invention is to be limited only by the scope of the appended claims.

This application is a continuation of application Serial No. 4,434, filed January 25, 1960, now abandoned.

I claim:

1. A hopper outlet device for bulk solid materials adapted to be mounted on the lower end of a substantially hollow hopper, said hopper outlet device comprising a peripheral wall converging downwardly and concaving inwardly and having a discharge opening at the lower end thereof, said peripheral wall having a curvilinear inner surface formed in accordance with the formula

\[ A = A_o \left(1 - e^{-c} \right) \]

wherein \( A_o \) is the transverse cross-sectional area at the upper end of the hopper outlet device, \( A \) is the transverse cross-sectional area at a plane spaced at a distance \( y \) below the upper end of the hopper outlet device and \( c \) is a constant corresponding to a predetermined rate of contraction of area.

2. A hopper outlet device for bulk solid materials adapted to be mounted on the lower end of a substantially hollow hopper, said hopper outlet device comprising a peripheral wall converging downwardly and concaving inwardly and having a discharge opening at the lower end thereof, said peripheral wall having a curvilinear inner surface formed in accordance with the hyperbolic equation:

\[ A = A_o \left(1 + \frac{e}{1 + e - 1} \right) \]

wherein \( A_o \) is the transverse cross-sectional area at the upper end of the hopper outlet device, \( A \) is the transverse cross-sectional area at a plane spaced at a distance \( y \) below the upper end of the hopper outlet device and \( e \) is the distance between the horizontal directrix of the hyperbolic equation and the upper end of the hopper outlet device.

3. A hopper outlet device for bulk solid materials adapted to be mounted on the lower end of a substantially hollow hopper, said hopper outlet device comprising a peripheral wall converging downwardly and concaving inwardly and having a discharge opening at the lower end thereof, said peripheral wall having a curvilinear...
inner surface formed in accordance with a curve lying between and including a curve defined by the expression:

\[ A = A_2(e^{-\alpha y}) \]

wherein \( A_2 \) is the transverse cross-sectional area at the upper end of the hopper outlet device, \( A \) is the transverse cross-sectional area at a plane spaced at a distance \( y \) below the upper end of the hopper outlet device and \( c \) is a constant corresponding to a predetermined rate of contraction of area and a curve defined by the expression:

\[ A = \frac{A_3 K_3^2}{(K_3+y)^3} \]

wherein \( A_3 \) is the transverse cross-sectional area at the upper end of the hopper outlet device, \( A \) is the transverse cross-sectional area at a plane spaced at a distance \( y \) below the upper end of the hopper outlet device and \( K_3 \) is the distance between the horizontal directrix of the hyperbolic equation and the upper end of the hopper outlet device.

4. A hopper for discharging bulk solid materials having a hopper outlet device comprising a peripheral wall having an inner curvilinear surface, said hopper outlet device having a material discharge opening at the lower end thereof, said inner surface defining a curve lying in the range defined by two curves one of which is an inwardly concave exponential curve curving downwardly toward a vertical directrix and the other curve being an inwardly concave hyperbolic curve curving downwardly toward said vertical directrix, said two curves lying within said range, all of said curves in said range being related curves and extending toward said vertical directrix from a substantially common point.

5. A hopper for discharging bulk solid materials having a hopper outlet device comprising a peripheral wall having an inner curvilinear surface, said hopper outlet device having a material discharge opening at the lower end thereof, said inner surface having a configuration such that the rate of area contraction of the transverse cross-section of the hopper outlet device is substantially constant toward said discharge opening.

6. A hopper for discharging bulk solid materials having a hopper outlet device comprising a peripheral wall having an inner curvilinear surface, said hopper outlet device having a material discharge opening at the lower end thereof, said inner surface having a configuration such that the rate of area contraction of the transverse cross-section of the hopper outlet device decreases progressively slightly toward said discharge opening, the limit of said configuration being a hyperbola.

7. A hopper for discharging bulk solid materials having a hopper outlet device comprising a peripheral wall curving downwardly and concaving inwardly and having a discharge opening at the lower end thereof, said peripheral wall having a curvilinear inner surface formed in accordance with the formula

\[ A = A_4(e^{-\alpha y}) \]

wherein \( A_4 \) is the transverse cross-sectional area at the upper end of the hopper outlet device, \( A \) is the transverse cross-sectional area at a plane spaced at a distance \( y \) below the upper end of the hopper outlet device and \( c \) is a constant corresponding to a predetermined rate of contraction of area.

8. A hopper for discharging bulk solid materials having a hopper outlet device comprising a peripheral wall curving downwardly and concaving inwardly and having a discharge opening at the lower end thereof, said peripheral wall having a curvilinear inner surface formed in accordance with the hyperbolic equation:

\[ A = \frac{A_5 K_4^2}{(K_4+y)^3} \]

wherein \( A_5 \) is the transverse cross-sectional area at the upper end of the hopper outlet device, \( A \) is the transverse cross-sectional area at a plane spaced at a distance \( y \) below the upper end of the hopper outlet device and \( K_4 \) is the distance between the horizontal directrix of the hyperbolic equation and the upper end of the hopper outlet device.

9. A hopper for discharging bulk solid materials having a hopper outlet device comprising a peripheral wall converging downwardly and concaving inwardly and having a discharge opening at the lower end thereof, said peripheral wall having a curvilinear inner surface formed in accordance with a curve lying between and including a curve defined by the expression:

\[ A = A_5(e^{-\alpha y}) \]

wherein \( A_5 \) is the transverse cross-sectional area at the upper end of the hopper outlet device, \( A \) is the transverse cross-sectional area at a plane spaced at a distance \( y \) below the upper end of the hopper outlet device and \( c \) is a constant corresponding to a predetermined rate of contraction of area and a curve defined by the expression:

\[ A = \frac{A_6 K_5^2}{(K_5+y)^3} \]

wherein \( A_6 \) is the transverse cross-sectional area at the upper end of the hopper outlet device, \( A \) is the transverse cross-sectional area at a plane spaced at a distance \( y \) below the upper end of the hopper outlet device and \( K_5 \) is the distance between the horizontal directrix of the hyperbolic equation and the upper end of the hopper outlet device.

10. A hopper outlet device adapted to be mounted on the lower end of a hopper, said hopper outlet device comprising a peripheral wall having an inner curvilinear surface, said hopper outlet device having a material discharge opening at the lower end thereof, said inner surface having a configuration such that the rate of area contraction of the transverse cross-section of the hopper outlet device is substantially constant toward said discharge opening.

11. A hopper outlet device adapted to be mounted on the lower end of a hopper, said hopper outlet device comprising a peripheral wall having an inner curvilinear surface, said hopper outlet device having a material discharge opening at the lower end thereof, said inner surface having a configuration such that the rate of area contraction of the transverse cross-section of the hopper outlet device decreases progressively slightly toward said discharge opening, the limit of said configuration being a hyperbola.

12. A hopper outlet device adapted to be mounted on the lower end of a hopper, said hopper outlet device comprising a peripheral wall having an inner curvilinear surface, said hopper outlet device having a material discharge opening at the lower end thereof, said inner surface having a configuration such that the rate of area contraction of the transverse cross-section of the hopper outlet device decreases progressively slightly toward said discharge opening, the limit of said configuration being a hyperbola.

References Cited in the file of this patent

UNITED STATES PATENTS

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,071,297

Yee Lee

It is certified that error appears in the above identified patent and that said Letters Patent are hereby corrected as shown below:

Column 1, line 25, "coil" should read -- coal --. Column 2, line 8, "mechanically" should read -- mechanically --. Column 3, line 24, after "hopper" insert -- walls are fixedly secured the upper ends of the hopper --. Column 6, lines 2, 3 and 41, Column 7, lines 21 and 26, Column 10, lines 23 and 24, and Column 11, lines 10 and 27, "n", in italics, each occurrence, should read -- n --. Column 8, equation (4), the right-hand portion reading

\[(e^{-c_1 V})\]

should read \[(e^{-c_1 y})\]

Signed and sealed this 12th day of August 1969.

(SEAL)

Attest:

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