Local exhaust ventilation with reduced energy consumption during bulk materials overloads into receiving cones of coarse crushing plants

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Abstract. An intense dust emissions occur when bulk materials are unloaded by wagons into receiving cones of coarse crushing bodies (CCB). The most reliable, yet energy-intensive way to localize dust emissions is the use of local exhaust ventilation systems. For the correct calculation of the performance of the exhaust ventilation system, it is necessary to determine the flow rate of air entrained in bulk material (flow rate of ejected air), which is the main source of dust emission distribution. The volume of air carried away by bulk material is determined based on the use of the classical theory of mechanics of two-component flows. Using the methods of boundary integral equations, a mathematical motion of the air flow in the cavity of the receiving cone of the CCB has been developed. A laboratory model of the CCB receiving cone was created, where the air flow carried away by the bulk material was modelled using a smoky jet flowing out of the supply nozzle. Based on the conducted computational and field experiments, the location of the local ventilation suction and mechanical screens are selected to increase the efficiency of local exhaust ventilation and reduce the energy consumption of the aspiration system.

1. Introduction

Intense dust releases (Fig.1) occur when loose materials are unloaded from railway cars into intake funnels of coarse crushing bins (CCB). Local exhaust ventilation systems [1,2] are the most reliable yet energy-intensive method of containing dust releases. To perform performance calculations necessary for correct design of an exhaust ventilation system, the flow rate of air entrained by loose material (ejection airflow rate) must be known. With the development of computers it has become possible to transition from empirical formulas to fundamental studies of air injection along chutes or in free jets underpinned by the classical theory of mechanics of a two-component stream and aerodynamics of uniformly accelerated airflow in chutes and discrete-particle jets [3-5].
Figure 1. Unloading iron ore from rail cars at Stolensky Ore Processing Plant.

The flow rate of evacuated air (the performance of the local exhaust ventilation system) must be sufficient for capturing dust releases while expending as little energy as possible. There are numerous research papers studying the effect of flanges, canopies and mechanical baffles on contaminant capture efficiency in open-type local exhaust devices, thus addressing performance bottlenecks in exhaust ventilation systems. It is shown in [6] that the addition of flanges (mechanical baffles) increases contaminant trapping efficiency by 88%. With a flange added, contaminants are captured at a greater velocity than without the flange [7,8]. A gas guide device is proposed [9] as a means of increasing airflow velocity near a local exhaust hood. The use of thin hoods facilitates an improvement in local exhaust efficiency when approached by an incident flow of air [10].

This study is concerned with a dual objective of designing a local exhaust ventilation system for a CCB that reduces exhaust airflow rate by virtue of mechanical baffling, as well determining the required air evacuation rate.

The intake funnel of a coarse crushing bin comprises a parallelepiped 18 meters long and 8.6 meters wide, buried 5 meters underground. Dump cars are unloaded from both sides at the same time. The 2VS-105 dump car with a load capacity of 105 metric tons is most commonly used in Russia for these funnel dimensions. Computations of ejected airflow assumed that ore is unloaded specifically from a 2VS-105 dump car with the following body dimensions: length at top – 13400 mm, length at bottom – 13000 mm, width at top – 3150 mm, width at bottom – 2630 mm, body height – 1300 mm. The dump car takes 5 seconds to unload. The average size of ore lumps is 200 mm. The ore unloading process is a dynamic, that is, non-constant over time. Ore unloading rate varies, with mass flow rate increasing gradually as the dump car is tilted, then decreases as unloading is about to end. Moreover, pieces of ore leave the car at different velocities having fallen different distances inside the car. Consequently, the amount of ejected air would be varying in the course of unloading.

2. Methods

A combination of boundary integral equation (BIE) method and discrete vortex method (DVM) [11-14] was used for airflow simulation. With the BIE method, dummy sources (sinks) of intensity unknown beforehand were planned along the flow area boundary. They were sized so that their total effect at boundary points would induce velocities in the same points with a specified value of the normal component. The flow boundary was quantized with straight-line sections. Intensities were determined from a solution of combined linear algebraic equations (CLAEs), with each equation expressing the effect of sources/sinks on the median point of the boundary section. Velocities inside the flow area were expressed via a sum of sources/sinks identified at the previous stage. Mathematically this is the numerical method for solving the Fredholm boundary integral equation of the second kind. The flow area boundary was broken down into straight-line sections (boundary elements). The intensity of sources/sinks remains unchanged along each section.

The main idea behind DVM is that the area boundary is quantized into attached vortices and computation points while accounting for the separation of free vortices from sharp edges and flat surfaces in points where the tangential velocity component changes direction. Intensities of attached vortices were determined from solving CLAEs where every equation expresses the effect of attached and free vortices on the computational point at a particular instance of time. After determining the unknown
circulations of attached vortices the velocity at initial time in an arbitrary point along a particular direction was determined. New free vortex positions must be determined at every computational time point.

The flow of loose material from a car being unloaded was assumed to comprise uniformly accelerated particles of identical dimensions. Particles were assumed to be distributed evenly in the cross-section of the jet along free-fall height. Proceeding from an integral relationship expressing the momentum conservation law for air in elemental volume in view of mass forces of an interaction between components, a differential equation is obtained for air ejection in a one-dimensional jet of falling particles [15, 16] whence the velocity of ejected air is determined.

We carried out natural experiments using an experimental setup of our design (Fig. 2) at a scale one-twenty fifth the size of a real coarse crushing bin. Additionally, exhaust ducts were sandwiched between two flat planes enabling the problem to be reduced to two-dimensional settings for numerical computation.

![Figure 2. Geometrical dimensions of the model: a) General appearance: 1 – baffle; 2 – exhaust windows; b) dimensions of exhaust windows with lateral exhaust (in centimeters).](image)

A jet of ejected air was simulated using smoke-filled air (Fig. 3). The Frude’s similarity criterion was used. Measurements were taken using a Testo 425 instrument at the funnel outlet and vertically, in a cross-section passing through the end of the baffle (Fig. 4).

### 3. Results and discussion

According to computational findings, the flow rate of handled material is 21 000 kg/s; the minimum volume of ejected air is 32.3 m³/s with an airflow velocity of 6.86 m/s; the maximum volume of ejected air is 39.3 m³/s with an airflow velocity of 7.09 m/s.

Computational and experimental velocity readings show velocity to be increasing at outlet with longer screens preventing the carryover of particles from the receiving funnel of the coarse crushing bin (Fig. 5).

The following curves and points are plotted in Fig. 5: 1 – experimental readings with a baffle sized 1/3 of the total outlet size; 2 – computed curve for a baffle sized 1/3 of the total outlet size; 3 – experimental readings with a baffle sized 1/2 of the total outlet size; 4 – computed curve for a baffle sized 1/2 of the total outlet size; 5 – experimental readings for a baffle sized 2/3 of the total outlet size; 6 – computed curve for a baffle sized 2/3 of the total outlet size; 7 – experimental readings with no baffle; 8 – computation with no baffle; 9 – discrete vortex method-based computation with a baffle sized 2/3 of the total outlet size; 10 – discrete vortex-method based computation with a baffle sized 1/2 of the total outlet size. Computations using the BIE method are close to experimental readings in the middle of the outlet, rising sharply toward its edges. Velocities computed using the discrete vortex method are biased toward lower values even as vortex formation at sharp edges of the screen and funnel is accounted for.
Figure 3. Ejected airflow distribution pattern obtained experimentally without removal of air by ventilation.

Figure 4. Measurement points and exhaust hood locations: 1 – baffle; 2 – curtain; 3 – cross-sectional measurement points; 4 – measurement points at outlet, 5 – top exhaust abutting a corner; 6 – top exhaust at the left edge of the baffle; 7 – lateral exhaust.

The curves and points are indicated in Fig. 6 in the same manner as in Fig. 5. Here the greatest and smallest velocities are observed with a baffle length 2/3 times outlet size. According to experimental findings (readings series 6, Fig. 6), velocity reaches its maximum toward the bottom of the intake funnel thus promoting containment of the jet of ejected dust-laden air.

Computations and experiments show that the exhaust system is more effective with a baffle length 2/3 times outlet length. However, for process reasons baffle length cannot exceed one-half of outlet length.

With a baffle length fixed at one-half outlet length, there is little change in velocity distribution (both experimental and computational) as curtain length is increased, however the distribution tends to be more uniform with longer curtains.

Velocity readings in the characteristic cross-section obtained both computationally and experimentally rise as curtain length is increased, promoting the capture of the ejected jet of dust-laden air.

A lateral hood has a small, yet noticeable advantage as its minimum outlet velocity is the highest among cases considered.
Figure 5. Change in velocity in the open part of CCB intake funnel outlet.

Figure 6. Cross-sectional velocity readings.

With smoke-filled air supplied to imitate the approaching flow of dust-laden air at velocity $v_e$, the minimum exhaust air velocity $v_0$ was chosen so as to prevent smoke from being knocked out of the funnel cavity. The plotted relationship between $v_e$ and velocity $v_0$ (Fig. 7) illustrates the effect of the screen and curtain on velocity and consequently aspiration volume. These experimentally observed laws also support the rationale for installing a baffle $1/2$ times outlet length and a curtain $1/3$ times inlet funnel length. However, it should be noted that the curtain has a much smaller effect than the baffle.

With ejected air velocity of 7.09 for the case of a baffle sized $? \times$ times outlet length and a curtain sized $1/3$ to $2/3$ times intake funnel height the velocity in the exhaust hood reads 4.8 m/s. Considering that the intake funnel can accommodate up to 9 pairs of exhaust devices of this design, the air flow rate would be 38.7 m$^3$/s. For an exhaust hood without no baffle and no curtain, velocity in the exhaust hood reads 5.55 m/s with an air flow rate of 43.3 m$^3$/s i.e. 5.5 m$^3$/s or about 20000 m$^3$/h greater.

4. Summary

Based on our computations we have designed the following structural layout of the exhaust ventilation system (Fig. 8). This design includes a baffle 1 (Fig. 8) comprising a foldable rectangular duct with a length equal to 25-75% of intake funnel width, two wheels 3, an articulated deflecting curtain 2 on the of the baffle 1 and a hydraulic cylinder 6. Wheels 3 of the baffle 1 are mounted in guides 4.

When a car approaches for loading, a motion sensor mounted on rails sends a signal to the central control console that brings the dust collection system online. At the same time a signal to the hydraulic cylinder 6 makes it extend as oil is supplied under pressure. In turn, the baffle 1 unfolds from the side opposite the unloading side with wheels 3 moving along guides 4.
In Figure 8, the cross-section of an intake funnel with a baffle mounted is shown. Limit switches in the baffle control the unfolding/folding process. One switch closes to prevent further folding once the baffle is folded completely, and another switch closes once the baffle is unfolded completely to prevent further unfolding.

During loading, the flow of air reaches the bottom of the intake funnel, is deflected by it and rises along the wall opposite the loading side before being deflected by baffle 1 and curtain 2 to form a vortex and be removed through dust collection windows 5 in the wall of the intake funnel. No dust-laden air is kicked out of the intake funnel in the process.

Air ejection rate during the unloading of a dump car varies between 32.33 m³/s and 39.34 m³/s while the velocity of ejected flow varies between 6.86 m/s and 7.09 m/s respectively.

The length of the mechanical baffle must be at least half the width of the intake funnel width while the curtain must reach at least half of its height. The intake opening of the local ventilation hood must be located in the upper corner of the intake funnel, opposite to the car unloading location. The required flow rate of evacuated air stands at 38.7 m³/s in this case. The use of a baffle together with a curtain enables the required flow rate of evacuated air to be reduced by about 20000 m³/h.

Findings reported in this study are in the vein of our past studies of air ejection by a flow of loose material. We believe these findings may be useful for designers of high-efficiency industrial ventilation systems [17-23].

5. References

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