Smart Electronic Cigarettes with Built-in Aerosol Sensors

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***Abstract*—This work introduces an emerging application of aerosol sensors integrated inside electronic cigarettes. Using the aerosol sensors, particle size distribution, aerosol temperature, and target chemicals of the generated aerosols are measured before the aerosol is inhaled by a user. When a hazardous aerosol is detected, the user will be warned immediately to stop vaping. With extensive sensor data collected from every puff, an electronic cigarette becomes a smart mobile device, capable of tracking and improving a user's vaping habits. Experimental results on a prototype are presented and have shown great promises towards minimizing the health risks of vaping.**

***Index Terms*—electronic cigarette, vaping, optical particle sensor, photometric measurement, particulate matter**

I. Introduction

An electronic cigarette (e-cigarette), also known as an electronic nicotine delivery system (ENDS), is a battery-powered electronic device that can atomize an e-liquid into an aerosol to be inhaled by a user. The generated aerosol is comprised of high-density nicotine-containing fine particles, and can mimic traditional cigarette smokes generated from burning tobaccos. The use of e-cigarette is growing in popularity in recent years, as they are generally believed to be healthier than smoking combustible tobacco and can be beneficial for cessation of traditional smoking [1]. Generally speaking, properly vaping high-quality e-cigarette products can be less harmful than smoking traditional cigarettes of combustible tobacco. One study showed that the levels of carcinogens and toxicants in the aerosols produced from e-cigarettes were one to two orders of magnitude lower than from traditional cigarette smoke [2]. However, poorly manufactured e-liquids and e-cigarettes can generate even more harmful constituents than traditional cigarettes [3]. Furthermore, many e-cigarette users tend to vape in harmful fashions unknowingly. For example, certain e-cigarette users have strong cravings for rich content of nicotine in the aerosols and tend to overheat the e-liquids to gain more nicotine output. Such types of vaping habits can cause users to inhale very harmful carcinogenic constituents including volatile organic compounds (VOCs) and aldehydes, which are produced due to thermal decompositions of e-liquids at too high temperatures [4].

There is a great deal of concern about the health risks associated with usage of e-cigarettes and the regulation of e-cigarette products is currently one priority mission, as well as a severe challenge, for U.S. Food and Drug Administration (FDA) [5]. Due to the lack of standardization in e-cigarette and e-liquid manufacturing and quality control, harmful compounds in e-cigarette aerosols, including trace metals, formaldehyde, acrolein, and other carcinogenic compounds, vary among e-cigarette manufacturers [6]–[8] and device types [9]. Another important consideration of e-cigarette aerosol is the particle size distribution in the aerosol, which determines the penetration of particles into the respiratory system [1]. Studies have shown that the particle size distribution of an e-cigarette aerosol mainly depends on the smoking habit of the user, known as that user's puffing topography [1], [8] and can also vary among different e-cigarette brand devices [1]. These aforementioned variations, including e-cigarette brand/manufacturer, device type, quality control, and puffing topography among individual users, demonstrate the urgent needs for developing solutions to monitor and analyze e-cigarette aerosols for individual users.

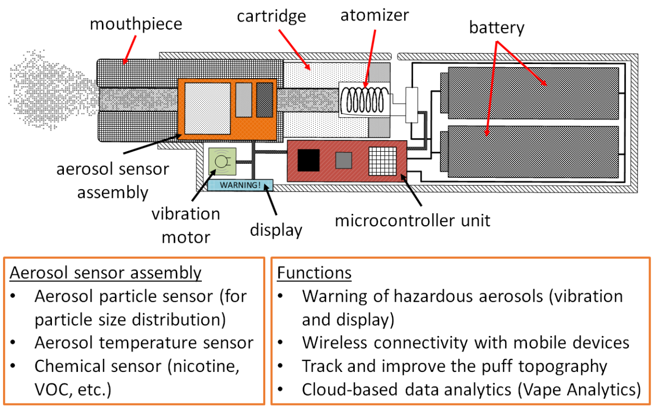

Fig. 1. Concept of smart e-cigarette with built-in aerosol sensors.

This work introduces a concept of smart e-cigarettes with built-in aerosol sensors, which can measure the e-cigarette aerosols before being inhaled and can also track user's every puff to analyze personal puffing topographies, in order to minimize health risks in vaping e-cigarettes. As shown in Fig. 1, a smart e-cigarette is essentially an e-cigarette equipped with an aerosol sensor assembly installed onto the aerosol passage. The aerosol is generated when the power supply (battery) heats the coil housed in the atomizer, which contains a wicking material saturated with e-liquid (stored in the cartridge). When the coil heats up, the e-liquid in contact with the coil vaporizes, and then quickly condenses into an aerosol of fine particles. The aerosol sensor assembly is comprised of an aerosol particle sensor for measuring the particle size distribution and concentration, an aerosol temperature sensor, and a chemical sensor for detecting nicotine, VOCs and other chemicals in the aerosol. Using the sensor data collected from each puff, the potential health risks can be immediately evaluated before the aerosol is inhaled by the user and a warning can be triggered to prevent the user from inhaling the bad aerosols. When a hazardous aerosol is detected, a warning message is flashing on the display and the device also vibrates via the built-in vibration motor.

The smart e-cigarette is wirelessly connected with a smart mobile device to enable more advanced applications. The sensor data can be stored and processed using the app installed on the mobile device to track the user's puffing topography. Furthermore, the collected individual data can be uploaded into a cloud-based data analytics service to predict the user's health risks, to make effective guidance for improving the puffing topography, and to study the links between vaping and certain cardiovascular/respiratory diseases (a concept called "Vape Analytics" [10], developed by the author).

II. Materials and Methods

A. Aerosol sensor assembly

The major components of the aerosol sensor assembly are shown in Fig. 2(a). For the photometric aerosol particle sensor, this work implements a commercial optical smoke sensor MAX30105 (manufactured by Maxim Integrated), which was pre-soldered on a breakout board (by Pimoroni). The temperature sensor and chemical sensor are combined into one sensor on a commercial gas sensor BME680 (manufactured by Bosch), which was pre-soldered on a breakout board (by Adafruit). BME680 sensors have been used to detect indoor e-cigarette aerosols that were already released into a room [11]. However, it has not been implemented for built-in sensing application yet. Inside the BME680 sensor, the aerosol temperature is directly measured from the thermistor inside, while the VOC chemicals in the gas is measured from the resistance of a metal oxide sensing layer which is altered by the concentrations of VOCs. The microcontroller unit (MCU) is a M5-StickC (manufactured by M5STACK), which has an ESP32 microprocessor (by Espressif), a built-in battery, a color display, push buttons, and wireless communication module. The MCU was programmed using Arduino C. The MAX30105 and BME680 sensors are both connected with the MCU through Inter-Integrated Circuit (I2C) communication protocol.

B. Photometric measurement of e-cigarette aerosols

Mulder et al. have demonstrated strong links between the aerosol particle size distribution and the operating condition of an e-cigarette, particularly when the generated aerosol contains harmful substances above a safety limit [12]. Floyd et al. have revealed that when an e-cigarette's atomizer is overheated, the mass ratio of smaller particles in the generated aerosol will decrease [13]. Therefore, it is viable to monitor the operating

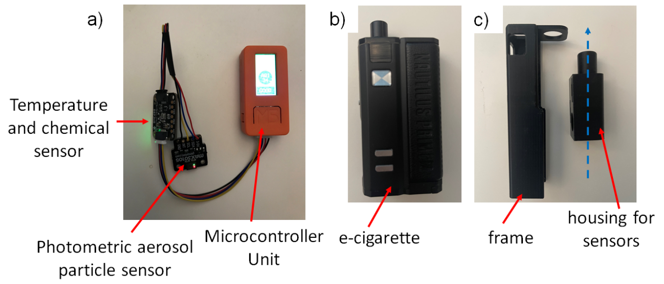

Fig. 2. Components used in constructing a smart e-cigarette. (a) Sensor assembly comprising a photometric aerosol particle sensor, a combined temperature and chemical sensor, and a microcontroller unit. (b) E-cigarette module. (c) 3-D printed frame and housing components. The blue dashed line shows the aerosol passage inside the printed housing for sensors.

condition of an e-cigarette by analyzing the ratio of smaller particles over larger particles. In this work, the particle size distribution is estimated through a simple configuration based on photometric measurement using multiple wavelengths. Fig. 3(a) shows the schematic of using MAX30105 sensor for conducting multi-wavelength photometric measurement. The three LEDs emit light at center wavelengths of 527 nm (green LED), 660 nm (red LED), and 880 nm (near-infrared LED). The three LEDs are switched on in an alternating fashion such that only one color of light is detected by the photodiode at a time. The intensity signals collected from the photodiode indicate the light scattering for the different wavelengths, given as I_{527nm}, I_{660nm}, and I_{880nm}, respectively. Due to the nature of MIE scattering [14], the near-infrared light is more sensitive to larger particles while the green light is more sensitive to smaller particles. Such a photometric response is confirmed by the curves shown in Fig. 3(b), which were calculated using MiePlot [15]. Herein, the particle size distribution is estimated by a number named as particle size distribution index (PSDI), calculated as $PSDI = A_0 I_{527nm}/I_{880nm}$, in which A_0 is a constant to normalize the PSDI. The calculated PSDI essentially tells the mass concentration ratio of smaller particles over larger particles. The value of A_0 is experimentally calibrated such that a PSDI of 50 is a threshold for making decisions on the aerosol quality.

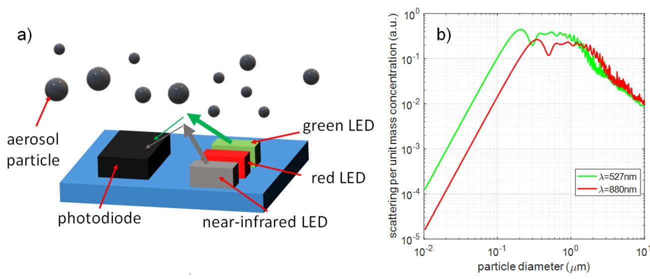

Fig. 3. (a) Schematic of photometric measurement in the aerosol particle sensor. (b) Theoretical calculation of light scattering intensity per unit mass concentration vs. particle diameter for two different wavelengths 527 nm and 880 nm.

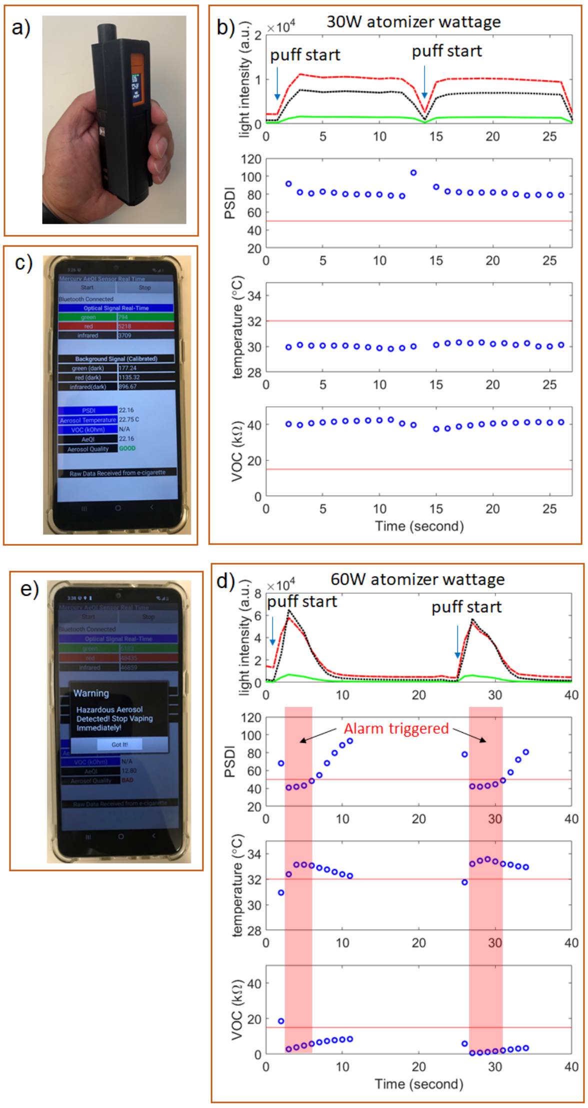

Fig. 4. Experimental results of a smart electronic cigarette prototype. (a) Photograph of the prototype. Real-time sensor signals collected from the electronic cigarette operating at (b) 30 W atomizer wattage (normal heating condition) and (d) 60 W atomizer wattage (over-heated condition). The black, red, and green curves are signals from wavelength 880 nm, 660 nm, and 527 nm, respectively. The horizontal red lines in the graph mark the safety thresholds for individual parameters. Photograph of the connected smartphone screen for (c) normal heating condition and (e) over-heated condition.

C. Integration of aerosol sensor assembly with e-cigarette

Fig. 2(b) shows the e-cigarette module used in this work, which is an Aspire Nautilus Prime X, equipped with a BP mesh coil (0.3 Ω) and filled with an e-liquid (KSPR by BB VAPES BRVND, nicotine 11.59 mg/mL). The housing and retaining frame were designed with SOLIDWORKS and 3-D printed using PLA plastic, as shown in Fig. 2(c). There are ports on the housing to insert the sensors inside to access the aerosol, and the aerosol passage in the housing is connected to the mouthpiece of the e-cigarette. All connections are sealed with soft silicone to be air-tight.

D. Wireless data communication

The e-cigarette is wirelessly connected to an Android smartphone via Bluetooth. The Android app on the smartphone was programmed using MIT App Inventor (shown in Fig. 4(c)(e)). The sensor data are communicated in real-time. When a hazardous aerosol is detected, besides the warning on the smart e-cigarette device, a push notification will also be triggered on the connected smartphone to warn the user of the dangerous vaping action.

III. Results and Discussion

Fig. 4 shows the experimental results of the sensor signals collected from the constructed prototype of smart e-cigarette. When the atomizer of the e-cigarette was operating in a manufacture-recommended heating condition, such as 30 W wattage(Fig. 4(b)(c)), the measured sensor signals indicated high quality aerosols. The PSDI reached about 80, which is above the safety threshold and no alarms were triggered. It should be noted that the PSDI, temperature, and VOC (resistance) are only calculated when aerosol concentration is sufficiently high (meaning that there is actual aerosol inside the aerosol passage), which is determined from the scattered light intensity. When the atomizer wattage is increased into 60 W(Fig. 4(d)(e)), which is an over-heated condition, the sensor picked up a PSDI about 40, which was below the safety threshold. The alarm was immediately triggered, the device vibrated immediately, warning message was flashing on the display, and a push notification was also triggered on the connected smartphone (Fig. 4(e)). The results have shown the great potentials for using the sensors to prevent users from inhaling dangerous e-cigarette aerosols.

The readings of the aerosol temperature and the VOC sensor resistance match well with the measured PSDI in real time. For the over-heated condition, the aerosol temperature can reach $33°C$, which is generally not a comfortable temperature for a user to inhale. The VOC sensor's resistance decreases significantly when the aerosol is generated from the over-heated atomizer, indicating the concentration of VOC is increasing. It should be noted that, the readings of temperature and VOC resistance have much stronger hysteresis than the PSDI. The entire sensor assembly of the prototype consumes about 2.7 watts power of the battery.

IV. Conclusion

A prototype of smart electronic cigarette incorporating aerosol sensors has been demonstrated in this work. The experimental results have shown the sensor system functions as expected and is effective in preventing the user from inhaling dangerous aerosols. This emerging application can open new routes for minimizing health risks in vaping and can also enable vape analytics for tracking and modifying users' puffing topography.

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