High Accuracy Model for Measurement of Ozone Concentration Generated by Corona Discharge Ozone Generator

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Abstract

Measurement of ozone concentration via commercial ultraviolet based ozone monitor is fast and reliable, but expensive. Thus, we derive an empirical model based on experiment result to measure ozone concentration using output sample flow rate from corona discharge ozone generator. Experiment result shows the higher the ozone generator output sample flow rate, the higher the ozone concentration generation. The model is verified for ozone concentration from 514.4 ppm to 973.0 ppm and output flow rate from 1.317×10^{-5} m^3 s^{-1} to 2.540×10^{-5} m^3 s^{-1}. Linearity test confirms derived model to overestimate less than 0.3556 % compared to actual ozone concentration.

Keywords: Ozone; Accuracy; Concentration; Corona Discharge; Flow Rate; Model; Sensor

1. Introduction

Today corona discharge technique is commonly applied in commercial ozone generators for stable production of ozone concentration. The technique has received much attention from researchers for the past few years. Ozone has been generated using various gases. For example, researchers have attempted to feed dry air (Yehia A. *et al*., 2004; Yehia A., 2007; Yehia A. and Mizuno A., 2013), nitrogen and oxygen mixture (Hadji K. *et al*., 2024), pure oxygen (Mennad B. *et al*., 2010; Pontiga F. *et al*., 2002; Vijayan T. and Patil J. G., 2011; Yanallah K. *et al*., 2009; Yanallah K. *et al*., 2011; Yanallah K. *et al*., 2012), humid air (Awad M. B. and Castle G. S. P., 1975; Bo Z. *et al*., 2013; Castle G. S. P. *et al*., 1969; Wang P. and Chen J., 2009), carbon dioxide (Mikoviny T. *et al*., 2007; Skalny J. D. *et al*., 2007), n-heptane contaminated air (Pekárek S., 2008) or halomethane contaminated oxygen (Skalný J. D. and Mason N. J., 2002) for ozone generation by corona discharge method. Concentration of ozone generated depends on type of gas input. The higher the oxygen to nitrogen content ratio that is fed to ozone generator, the higher the ozone density generation (Hadji K. *et al*., 2014). This is because oxides of nitrogen are formed along with ozone when nitrogen and oxygen are fed to ozone generator (Hadji K. *et al*., 2014; Yehia A. and Mizuno A., 2013).

Commercial ultraviolet based ozone monitor is preferred for ozone concentration measurement due to high accuracy, high speed measurement and long term reliable usage. However, high cost of measurement of ozone concentration generated by ozone generator has motivated researchers to measure ozone concentration using secondary variables (Zhang H. *et al*., 2010). For example, soft sensor has been developed to reduce cost of direct measurement of ozone concentration, but the sensor has large relative error of concentration of less than 5 % (Zhang H. *et al*., 2010). Furthermore, models that relate ozone concentration and gas flow rate to ozone generator are previously established (Awad M. B. and Castle G. S. P., 1975; Castle G. S. P. *et al*., 1969; Hadji K. *et al*. 2014; Yehia A. *et al*., 2004; Yehia A., 2007; Yehia A. and Mizuno A., 2013). However, previous work relates ozone concentration with input gas flow rate to corona discharge ozone generator. The models serve as ozone concentration controllers for ozone generator. They are useful for optimization and design of a new corona discharge ozone generator, but does not serve as ozone concentration sensor. Relation between output gas flow rate from ozone generator and ozone concentration is rarely discussed in the literature. Thus, there is a need to relate these two parameters for low cost measurement of ozone concentration generated by corona discharge ozone generator.

We develop an empirical model for corona discharge ozone generator based on experiment result and verify its accuracy to calculate ozone concentration. The model calculates ozone concentration generated by Longevity Resources corona discharge ozone generator EXT50, as it is available in our laboratory. The model reduces cost of direct ozone concentration measurement by measuring secondary variable, output sample flow rate from ozone generator. This is because commercial dry ozone compatible flow meter is very much cheaper than commercial ultraviolet based ozone monitor. The model calculates ozone concentration for medium range ozone concentration application such as fungicide removal from strawberry (Heleno F. F. *et al*., 2014). This work illustrates an example for corona discharge ozone generator users to derive a model for low cost measurement of ozone concentration at high accuracy.

2. Experiment Setup

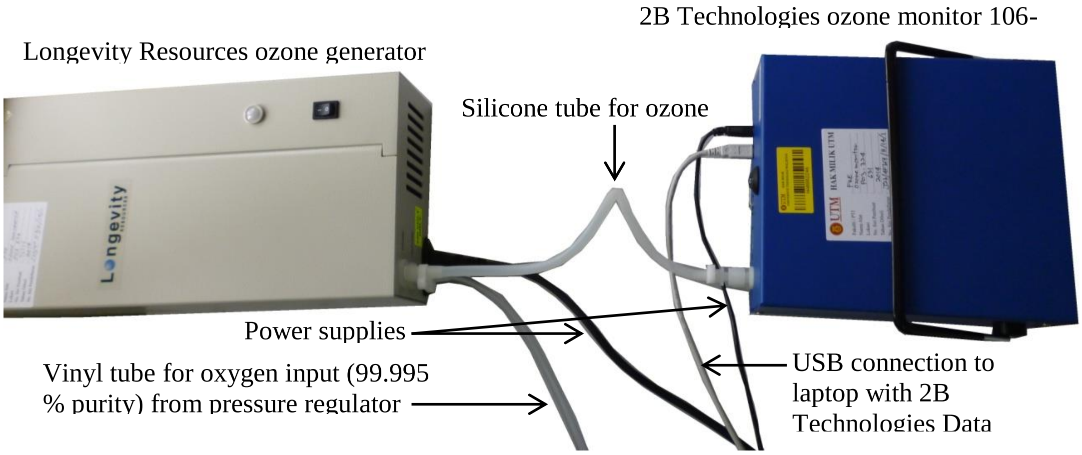

Figure 1. Experiment setup to use 2B Technologies ozone monitor 106-M for measurement of ozone concentration and output sample flow rate generated by Longevity Resources corona discharge ozone generator EXT50

Firstly, equipments that consist of pure oxygen supply, pressure regulator, ozone generator, ozone monitor, silicone tube, vinyl tube and pneumatic fittings are arranged for experiment preparation according to Figure 1 in our laboratory. An hour is allocated for warm up of 2B Technologies ozone monitor 106-M before commencement of experiment. Ozone compatible pneumatic fittings are used for gas leakage prevention. After that, pure oxygen supply of 99.999% purity by Southern Industrial Gas is fed to Longevity Resources corona discharge ozone generator EXT50 using vinyl tube. Next, ozone generator is on. The input flow of oxygen supply to ozone generator is controlled step by step via pressure regulator from high flow rate to low flow rate. After that, ozone generated from ozone generator is fed directly via silicone tube to 2B Technologies ozone monitor 106-M for measurement of ozone concentration and output sample flow rate from ozone generator. Measurements from the ozone monitor are transferred to laptop every 10 s using USB cable and 2B Technologies Data Display Application. Finally, a model is empirically derived based on experiment result and verified for its accuracy to calculate ozone concentration.

3. Model Derivation

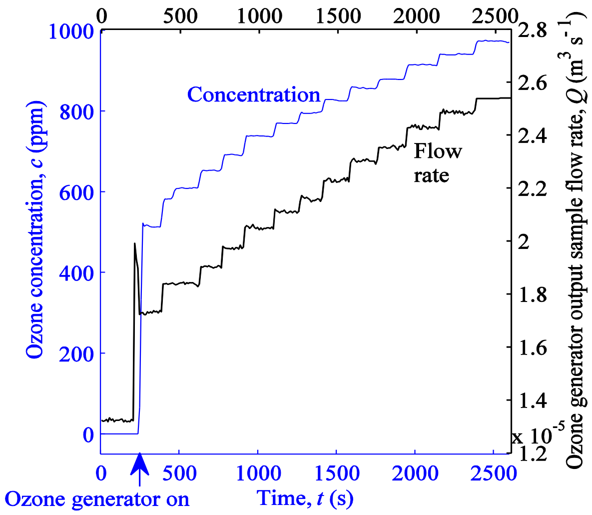

Figure 2. Simultaneous experiment measurements of ozone concentration and ozone generator output sample flow rate by 2B Technologies ozone monitor 106-M for 43 minutes and 20 seconds

Figure 2 shows experiment result obtained from 2B Technologies ozone monitor 106-M for simultaneous measurements of ozone concentration and ozone generator output sample flow rate. During the course of experiment, ozone monitor gas cell temperature increases from 302.8 K to 306.4 K; whereas, ozone monitor gas cell pressure slightly fluctuates in between 1.1903 atm and 1.1904 atm after ozone generator is on. The change in temperature and pressure has been considered in 2B Technologies ozone monitor 106-M for calculation of ozone concentration. Time for ozone concentration to stabilize is between 20 s and 30 s. The response time is acceptable compared to other ultraviolet based ozone sensors reported in previous work (0.7 s to 60 s) (Aoyagi Y. *et al*., 2012; Degner M. *et al*., 2009; Degner M. *et al*., 2010; Maria L. D. *et al*., 2008; Maria L. D. and Bartalesi D., 2012; O'Keeffe S. *et al*.,2007; O'Keeffe S. *et al*., 2005). Based on Figure 2, we infer that ozone concentration generated by ozone generator depends on output sample flow rate from ozone generator. Discussion of result is continued in Figure 3.

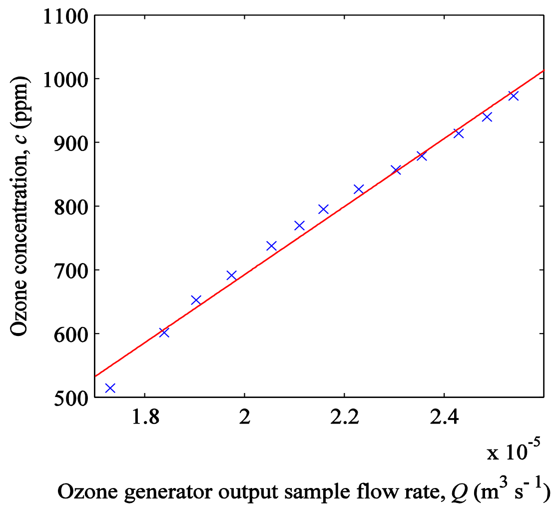

Figure 3. Graph of ozone concentration versus ozone generator output sample flow rate deduced from Figure 2

Figure 3 shows graph of ozone concentration versus ozone generator output sample flow rate deduced from Figure 2. Data points after 30 s of step change in Figure 2 are averaged so that only stable ozone concentration and ozone generator output sample flow rate are considered to plot Figure 3. Figure 3 shows ozone concentration increases linearly from 514.4 ppm to 973.0 ppm when ozone generator output sample flow rate increases from 1.317×10^{-5} m^3 s^{-1} to 2.540×10^{-5} m^3 s^{-1}. This linearity is not observed above ozone concentration of 1000 ppm because 2B Technologies ozone monitor 106-M is calibrated to measure 0 ppm to 1000 ppm only. Longevity Resources ozone generator EXT50 is found to generate minimum concentration of 514.4 ppm using 99.999% purity input oxygen. Based on Figure 3, an empirical equation to relate ozone concentration and output sample flow rate from ozone generator is derived based on linear regression analysis via MATLAB as shown in equation (1).

$$c = 5.3413\times10^{7}Q - 374.12 \qquad (1)$$

c is concentration of ozone generated by corona discharge ozone generator in parts per million by volume (ppm)
Q is output sample flow rate from corona discharge ozone generator in m^3 s^{-1}

According to experiment result in Figure 1, step by step decrease of oxygen input flow rate to ozone generator has caused step by step increase of ozone generator output sample flow rate and ozone concentration. The finding is in good agreement with previous work (Awad M. B. and Castle G. S. P., 1975; Castle G. S. P. *et al.*, 1969; Hadji K. *et al*. 2014; Yehia A. *et al.*, 2004; Yehia A., 2007; Yehia A. and Mizuno A., 2013). Previous work models show the lower the input gas flow rate to ozone generator, the higher the ozone concentration generation (Awad M. B. and Castle G. S. P., 1975; Castle G. S. P. *et al.*, 1969; Hadji K. *et al*. 2014; Yehia A. *et al.*, 2004; Yehia A., 2007; Yehia A. and Mizuno A., 2013). This is because low input gas flow rate to ozone generator has long residence time in a fixed volume of ozone generator reactor for ozone production (Hadji K. *et al*. 2014; Yanallah K. *et al.*, 2011; Yehia A. *et al.*, 2004; Yehia A., 2007; Yehia A. and Mizuno A., 2013). In addition, experiment result in Figure 2 shows the higher the output sample flow rate from ozone generator, the higher the ozone concentration generation. In other words, high concentration of ozone is produced at low input gas flow rate to ozone generator. Since large amount of ozone is produced, flow rate of ozone that leaves ozone generator is high. Thus, high output sample flow rate from ozone generator corresponds to high ozone concentration generation. Based on this fact, we develop a model in equation (1) to calculate ozone concentration based on output sample flow rate from ozone generator. Previous work models may be used to control ozone concentration generated by corona discharge ozone generator, but derived model may be used to sense ozone concentration generated by corona discharge ozone generator.

4. Model Verification

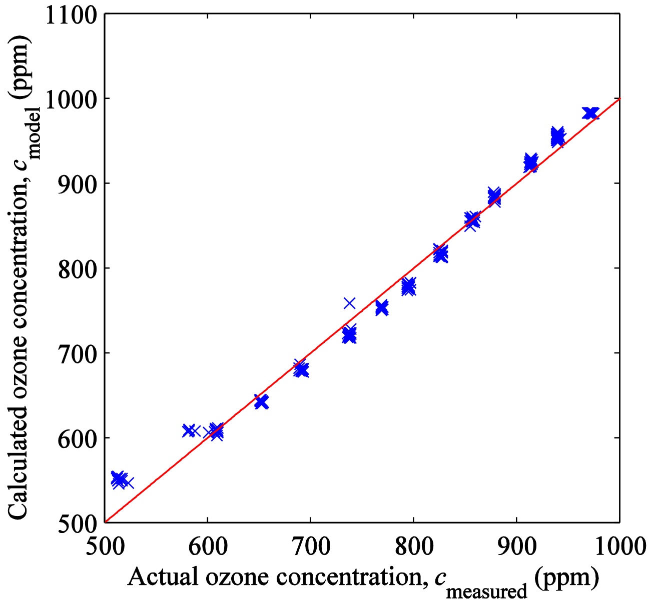

Figure 4. Linearity test for verification of model calculated ozone concentration with actual ozone concentration measured experimentally via commercial 2B Technologies ozone monitor 106-M

Figure 4 shows linearity test to verify accuracy of concentration calculation by derived model in equation (1) in comparison to actual ozone concentration measured experimentally by commercial 2B Technologies ozone monitor 106-M. Best fit line obtained via MATLAB R2013a in Figure 4 is shown in equation (2). As a result, the derived model has high calculation accuracy in comparison to actual concentration, because slope of graph, 0.99897 is close to 1 in equation (2). Based on linearity test result in equation (2), derived model slightly overestimates actual ozone concentration measured by ozone monitor 106-M by less than 1.8291 ppm. The value is considered small for ozone concentration measurement range between 514.4 ppm to 973.0 ppm (overestimation of less than 0.3556 % calculated from 1.8291/514.4×100). Previous work model has prediction error of less than 5 % (Yehia A. *et al*., 2004). Thus, model is verified to have high accuracy for calculation of ozone concentration based on ozone generator output sample flow rate. The discrepancy may be due to ozone destruction due to high corona current (Yehia A., 2007; Yehia A. and Mizuno A., 2013), saturation of ozone concentration generation (Yehia A. and Mizuno A., 2013), ozone decomposition due to wall effect (Mennad B. *et al*., 2010) and ozone decomposition due to long residence time of ozone in generator (Wang P. and Chen J., 2009), that are not taken into consideration during the course of model derivation. This shows the need to improve accuracy of model in future work by identifying factors that overestimate ozone concentration.

$$c_{\text{model}} = 0.99897 c_{\text{measured}} + 1.8291 \quad (2)$$

c_{model} is calculated concentration of ozone via derived model in equation (1) in parts per million by volume (ppm)

c_{measured} is measured concentration of ozone in experiment via commercial 2B Technologies ozone monitor 106-M in parts per million by volume (ppm)

5. Conclusions and Recommendations

An empirical model in equation (1) is derived for corona discharge ozone generator to relate primary variable, ozone concentration and secondary variable, output sample flow rate from ozone generator. The model is derived based on experiment result using Longevity Resources corona discharge ozone generator EXT50 and 2B Technologies ozone monitor 106-M. Experiment result shows the higher the output sample flow rate from ozone generator, the higher the ozone concentration generation. Due to range limitation of equipments, the model is verified for specific range of ozone concentration (514.4 ppm to 973.0 ppm) and output sample flow rate from ozone generator (1.317×10^{-5} m^3 s^{-1} to 2.540×10^{-5} m^3 s^{-1}). The model calculates ozone concentration at high accuracy, as linearity test confirms slight overestimation of less than 0.3556 % compared to actual concentration measured by ozone monitor 106-M. Since direct measurement of ozone concentration is expensive, the proposed method is relevant for corona discharge ozone generator users to derive high accuracy model to calculate ozone concentration based on low cost measurement of ozone generator output sample flow rate. Finally, we recommend future work to incorporate ozone decomposition factors in model to improve accuracy of ozone concentration calculation.

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