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Determination of the PM_{10} emission rate from an aerial grain conveyor belt by a set of SDS011 sensors by the upwind-downwind method

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1. INTRODUCTION

Fugitive emissions are a challenge for air quality managers because traditional techniques for measuring air emissions do not apply. Even so, for many situations, such as atmospheric dispersion modeling, it is necessary to have a number for this emission, usually obtained through an emission factor from the specialized literature. However, the available emission factors have a series of restrictions that compromise their applicability. In the case presented in this work, research was carried out on the emission factor of an outdoor conveyor belt that transported soybeans. The emission factor found was for "grains", without differentiating between types of grain and was based on a typical length of the conveyor belt, without relating the emission to the specific length of the transport system. This data was considered insufficient for the purpose of the study and therefore the upwind-downwind method was applied to measure the fugitive emissions using a set of SDS011 sensors and a TEOM 1405 monitor as a reference method.

2. Upwind-downwind method

Available techniques to quantify fugitive emissions are presented in Frankell (1993). Of these, the most suitable for an air conveyor belt was considered the upwind-downwind method, as it requires a small number of sensors in viable installation locations. However, in addition to the PM_{10} sensors, it was necessary to monitor the meteorological conditions: wind direction and speed and atmospheric stability.

2.1 Theoretical foundation

Using the Gaussian atmospheric dispersion model, the relationship between the emission rate Q and the concentration c is expressed by formula (1).

$$c\,(x,y,z) = \frac{Q}{2\pi v \sigma_y \sigma_z} \cdot e^{-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2} \cdot \left(e^{-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2} + e^{-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2}\right) \quad (1)$$

In this equation: c(x,y,z) represents the concentration, x is the horizontal distance from the source parallel to the wind direction, y is the horizontal distance from the center of the plume perpendicular to the wind direction, z is the vertical distance from the ground of the source, Q represents the emission rate, v is the average wind speed (m/s), σy and σz are the dispersion coefficients in the y and z directions and H represents the source height.

This equation can be simplified because the elevation of the plume is zero and the height z of the impact point is equal to height H, because the mounting of the sensors took place at the height of the effective emission H, so z=H. The position of sensors attached to the rod and selection of concentration data only in upstream to downstream wind situations imply that y=0 in the equation above. In this way, equation (1) is simplified according to equation (2), published by Turner, (1994):

$$c\,(x,y,z) = \frac{Q}{2\pi v \sigma_y \sigma_z} \quad (2)$$

It is observed in equation (2) that the emission rate Q depends on the measured concentration c, the wind speed v and the coefficients σ_y and σ_z which in turn depend on the meteorological conditions. All these information are available or calculable.

Considering the particularities of the line source, the Pasquill-Gifford horizontal dispersion coefficients, σ_y and σ_z, are presented in equations (3) and (4) (EPA, 1995):

$$\sigma_y = \frac{W}{2,15} \tag{3}$$

$$\sigma_z = a x^b \tag{4}$$

Where W is the source width. A source width of 1 meter was considered, which means that the emission rate per meter of conveyor belt was calculated. This methodology is suggested in the EPA's ISC3 model manual for linear sources (1995). In addition, the coefficients a and b are obtained in Table 1 below according to Turner, (1994) as a function of Pasquill's Stability Class.

Table 1. Values for the coefficients a and b as a function of atmospheric stability for distances x up to 1 km.

Pasquill´s Stability Class	a	b
A	122,800	0,94470
B	90,673	0,93198
C	61,141	0,91465
D	34,459	0,86974
E	24,260	0,83660
F	15,209	0,81558

Source: Turner (1994).

The Pasquill classification system is a scheme used to classify atmospheric stability based on accessible ground-level meteorological observations, according to Seinfeld and Pandis (1998). These classes depend on wind speed, solar radiation during the day or the fraction of cloud cover at night, information that was obtained by the meteorological station installed at the site and by observational estimates of cloudiness. Thus, it was possible to attribute to each analyzed data interval the atmospheric stability condition.

3. EXPERIMENT SETUP

3.1 Equipment

The setup of the experiment included the installation of 6 SDS011 sensors, a reference equipment for PM_{10} (THERMO FISHER SCIENTIFIC TEOM 1405) and a meteorological station from the manufacturer RainWise with an internal datalogger. SDS011 sensors were coupled to Raspberry Pi microcomputers that recorded the concentration of PM_{10} every minute.

3.2 Arrangement of experiment

The object of the study was a double aerial conveyor belt for transporting soybeans, 35 m long and mounted at a height of 22 m. Between the two belts and on the sides, there were walkways that allowed access and installation of equipment, as shown in Figure 1.

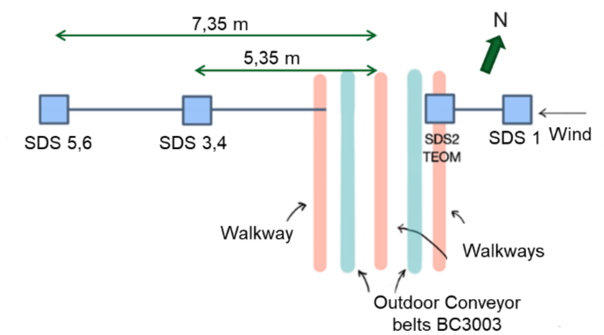

Fig. 1. Installation of SDS011 sensors mounted on rods upwind and downwind of the conveyor belts.

The rods with the SDS011 sensors, from now on just called SDS, were mounted on the handrail of the conveyor belt. SDS1 was positioned in the upwind direction to the predominant wind direction recording the background concentration of PM_{10}. The second SDS2 was mounted next to the TEOM inlet, the reference equipment for PM_{10} concentration. This sensor worked as a beacon for all SDS used, as the correlation between SDS2 and TEOM (shown in Figure 2) was applied to all SDS sensors.

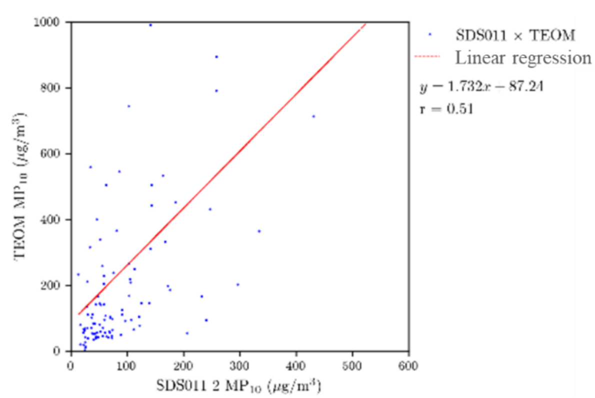

Fig. 2. Calibration curve for SDS sensors.

The correlation curve between SDS2 and TEOM was based on means of 30 minutes, as this interval showed the best correlation.

The four sensors SDS3 through SDS6 were mounted on the rod downstream of the source in duplicates at 5.35 and 7.35 m distances respectively. Each one of them provided every minute a reading that allowed the calculation of the emission rate Q per meter of belt, therefore a value in mg/(ms).

The experiment was collecting data for approximately 5 days (120h), between 20 and 25/05/2021.

3.3 Operational data

The next Figure 3 shows the operational periods and whether these coincided with the favorable wind direction. It can be observed that there were periods, such as on 05/21, with winds in the right direction, but the conveyors were not transporting grain. Then on 05/22 the belts operated, but the wind did not blow from the necessary sector. Therefore, it was necessary to run the experiment for several days to obtain sufficient data for the evaluation.

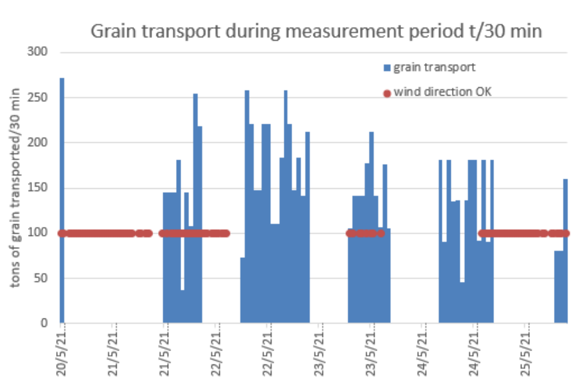

Fig 3. Transport and wind direction during the measurement campaign.

3.4 Data Processing

The sampled period started on 05/20/2012 at 4:08 pm until 05/25/2021 at 1:43 pm, totaling 7056 1-minute readings. This dataset was filtered according to the wind direction, using only the wind directions between 23 and 113 degrees. This range of winds corresponds to the alignment of the winds with the installed rod, which was aligned with northeasterly winds of 68º. Applying a tolerance range of ±45º (23 to 113º), the sector winds characterized an upwind/downwind situation consistent with the mounting of the SDS sensors.

For the purpose of calculating the emission rate, all wind records between 23 and 113º were speed corrected, using only the component of wind aligned with the rod, called the v_{corr}. Thus, it was possible to calculate the emission rate per meter of conveyor belt every minute for each of the 4 SDS according to equation (5).

$$Q = (c - c_{\text{background}})\, 2\pi v_{\text{corr}} \sigma_y \sigma_z \qquad (5)$$

In this calculation, the background concentration is variable, that is, changes from minute to minute. From the four individual results of the SDS3 to SDS6 sensors, the average was calculated.

In a first approach, emission rates were calculated for intervals of 30 minutes, because the correlation between the SDS sensors and the reference equipment showed a better result for this interval. In this way, the measured period was summarized in 107 values of 30 minutes each.

In the second approach, the results were calculated for 1-minute intervals only. Instead of 107 values, there were 2161 emission rate values. One percent of the maximum and minimum values were classified as outliers and disregarded, leaving 2139 valid results. This number of results made it possible to link emission rates with the amount of grain transported as well as with wind speed. For this purpose, the amount of mass transported by the conveyor was divided into six categories and the wind speed into five, as shown in Table 2.

Table 2. Classification of mass transport and wind speed.

Class	Mass transport (t/30min)	Wind speed (m/s)
A	0 - 50	0 - 0,4
B	50 - 100	0,4 - 0,8
C	100 - 150	0,8 - 1,2
D	150 - 200	1,2 - 1,6
E	200 - 250	>1,6
F	250 - 300	

The combination of these two parameters adds up to 30 possible configurations, and for 27 of these it was possible to calculate a result.

4. RESULTS

In the approach of emission at intervals of 30 minutes, the average emission was 36.56 mg/(m.s) of PM_{10}. Average grain transport was 103.95 t/h. Dividing the emission rate by the transported mass, an emission factor of 1.266 g/(t.m) was obtained. To estimate the result of the emission of total suspended particles (TSP) a TSP/PM_{10} ratio = 3.78 was applied. This factor had been verified in a particle size study in the same unit. Applying this factor, the emission of PTS was 4.788 g/(t.m).

A result in the unit g/(t.m) made it possible to calculate the atmospheric emission as a function of the mass of grains transported and the extension of installed belts, a parameter that can vary greatly from one unit to another.

In the results of the 1-minute intervals approach, shown in the next Table 3, it can be seen that most records were in the range of 0 - 50 t/30min, and for wind in the class between 1.2 and 1.6 m/s. Three combinations were left blank, that is, no data of these combinations were recorded during the measurement period.

Table 3. Count of records available in each class.

		Transport classes						
	Count	A 0-50	B 50-100	C 100-150	D 150-200	E 200-250	F 250-300	Total
Wind classes	A 0-0,4	147	1	5	22	10	12	197
	B 0,4-0,8	409	8	25	22	35	33	532
	C 0,8-1,2	471	22	70	30	7	13	613
	D 1,2-1,6	507	34	57	65			663
	E >1,6	101	10	14	6	3		134
	Total	1635	75	171	145	55	58	2139

The next Table 4 shows the emission rate results in mg/(m.s) for the same dataset.

Table 4: Emission rates in mg/(ms) for 1-minute intervals.

		Transport classes						
	(mg/ms)	A 0-50	B 50-100	C 100-150	D 150-200	E 200-250	F 250-300	Total
Wind classes	A 0-0,4	13,5	12,7	82,9	4,8	5,8	10,0	13,70
	B 0,4-0,8	12,8	55,9	48,7	23,8	17,4	40,4	17,62
	C 0,8-1,2	12,0	47,6	45,1	53,2	41,3	91,7	21,08
	D 1,2-1,6	12,0	53,5	54,4	98,3			26,23
	E >1,6	28,9	69,1	29,0	110,1	109,6		37,34
	Total	13,4	53,6	48,5	64,0	23,4	45,6	22,15

The average emission was 22.153 mg/(m.s). When calculating the ratio of this value by the average of the mass transported in the period (78.95 t/h), emission factors of 1.010 g/(tm) for PM_{10} and 3.82 g/(tm) for TSP were calculated.

The means of the 30-min and 1-min approaches were not equal because 30-min means were validated, even if there was only one valid 1-minute value. So, a 30-minute average with a few 1-minute values had the same weight as another average with all 30 available 1-minute values. As the absence of values was more frequent in situations with high emissions, the overall result of the average of 30 minutes was 25% higher than that of 1 minute.

Studying the dependence of the emission rate of the transported grain mass, the behavior shown in the next Figure 4 was observed.

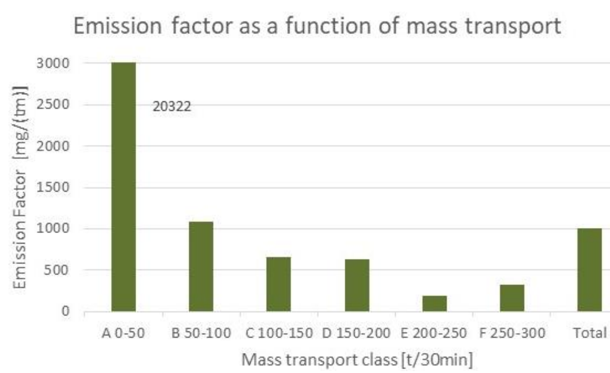

Fig. 4. Emission factor as a function of mass transport.

The high emission factor in first class is explained by the small mass of transported grain. As the transported mass increases, emissions also increase, but to a lesser extent, so the emission factor is reduced until reaching the minimum value in class E.

The influence of wind speed on emissions is shown in Figure 5. As expected, wind has great relevance on emissions. Strong winds can multiply emissions, as seen in class E, which resulted in 4 times the emission observed in class A.

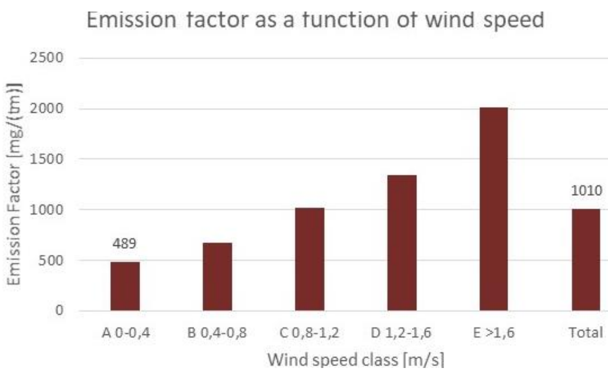

Fig. 5. Emission factor as a function of wind speed.

5. DISCUSSION

Comparing the result of the TSP emission of 3.82 g/(tm) with the work of Gorman et al. (1974) where there is an emission factor for tunnel belt of 0.7 kg/t, it is verified that the two emission rates are equal for a belt length of 183 meters, a reasonable value for an average grain processing unit. For this reason, the results obtained by the upwind-downwind method were considered satisfactory. But the use of the 0.7 kg/t factor would have greatly underestimated the emission of the unit where the monitoring was carried out, because it has an outdoor conveyor system including many steps which in total is much longer than just 187 m.

Another important information obtained was that transport at low load by conveyors causes excessive particulate emissions. Different from what is suggested by the emission factor unit in kg/t, the emission rate remained similar between the transport classes from B to F, shown in the next Figure 6.

Fig. 6. Emission rate of PM_{10} as a function of mass transported.

This explains, for example, why even the highest emission rate of class D obtained a lower emission factor than classes A, B and C, as shown in Figure 4. Therefore, the emission behavior of the conveyor belt is similar to many other technical equipment that show the best performance near the nominal load.

In relation to wind, a positive correlation between wind speed and emission rate was already expected, but the results showed a stronger correlation than expected. In Figure 7 it is shown how the emission rate varied with the wind speed class. It has an emission of 37.3 mg/(m.s) in class E, three times the value measured in the first class A, where a rate of only 13.7 mg/(m.s) was verified. This reinforces the importance of measures to protect the transport system against the action of the wind.

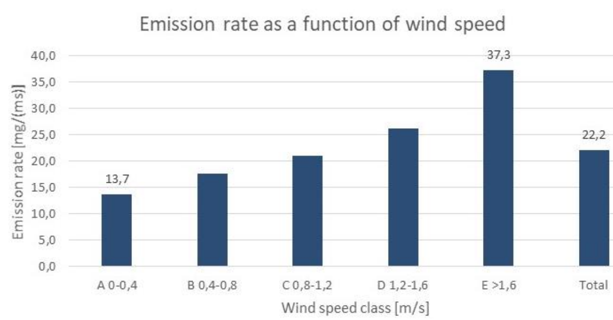

Fig. 7: PM_{10} emission rate as a function of wind speed.

The lowest emissions were recorded for the combination of wind class A with transport classes D and E, with results of 0.0479 g/(t.m) and 0.0475 g/(t.m) respectively, shown in Table 5.

Table 5. Best performance operation combination.

		Transport classes						
	g/(tm)	A 0-50	B 50-100	C 100-150	D 150-200	E 200-250	F 250-300	Total
Wind classes	A 0-0,4	97,93	0,29	1,10	0,0479	0,0475	0,07	0,48
	B 0,4-0,8	11,74	1,16	0,62	0,24	0,14	0,28	0,67
	C 0,8-1,2	13,22	0,97	0,61	0,53	0,34	0,62	1,04
	D 1,2-1,6	33,29	1,08	0,76	0,97			1,39
	E >1,6		1,40	0,43	1,09	0,93		2,09
	Total	20,32	1,09	0,66	0,63	0,19	0,32	1,01

Values as low as these are in agreement with experiments conducted in environments absolutely protected from the wind, such as an underground tunnel, where PM_{10} emission rates around 0.002 g/(t.m) were monitored. This demonstrates the potential for emission reduction by using wind protection.

6. REFERENCES

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