Development of a Soot Sensor for Measuring Emissions from Candle Combustion

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1 Introduction

Candle combustion generates carbon soot nanoparticles, which can cause adverse health effects. This has led to the development of some basic emission standards[1,2], which are based on visibility criteria. However, these basic standard methods, involving the measurement of light transmission through a soot loaded glass plate, are labor intensive and excessively time consuming. Typically, 12 hour testing is required to evaluate one candle. Therefore, cheaper, less time consuming, and more meaningful methods are needed for candle evaluation and for quality-check purposes in the candle production process.

2 Objectives

This research project had two objectives. First, to measure physical properties of particle emissions from the combustion of three types of candles with state-of-the-art instrumentation including scanning mobility particle sizer (SMPS), condensation particle counter (CPC), cavity attenuated phase shift single scattering albedo monitor (CAPS PMssa), and scanning electron microscope (SEM). Second, to develop the commercially available low-cost light scattering sensor and evaluate its performance to characterize the particle emissions from candle combustion.

3 Methods

3.1 Physical properties of emissions from candle combustion

- Experimental setup

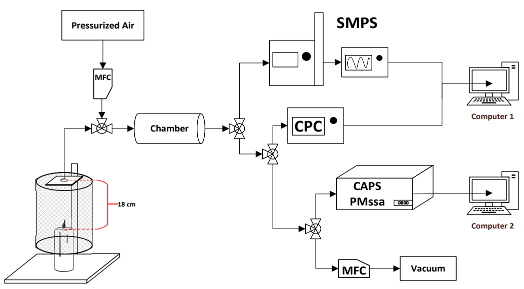


Figure 1: Experimental setup for characterization of physical properties of emissions from candle combustion using SMPS, CPC, and CAPS PMssa

- Number and mass concentrations were obtained from CPC and CAPS PMssa, respectively. Emission factors and emission rates were calculated from the averaged concentration during four hours of experiment.

3.2 Performance of the light scattering sensor

- The sensor was installed into an air-sealed box.
- Limit of detection (LOD) of the sensor was determined using Allan analysis.
- Experimental setup: the sensor performance

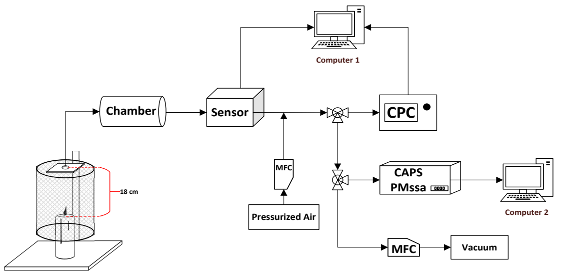


Figure 2: Experimental setup for determination of the sensor performance

- Moving average was used to smooth the data with window sizes of 1 minute and 5 minutes.
- Correlation between the sensor signals and the mass concentrations calculated from CAPS PMssa data was determined using linear relationship.

4 Results and discussion

4.1 Physical properties of emissions from candle combustion

- Concentrations, emission factors, and emission rates of emissions from candle combustion are summarized in **Table 1**.
- The hand-made paraffin outdoor candles and the paint-coated paraffin candles had similar mass and number emission levels.
- Candle soot particles were highly agglomerated (**Figure 3**). Sizes of agglomerates of the hand-made paraffin outdoor candles and the paint-coated paraffin candles ranged from 200 nm to > 1µm, while those of the standard machine-made paraffin indoor candles were less than 200 nm.
- The mode of the particle size distribution (**Figure 4**) of the paint-coated paraffin candles ranged from 200 to 350 nm, while those from the standard machine-made paraffin indoor candles were ~25 nm.

Table 1: Summary of means and standard deviations (S.D.) of the emissions from three candles.

Parameters	Units	Hand-made Paraffin Outdoor Candles (6*)		Paint –coated Paraffin Candles (4*)		Standard machine-made paraffin indoor Candles (6*)	
		Mean	S.D.	Mean	S.D.	Mean	S.D.
Concentration	[#/cm^3]	2.76E+05	2.31E+05	2.60E+05	2.59E+05	6.51E+04	9.58E+04
	[µg/m^3]	1.09E+03	9.58E+02	8.28E+02	8.71E+02	7.15E+00	3.58E+00
Emission Factor	[#/g wax]	5.42E+11	4.28E+11	6.63E+11	6.57E+11	1.45E+11	1.92E+11
	[mg/g wax]	2.11E+00	1.68E+00	2.09E+00	2.19E+00	1.89E-02	7.56E-03
Emission Rate	[#/h]	4.00E+12	3.28E+12	2.88E+12	3.44E+12	9.42E+11	1.39E+11
	[mg/h]	9.00E+00	7.74E+00	6.53E+00	6.88E+00	5.84E-02	2.92E-02

*The number of experiments performed for each candle.

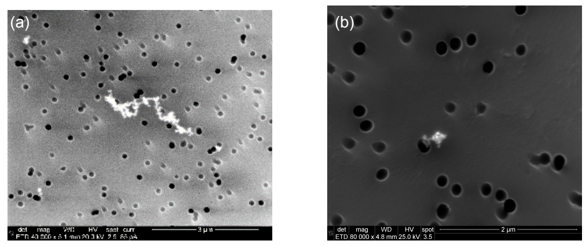


Figure 3: SEM images of soot particles from (a) the paint-coated paraffin candles and (b) the standard machine-made paraffin indoor candles

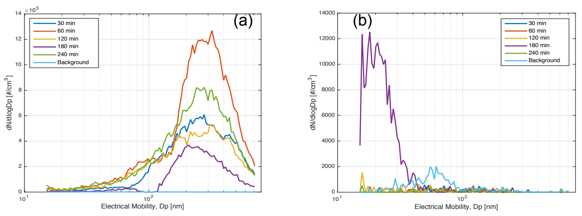


Figure 4: Number based particle size distributions from (a) the paint-coated paraffin candles and (b) the standard machine-made paraffin indoor candles

4.2 Performance of the sensor

- Allan deviation of the sensor signal is 3.34×10^{-4} V at 90 s (**Figure 5**). The LOD of the sensor is 1.30 mV, which corresponds to 0.8 µg/m^3.
- **Figure 6** shows good correlations between the sensor signals and the mass concentrations. **Table 2** shows correlation of determination (R^2) and correlation coefficients of the linear relationship between sensor signals and mass concentrations of 1-minute and 5-minute moving averages.
- Three types of candles had a similar trend for average mean sensor signals and soot index (**Table 3**).

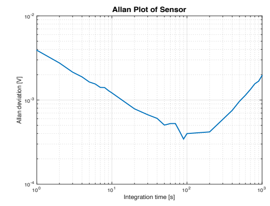


Figure 5: Allan plot of the sensor signals when the sensor was operated under filtered air condition. The Allan deviation decreases as a function of integration time. The minimum Allan deviation is at 90 s. When the integration time is more than 90 s, the Allan deviation increases again due to random noises such as the fluctuations in sensor detector electronics, temperature, or other unknown factors.

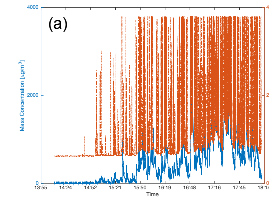


Figure 6: Plots of sensor signals and mass concentrations of (a) raw data, (b) 1-minute moving averages, and (c) 5-minute moving averages during experiment period. Moving average did improve the correlation between the sensor signals and the mass concentrations, but temporal resolution in the signal is lost.

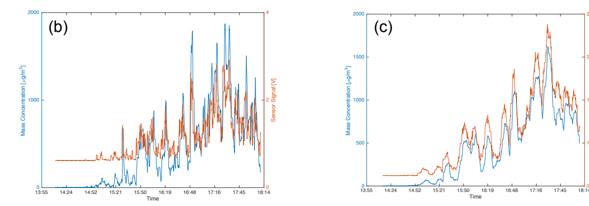


Table 2: R^2 and correlation coefficients (b0 and b1) of 1-minute and 5-minute moving averages using linear relationship Y = b0 + b1X

Data	R^2	b0	b1
1-min moving average	0.8528	-497.6	837.5
5-min moving average	0.9760	-544.4	905.3

Table 3: Average mean sensor signals and soot index of the three candles

Types of candles	Average mean sensor signals [V] (*)	Soot index [Si/h]**
Hand-made paraffin outdoor candles	6.11E-01 (1)	1.051
Paint-coated paraffin candles	7.40E-01 (5)	7.924
Standard machine-made paraffin indoor candles	6.10E-01 (2)	0.068

*The number of experiments performed for each candle.
**Data provided by Balthasar AG.

5 Materials

5.1 Candles (Figure 7)

(a) A hand-made paraffin outdoor candle
(b) A paint-coated paraffin candle
(c) A standard machine-made paraffin indoor candle

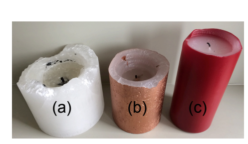


Figure 7: Three types of candles tested in this study

5.2 Light scattering sensor

The sensor tested in this study is shown in **Figure 8**.

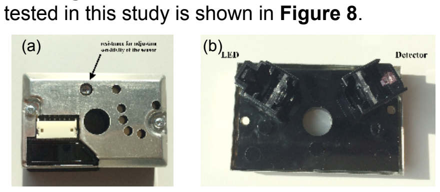
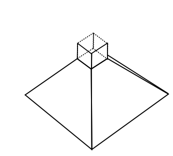


Figure 8: (a) Optical dust sensor GP2Y1010AU0F (Sharp) (b) the configuration of an incident light source (LED) and a detector

6 Conclusions and outlook

- The hand-made paraffin outdoor candles and the paint-coated paraffin candles had similar particle size distribution, while the standard machine-made paraffin indoor candles had smaller particle size. Three types of candles had non-significantly different emissions in terms of number concentration, number emission factor, and number emission rate with 95% confidence interval. The hand-made paraffin outdoor candles and the paint-coated paraffin candles had similar mass concentration, mass emission factor, and mass emission rate, while the standard machine-made paraffin indoor candles had significantly lower values with 95% confidence interval.
- The results suggest that the sensor is sensitive enough to have the potential to be employed in the candle industry for quality-check proposes.
- **Outlook:** The sensor should be further developed for the contribution to the application in candle industry. The authors recommend building the funnel as an inlet for the sensor in order to be able to collect as much emissions as possible (**Figure 9**). Moreover, further studies should be performed to correlate the sensor signals with the currently used soot index. This might allow to better correlate the sensor signal with the soot index.

Figure 9: The proposed model of the sensor for further study. The upper part is the sensor that is installed in an air-sealed box. The lower part is the funnel extending from the inlet of the sensor.



7 Acknowledgements

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We acknowledge Balthasar AG for providing equipment and soot index data of the candles.

8 References

[1] DIN EN 15426:2008-01; Kerzen-Spezifikation für das Russ verhalten; Deutsche Fassung EN 15426:2007
[2] ASTM F2326 - 04(2015); Standard Test Method for Collection and Analysis of Visible Emissions from Candles as They Burn

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