Detection of Smouldering Fires by Carbon Monoxide Gas Concentration Measurement

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Smouldering fires pose a serious threat in processes that handle organic dusts. They are difficult to detect but can have drastic consequences: besides deteriorating valuable product, they may evolve to open fires and even to dust or gas explosions with potential massive destructive effects. A large number of incidents have occurred in agricultural, food and chemical processing plants, in large storage silo's, drying equipment and mechanical processing apparatuses, such as mills, cutters or grinders. Smouldering is difficult to detect, because combustion happens at lower temperature, without flames, often in the internal of a porous heap of organic material where the oxygen level is reduced but maintained by diffusion through the porous medium. Detection of smouldering based on carbon monoxide concentration measurement is regularly used in industry. This work presents experimental results of smouldering of several organic products, where the size and temperature of the smouldering nest and the available oxygen is correlated with the emission level of carbon monoxide. This information is essential for the design of reliable smouldering detection systems based on CO gas sensors, especially when process ventilation dilutes combustion gases and low detection levels are required for an early response. Based on new and earlier reported experiments, required detection levels for use in milk spray driers are given.

1. Introduction

Several investigations (BIA, 1997, CSB, 2005, Febo, 2013) indicate that smouldering is by far the most occurring ignition source for fires and dust explosions in silos and dryers processing organic products. Also in milling systems, smouldering often occurs as a result of mechanical malfunction, before a larger fire or dust explosion is ignited.

Short residence time, thorough cleaning practices and low process temperatures lower the risk for product to start smouldering. Inerting may be a solution but impractical for large throughput systems. A more cost-effective solution is detection and control of smouldering in an early phase. Possible detection techniques include temperature sensors, infrared light sensors and combustion gas sensors. The combustion gas sensors are typically installed on the silo roof or in the exhaust air of continuous air flow systems, such as driers or milling systems. Industry standards exist which specify procedures and evaluation criteria for the smouldering ignition behavior of dust accumulations. The hot plate test (ASTM E2021, IEC 61241-2-1, EN 50281-2-1, VDI 2263-1) determines the minimum ignition temperature of dust layers on a hot plate. The hot storage test (UN N.4, EN15188, VDI 2263-1) determines the self-ignition temperature of dust samples when stored in ovens at constant temperature. The Grewer test (VDI 2263-1) determines the self-ignition temperature of dust samples in a stream of air with temperature increasing at 1°C/min.

Frank-Kamenetskii (1969) and Bowes (1976) showed that the process of smouldering initiation can be modeled as a heat balance process where the temperature rise of the product sample is governed by heat transfer between product sample and environment (hot plate, ambient air, oven air, ..), conductive heat transfer through the product sample and heat generation inside the product sample due to combustion. If the product sample is excited such that it reaches a temperature where the heat generation due to combustion exceeds the heat conducted to the environment, the combustion reaction runs away and auto-ignition occurs.

Once smouldering is initiated, it progresses as a slow, flameless form of combustion that emits heat, carbon monoxide gas (CO), carbon dioxide gas (CO_2), water vapor (H_2O) and some product specific volatile organic

compounds generated during decomposition and volatilization of the heated solid smouldering product. Because CO_2 and H_2O are more abundantly present in normal air, CO gas is the most distinctive reaction product.

The correct and safe application of smouldering detection systems based on CO measurement requires knowledge on how much carbon monoxide is emitted under which circumstances. Especially in processes that operate under continuous air flow, such as driers and mills, combustion gases are diluted and detection levels should be set accordingly to prevent that the smouldering stays undetected.

This paper focuses on methods to determine CO emission amounts associated with smouldering, which is fundamental knowledge to the correct application of explosion prevention by means of CO detection at early stages.

2. Literature review

Most of the documented investigations were related to the use of early smouldering detection on dryers in the dairy and animal feed production industry. Relatively little is reported in literature on CO emission amounts during smouldering of organic powders.

Verdurmen et al. (2006) installed samples of skim milk powder in an oven set at 180°C and measured sample temperature, oven temperature and CO emission rate. The oven was poorly ventilated. They report peak CO emission rates for skim milk powder of 310 mL/min for a sample of 200 g. A sample of 950 g emitted up to 970 mL/min under the same conditions.

Steenbergen et al. (1989) investigated CO emission for different types of dairy powders, such as skim milk powder, fat milk powder and whey powders. Samples of these products were heated in poorly ventilated ovens at constant temperature (200 – 250 °C) and CO emission was measured. The influence of powder type and powder size was investigated. For skim milk powder peak CO emission rates of 290 mL/min, 472 mL/min and 624 mL/min were measured for sample sizes of 400 g, 900 g and 1900 g respectively. Fat milk powder produced less CO. Whey powders produced similar CO amounts as milk powders. In a next experiment, a lump of 500 g of fat milk powder was installed and brought to smouldering at the ceiling of an industrial spray dryer, so close to the hot air inlet. Now the CO emission rate peaked to 2480 mL/min.

Zockol (1985, 1992, 1996, 2011) investigated CO emission for cacao powder, for cereals such as wheat, starch and rapeseed and for dairy products such as milk powder. For the milk powder, Zockol (1992) preheated 1 kg of skim milk powder to 200°C, installed the heated sample at different heights above an industrial fluid bed dryer, and measured the air velocity at the sample installation position and CO emission rate. He showed a strong dependency of sample installation position and CO emission rate. Close to the fluid bed where air velocity was around 5 - 6 m/s, CO emission rate was 5600 mL/min, further away from the fluid bed where the air velocity was around 3 m/s, CO emission rate was only 2415 mL/min.

Chong et al. (2006) investigated CO emission for small skim and fat milk powder samples in a 300°C hot air stream. It was found that small samples (< 6 g) of skim milk powder were difficult to ignite and produced very little CO whereas small samples of fat milk powder reached smouldering temperatures up to 965 °C and produced much more CO (235 mL/min peak emission for 4,2 g of fat milk powder). They conclude that smouldering is much more difficult to detect in skim milk powder production plants than in fat milk powder. This is in contradiction with the findings of Steenbergen et al.

From these few studies it may be concluded that the amount of carbon monoxide emission during smouldering of organic products is highly dependent on product composition, amount of product smouldering and the level of aeration.

3. Experiments

3.1 Hot storage tests

In a first set of experiments samples of organic powders were put in cylindrical wire mesh baskets of 400 mL, 8 cm in diameter and stored for several hours in an oven. See Figure 1. The oven was set at a constant temperature, above the self-ignition temperature of the product sample, so to initiate smouldering. The oven was ventilated with a small amount of air (2 L/min) to prevent oxygen depletion during smouldering. The exhaust air of the oven became diluted in a secondary air stream into which a CO concentration sensor was installed. The dilution air stream was regulated such that CO concentration stayed within the CO sensor's measurement range. Oven and sample temperature (centre), as well as air flow and CO concentration were continuously recorded. The experiment was stopped when the smouldering had finished, when the sample temperature and CO concentration had dropped back to nominal values.
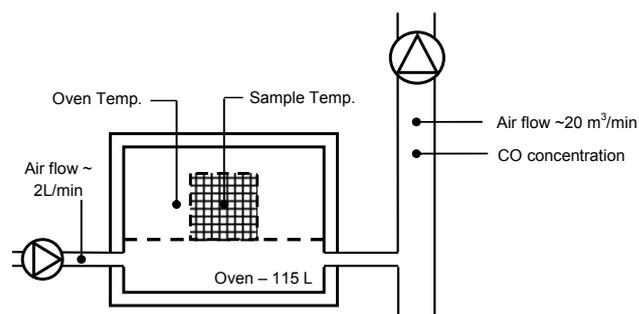
Figure 1: Hot storage test setup

Figure 2 shows hot storage test results for a sample of 400 mL (190 g) of skim milk powder (52% lactose, 26% protein, 0.5%fat, self-ignition at 156°C according Grewer) and for a sample of 400 mL (76 g) of methylcellulose and oven temperatures around 200°C. The CO emission rate was determined as the product of CO concentration and dilution air flow.
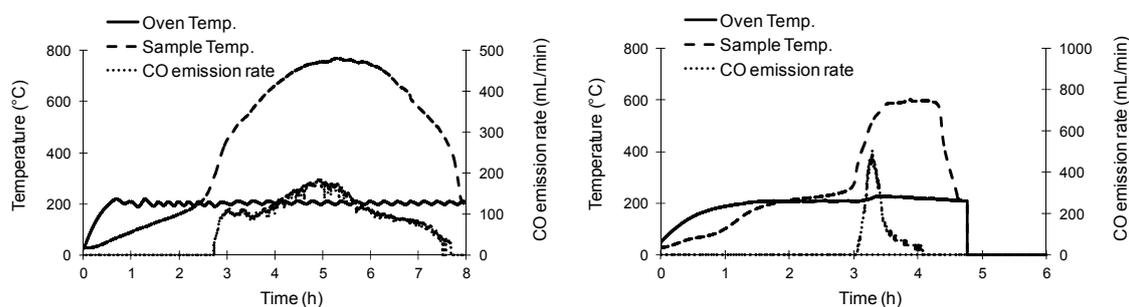
Figure 2: Hot storage test results; left 190 g of skim milk powder; right 76 g methyl cellulose

According to the evaluation criteria of EN15188, self-ignition of the milk powder occurs after 2 h 7 min when the milk powder temperature evolution over time shows an inflection point. The milk powder temperature at ignition is 198 °C, somewhat higher than what the Grewer test had indicated (156 °C). First CO emission was measured after 2 h 44 min when the milk powder temperature had reached 303°C. The delay between ignition and detection may have to do with the lower detection limit of the CO sensor, not measuring very small amounts of CO. CO emission peaked to 188 mL/s after 4 h 55 min. Milk powder temperature peaked to 769°C after 5 hours and 17 min. CO emission peak falls somewhat earlier than milk powder temperature peak, but generally speaking it can be said that CO emission is more or less proportional to sample temperature. The CO emission rate seems to be a good measure of combustion reaction intensity. The total amount of CO emitted during the experiment is 33,2 L or 38 g. Assuming lactose has a chemical composition similar to $C_{12}H_{22}O_{11}$ and protein similar to $C_{47}H_{48}N_3O_7S_2Na$ and assuming all carbon in the CO emission originates from the milk powder, it can be said that around 20 % of the milk powders carbon has reacted to CO, the other 80% must have been reacted to CO_2 or has been volatilized as organic compound.

The bulk density of methylcellulose (76 g / 400 mL) is much lower than skim milk powder (190 g / 400 mL). The porosity of the methylcellulose sample is therefore much higher. A drying phase is recognized as a 'plateau' in the methylcellulose temperature over time evolution somewhere halfway the first hour of the experiment. During drying, the sample temperature rises slower due to latent heat consumption. Start and end of drying phase can be identified by inflection points in the methyl cellulose temperature over time evolution. Using the inflection point criterion, drying occurs between 18 and 37 min, respectively between 48 °C and 68 °C methylcellulose temperature. Duration of combustion based on methylcellulose temperature is much longer than duration of combustion based on carbon monoxide emission. A possible explanation is that the methyl cellulose sample may have fallen apart shortly after auto-ignition and that remaining combustion happened in an oxygen rich environment favouring CO_2 emission at the expense of CO emission.

The peak CO emission rate (506 mL/min) for methylcellulose is much higher than for skim milk powder. Since the peak emission rate occurs before sample temperature peaked, the increased peak emission is probably due to the increased initial availability of oxygen in the more porous sample.

3.2 Spray dryer experiments

In a next experiment, an almost equal sample of skim milk powder (400 mL // 220 g) was installed at the ceiling of an operational spray drying, close to the hot air inlet. The hot air inlet flow velocity was around 20 m/s. Air stream temperature, product sample temperature (centre) and emitted carbon monoxide were measured. See results in Figure 3.
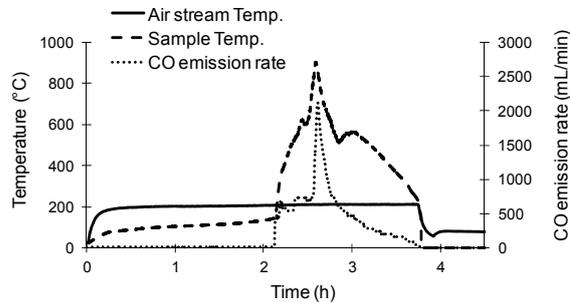
Figure 3: Spray drier test results 220 g of skim milk powder

Start of self-ignition based on the inflection point criterion is 156°C, a value lower than for the hot storage test, and the exact same value as determined by the Grewer test, which was also performed under aerated conditions.

The peak sample temperature (900°C) and peak CO emission rate (2110 mL/min) are much larger than for the hot storage test. However, the total combustion duration (1 h 38 min) is much lower than for the hot storage test. Aeration intensifies the combustion reaction. Remarkably, the total amount of CO (50.0 L) is also considerably larger than for the hot storage test. This seems in contradiction with what may be expected knowing that the availability of oxygen should favour the reaction to carbon dioxide at the expense of carbon monoxide. It may be that due to the higher sample temperature, volatilized organic compounds that stayed unburnt in the hot storage test, now do burn, eventually in gas phase, and contribute to both the CO and CO_2 emission level.

3.3 Hot air stream tests

In a third set of experiments different sizes of small skim milk powder samples were inserted in a +/- 300°C hot air stream and CO emission rate was measured. Refer to test setup in Figure 4 and test results in Table 1. All samples used a cylindrical basket of 100 mL and 5 cm in diameter which was filled to different levels. The air and sample temperatures were not measured.
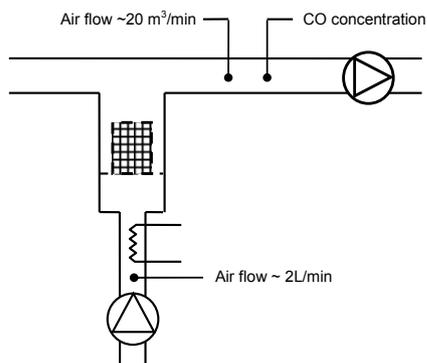
Figure 4: Hot air stream test setup

Table 1: Hot air stream test results

Sample size	CO emission duration	Peak CO emission	Total CO emission
5 g	5.8 min	95 mL/min	0.32 L
10 g	6.8 min	116 mL/min	0.69 L
15 g	12.8 min	163 mL/min	1.42 L
20 g	21.0 min	184 mL/min	2.13 L

Progressive browning of the milk powder was observed indicating that the combustion front propagated both from sample bottom upwards and from sample side inwards.

CO emission duration, peak CO emission rate and total CO emission clearly scale with sample size, but not linear. The CO emission duration is just a little less than linear proportional to the sample size. If the combustion front would only propagate from the sample side inwards, one would expect constant combustion duration, independent of sample size, since all samples had identical diameter. The almost linear correlation shows that bottom up combustion propagation is most determining for the total CO emission duration. This is in its turn due to the fact that the air temperature is higher at the sample bottom than at the sample side, since the hot air tube was not insulated.

The peak CO emission is far less than linear proportional to the sample size. This is due to the fact that not the entire sample burns simultaneously. The empirical correlations of this experiment are expressed as:

$$PeakCORate \sim TotalCO / CODuration \sim SampleSize^{1.4} / SampleSize^{0.9} \sim SampleSize^{0.5}$$

4. Design of early smouldering warning systems

Experimental investigations clearly indicate that the CO emission amount during smouldering of organic products is highly dependent on product composition, size of smouldering, intensity of the smouldering and the level of aeration. The largest experimental data set is available for skim milk powder. The chart in Figure 5 plots all available results for skim milk powder and illustrates the importance of smouldering size and level of aeration.
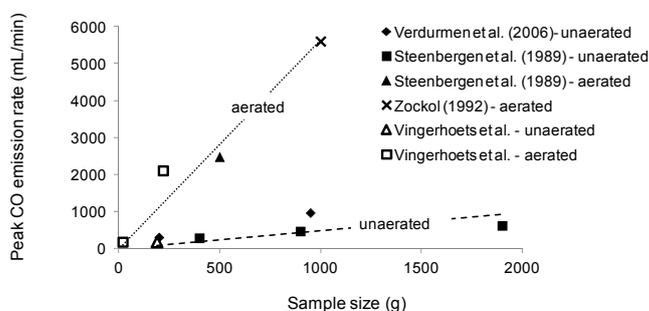
Figure 5: Summary of experimental data for skim milk powder

Early warning smouldering detection systems typically use sensors at the ceiling of silos or at the exhaust air of dryers and mills. These sensors measure the concentration of carbon monoxide in the process air, in percentages or in parts per million.

For silos, without continuous air flow, smouldering - even at a low intensity level - causes a continuous rise of carbon monoxide concentration. Therefore, the CO concentration in silos is a measure of how much material has smouldered after the silo was last filled with a new batch of product:

$$c_{CO} = \frac{\int Q_{CO, smouldering} \cdot dt}{V_{process}}$$

A smouldering detection system in silos is unable to discriminate between intense, hazardous smouldering - with an immanent risk for fire or dust explosion - and harmless, less intense smouldering continuing over a longer period of time. A minimum requirement is that when the CO concentration in the silo approaches its lower explosion limit (12%) a high priority alarm should be initialised.

In dryers and mills that operate under continuous air flow however, the CO concentration at the exhaust air is a measure of the actual size and intensity of smouldering. The CO concentration is now the ratio of CO emission rate and process air flow

$$c_{CO} = \frac{Q_{CO, smouldering}}{Q_{process\ air}}$$

In large processes that operate at high air flows, the CO emission can become diluted to such an extent that only low CO concentration levels appear at the exhaust air – in the order of parts per million or even lower and the smouldering must evolve to a larger size or intensity before it becomes detected. Table 2 specifies the minimum required detection level for early warning systems on skim milk spray dryers. It is based on experimentally measured CO emission rates in aerated conditions when the smouldering temperature was

600°C and 900°C and assumes a linear scaling of CO emission rate with smouldering size. The smouldering size should then be interpreted as "amount of simultaneously smouldering product at equal intensity".

It seems more appropriate to apply CO emission values under aerated conditions instead of unaerated values, because the risk for smouldering to start and to evolve to a fire or initiate a dust explosion is much higher in aerated conditions and locations of the drying plant. Experiments indeed do indicate a lower self-ignition temperature and higher peak temperatures in these cases.

Table 2: Required detection level for early smouldering warning systems

Process air flow	200 g		750 g		2000 g	
	600°C	900°C	600°C	900°C	600°C	900°C
20,000 kg/h	2.3 ppm	6.9 ppm	8.6 ppm	25.9 ppm	23.0 ppm	69.0 ppm
100,000 kg/h	0.5 ppm	1.4 ppm	1.7 ppm	5.2 ppm	4.6 ppm	13.8 ppm
200,000 kg/h	0.2 ppm	0.7 ppm	0.9 ppm	2.6 ppm	2.3 ppm	6.9 ppm

5. Conclusions

Smouldering can be initiated in laboratory experiments and CO emission levels can be measured for organic powders. A significant increase in CO emission is observed when the product sample is aerated. When product is brought to smouldering in industrial process equipment, similar CO emission levels than in lab test conditions are found. The level of aeration in the lab test should however match the condition of the industrial apparatus. Scaling for larger smouldering lump sizes is linear or less than linear. Set detection levels for early warning smouldering detection systems should take into account the anticipated size of the smouldering, the intensity of smouldering and the dilution effect of process air flow.

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