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Automated Volume Measurement, Adulteration Detection, and Tracking of Petroleum Products

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Abstract

The quantity of crude oil, petrol, diesel, or kerosene stored in storage tanks by the refineries, bulk oil terminals/depots, bulk consumers and petrol pumps is measured by taking the "dip" or height of the product in the tank. The process is manual, and open to theft, manipulation, and inaccurate reporting. Furthermore, petroleum products adulteration is another major challenge as there are no devices capable of detecting adulteration at point of sale (POS) terminals. A significant volume of petroleum products in Nigeria are being diverted and adulterated by corrupt officials to create artificial scarcity or smuggle to neighbouring countries to earn higher profits. The Petroleum Product Volume Estimator and Tracker (PPVET) is a portable electronic device that automatically measures the volume of a petroleum product contained with a receptacle, be it calibrated or uncalibrated. PPVET is also capable of detecting and identifying pure petroleum products, and tracking petroleum products during transportation.

The Petroleum Product Volume Estimator and Tracker has been designed, built, and tested in Effurun, Delta State, Nigeria. The unit accurately measured 9 L of kerosene in a vertical cylinder with a measurement error of 2.2%. The system also demonstrated the ability to distinguish between pure crude oil, diesel, kerosene and petrol, based on their chemical signature data from gas vapor emissions. PPVET demonstrated the ability to track the transportation of a petroleum product along an authorized route, to detect when the product was being diverted outside the authorized route, and to alert the appropriate authorities on the diversion occurence and the GPS location of the diversion.

Future work includes testing the system for automated volume measurement of underground storage tanks and petroleum product tankers, testing the PPVET's ability to detect adulterated petroleum products and to quantity the level of adulteration present in a given petroleum product, and testing the PPVET product tracking capability on a petroleum tanker transporting petroleum products across the country.

Key Words: Automated Volume Measurement, Adulteration Detection, Petroleum Product Tracking, Product Diversion

Introduction

The Department of Petroleum Resources (DPR) in Nigeria, in its procedure guide for determining the quantity and quality of petroleum products in Nigeria, states that the primary measurement method for determining the fiscal quantities of petroleum and petroleum products at all off/shore/onshore facilities and tank farms shall by dynamic measurement method [1]. For this to be possible, these facilities have to be equipped with certified meters such as Positive Displacement (PD) meters, turbine meters, ultrasonic flow meters, Coriolis meters, and Differential Pressure meters, as approved by DPR. However, many flow meters were installed without proper documentation, maintenance and regular calibration schedules [2]. Manual tank gauging, also known as static measurement, is the secondary method of volume measurement utilized by DRR [1]. The measurement of the level of petroleum or petroleum product in a tank is done by Manual Gauging or by Automatic Tank Gauging (ATG) of calibrated tanks. Calibration of vertical cylindrical tanks and horizontal cylindrical tanks is to be done every 5 years, after major repairs or maintenance, if the tank's current reading varies from its last calibration reading, or if the tank is relocated to another position. For manual gauging, a high-quality steel tape of continuous length to cover the total height of the tank is rubbed with paste to give a good contrast between wetted and dry areas, and then is gradually lowered through the dip hatch of the tank. First, the reference height of the storage tank is confirmed, before the tape is then reeled back and the last mark where the petroleum or petroleum product wets the tape is read and taken as the tank dip. Tape sagging or deviation from the vertical lane can introduce appreciable errors into the gauge reading [1].

The tank dip is referred to the appropriate tank calibration table to obtain the gross quantity of oils in barrels at tank temperature. The dip reading is then noted in the gauge tickets and is used to determine accurate level of petroleum or petroleum product in a tank before or after cargo off-take from the tank. Gauge Tickets are completed in quadruplicate and signed by both the officials of the Department of Petroleum Resources and the Company's facility operations supervisor on duty. The original and triplicate copies are given to the company and the duplicate is given to the Department of Petroleum Resources officer-in-charge [1]. The process is manual, and open to theft, manipulation, and inaccurate reporting. There is a need for a simple, portable, electronic device that can automate the manual gauging and product volume estimation and recording for calibrated and uncalibrated tanks. Moving towards an automated petroleum volume measurement system will ensure Nigeria can accurately quantify the volume of crude oil or petroleum products being produced in the country [3] Dip gauge is often used in petroleum filling stations in Nigeria to measure the depth and the volume of hydrocarbon left in the underground storage tank [4], and this process needs to be upgraded.

Adulteration of petroleum products is another major challenge for the Nigerian Oil and Gas Industry. Adulteration is the introduction of a foreign undesirable substance to a substrate which affects the quality of the substrate [5]. In Nigeria, the products that are majorly adulterated are Petrol, Kerosene, and Diesel [6]. Adulteration of diesel by mixing kerosene is a common and widespread practice [7]. Kerosene is often used as an adulterant for diesel and petrol [6]. Kerosene adulteration comes from the addition of water or Petroleum Motor Spirit (PMS) or petrol, or Automotive Gas Oil (AGO) or diesel, or gas condensate, depending on the price deferential between the product and the adulterant [8, 9]. The primary cause of adulteration is greed fuelled by differential tax system on different petroleum fractions [10]. Adulteration leads to increased tailpipe emissions of hydrocarbons, carbon monoxide, nitrogen oxides, particulate matter and the consequent ill effects on public health [10]. Adulterated petroleum products cause explosions that result in deaths, deformities and incalculable damages to consumers of the petroleum products in the country [11]. With a large number of adulterants available in the market (both local and imported) and the fact that adulterated products are difficult to detect at point of sale terminals (POS), the magnitude of these adulterations has grown to alarming proportions [8]. Current methods to detect adulteration in petroleum products require chemical laboratory experiments to measure parameters such as density, API gravity,

viscosity, flash point, evaporation point. These methods cannot be utilized by consumers at point of sale terminals (POS). Ongoing research is being conducted to incorporate sensors into automobile and machines for quick detection of fuel adulteration [12]. There is a crucial need for a portable electronic device capable of detecting and distinguishing between pure and adulterated petroleum products.

In delivering petroleum products to retail outlets there are some shortfall experienced. These are normally as a result of natural loss through evaporation but there are also instances of pilferage and diversion [13]. For example, in Kaduna Central Senatorial Zone, 16.3 percent filling stations lose 10,001-20,000 liters to diversion, while in Kaduna South Senatorial Zone, 34.8 percent filling stations lose 10,001-20,000 liters to diversion [13]. this reveals that the filling stations are faced with issues on diversion of petroleum products. There is a need for petroleum products distribution companies to employ an integrated monitoring and evaluation system to address the problem of product diversion during transportation.

This paper presents the design, fabrication, testing, and use of a portable electronic device for petroleum volume estimation, adulteration sensing, and product tracking during transportation. The device is known as the Petroleum Product Volume Estimator and Tracker (PPVET). PPVET can be used to measure the volume of a petroleum product in calibrated or uncalibrated tanks, and may prove to be valuable substitute for manual tank gauging in the Oil and Gas industry. With its ability to characterize the chemical signature of pure petroleum products using electronic vapor emission analysis, PPVET can be used to test for the presence of adulterants in petroleum products. The PPVET can also be installed in petroleum product transportation vehicles to detect and alert relevant authorities when and where product diversion is taking place.

Materials and Methods

The materials utilized to build a single unit of the Petroleum Product Volume Estimator and Tracker are listed below:

1. Customized Casing
2. Arduino Mega Board
3. Graphic Liquid Crystal Display
4. Ultrasonic Sensors
5. Liquid Level Sensors
6. Gas Vapor Emission Sensors
7. BreadBoard
8. 9V Battery Holders
9. 9 V Battery Power Supply
10. GSM/GPRS/GPS shield
11. KeyPad
12. LoRa communication shield.
13. 5V relay modules

Images of a fabricated PPVET unit are shown in Figure 1. The unit was designed for easy mounting on receptacles of various sizes.

When the unit is switched on, a welcome message is displayed on the GLCD, and the user is given four options to choose from: (a) Volume Estimation (b) Adulteration Sensing (c) Product Tracking, and (d) All three options. User input is received by the system using an integrated keypad (see Figure 1b).

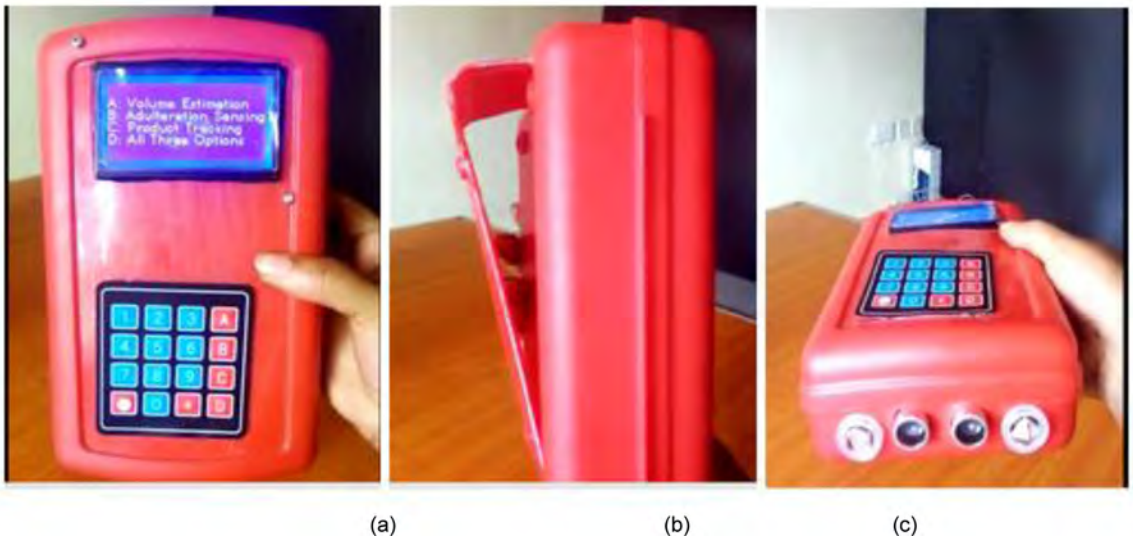

Figure 1—A sible Petroleum Product Volume Estimator and Tracker (PPVET) unit. (a) Front view showing user menu options for Volume Estimation, Adulteration Sensing, and Product Tracking. (b) Side view (c) Side View showing Volume Measurement Sensors.

Volume Estimation

The materials utilized to build a single unit of the Petroleum Product Volume Estimator and Tracker are The unit algorithm for volume estimation is shown in Figure 2. If the User selects volume estimation, the unit then requests the user to specify the shape of the receptacle holding the petroleum product. Four (4) options are available: horizontal cylinder, vertical cylinder, square tank, and rectangular tank. Based on the user's response, the unit then requests the user to input the size parameters for the receptacle. For vertical cylinders, the length and diameter in metres are required. For horizontal cylinders, the length and diameter in metres are required. For square tanks, the length and height of the tank are required. And for rectangular tanks, the length, width, and height in metres for the tank are required.

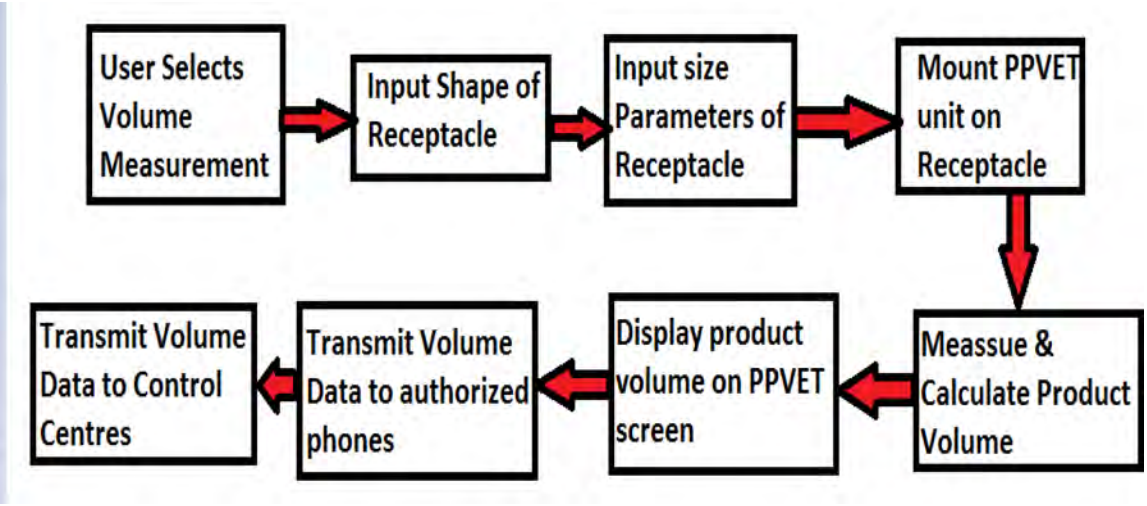

Figure 2—PPVET Algorithm for Automated Volume Measurement and Estimation.

After inputting size parameters, the user is then asked to place the PPVET unit in the receptacle containing the petroleum product and to press the ‘#" key for volume measurement to commence. The volume of the petroleum product contained within the receptacle is measured using ultrasonic sensors and liquid level sensors (shown in Figure 1c), and computed using an inbuilt algorithm for the selected receptacle shape. The

measured volume of the petroleum product is then displayed on the GLCD screen, and is also transmitted to an authorized mobile phone using the GSM/GPRS/GPS shield. For large scale industrial usage in automating petroleum volume measurement in the Oil and Gas industry, this data can also be transmitted wirelessly to dedicated control centres using the customised LoRa 868 MHz communication Network.

Volume Estimation

The unit algorithm for adulteration sensing is shown in Figure 3. If the user selects Adulteration sensing, the unit then asks the user to select the type of petroleum product he/she wishes to check for adulteration. Presently, four (4) options ae available: crude oil, diesel, kerosene, and petrol. After selecting the petroleum product, the user is asked to place the unit inside a receptacle containing a specific volume (1 L) of the petroleum product, press the '#' key, and to seal the receptacle for approximately two minutes. During this time, the unit analyzes the vapors emitted by the petroleum product for concentrations of formaldehyde, benzene, butane, propane, and natural gas. The PPVET has been utilized to obtain the chemical emission signature of pure crude oil, diesel, kerosene and petrol (see Figure 4), and this data has been used to develop a customized algorithm to detect and distinguish between pure crude oil, diesel, kerosene and petrol. It has also ben used to develop customised algorithms to detect the adulteration of any one of these four (4) petroleum products.

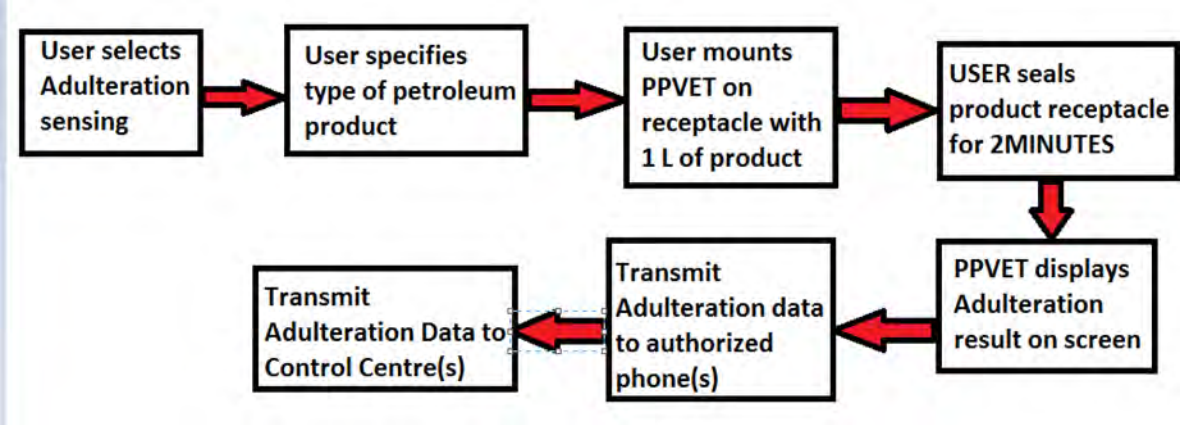

Figure 3—PPVET Algorithm for Automated Adulteration Sensing.

After two (2) minutes, the result of sensing is displayed on the GLCD, informing the user whether the petroleum product is pure or adulterated. This data is also transmitted to an authorized mobile phone using the GSM/GPRS/GPS shield. For large scale industrial usage in automating petroleum product adulteration sensing in the Oil and Gas industry, this data can also be transmitted wirelessly to dedicated control centres using the customised LoRa 868 MHz communication Network.

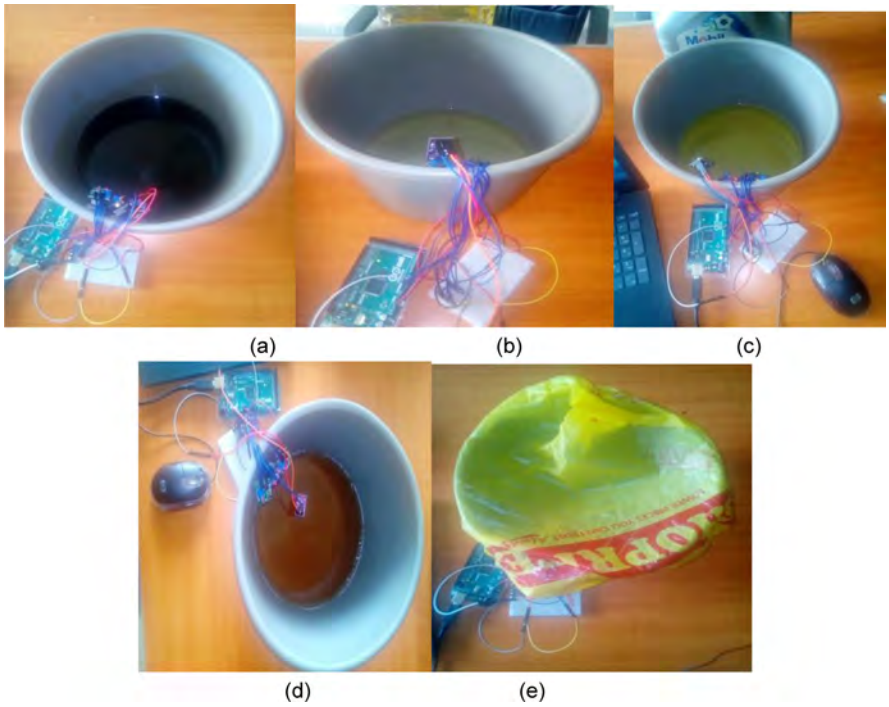

Figure 4—PPVET Adulteration Sensing. (a) Crude Oil Chemical Emission Signature Characterization (b) Kerosene Chemical Emission Signature Characterization (c) Petrol Chemical Emission Signature Characterization (d) Diesel Chemical Emission Signature Characterization (e) Adulteration Sensing by PPVET.

Product Tracking

The unit algorithm for adulteration sensing is shown in Figure 5. If the user selects Adulteration sensing, the unit then asks the user to select an authorized travel route for transporting the product. After selecting from one of four (4) available options, the unit calculates the time it will take to transport the product on that route. It then asks the user to specify the shape and size parameters of the transporting receptacle, and then to place the unit inside the transporting receptacle and to press the '#' key.

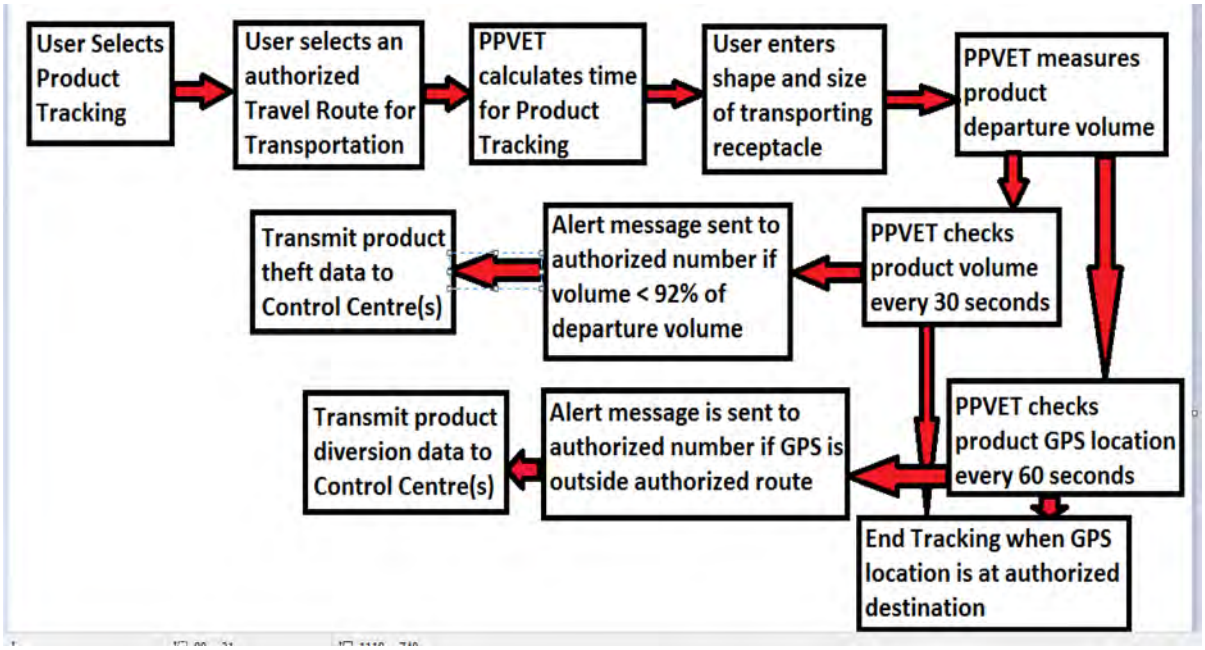

Figure 5—PPVET Algorithm for Product Tracking.

After this is done, the unit automatically measures the product volume prior to departure. Thereafter, every 30 seconds, the unit re-measures the volume of the product during transportation for volume accountability. During transportation, if the measured volume of the petroleum product drops to less than 92% of the measured departure volume, the unit sends an alert message to the authorized mobile phone number, indicating that volume theft occurrence, the volume of product that has been stolen, and the GPS location where the theft occurs. For large scale industrial usage in automating petroleum product tracking in the Oil and Gas industry, this data can also be transmitted wirelessly to dedicated control centres using the customised LoRa 868 MHz communication Network. Every 60 seconds, the PPVET unit checks the GPS location of the transporting receptacle to ensure it is on the authorized transport route that was selected. At any time, if the current GPS location of the transporting receptacle is outside of the authorized travel route, then product diversion has occurred. The unit will then send a diversion alert text message to the authorized mobile phone number indicating product diversion, and supplying the GPS locations where diversion has taken place. For large scale industrial usage in automating petroleum product tracking in the Oil and Gas industry, this data can also be transmitted wirelessly to dedicated control centres using the customised LoRa 868 MHz communication Network. PPVET continually monitors product volume and location for the time duration determined by the selected travel route. Figure 6 shows the PPVET being used to conduct volume measurements of various petroleum products.

Figure 6—PPVET (a) Unit requesting user to select shape of receptacle. (b) Unit requesting user to input height of receptacle in metres. (c) Unit requesting user to mount estimator on receptacle for volume measurement. (d) Vertical cylinder with 0.34 m inner diameter and 0.32 m height used for PPVET volume measurement tests. (e) PPVET mounted on vertical cylinder containing petroleum product. (f) PPVET conducting automated volume measurement and estimation of petroleum product.

In Figure 6a, the PPVET requested the user to select the shape of the receptacle holding the petroleum product. In Figure 6b, PPVET asked the user to input the height in metres of the receptacle holding the petroleum product. In Figure 6c, PPVET requested the user to mount the unit on the receptacle containing the petroleum product. This was done after the shape and size parameters of the receptacle had been received by the unit. In Figure 6d, the vertical cylinder used in testing the automated volume measurement feature of the PPVET is shown. It had an inner diameter of 0.34 m and a height of 0.32 m. In Figure 6e, PPVET was successfully mounted on the vertical cylinder containing the petroleum product. In Figure 6f, PPVET performed automated volume measurement and estimation of the petroleum product.

For testing of the product tracking feature of the PPVET, a customized transport route called "TEST ROUTE" was designed at the Federal University of Petroleum Resources (FUPRE). PPVET was programmed to detect when the petroleum product contained in the receptacle was taken outside of this authorized transport route. The results of our detailed testing of the PPVET are presented in the Results Section.

Results

Figure 7 shows the PPVET conducting automated volume measurement for a petroleum product. Approximately 9 L of kerosene was poured into a vertical cylinder with an inner diameter of 0.34 m and a height of 0.32 L (see Figure 6d). PPVET performed automated volume measurement of this sample. Figure 7a shows the result obtained by PPVET. The volume estimated by PPVET was 8.80, resulting in a measurement error of 0.2 L (approximately 2.2%). The value of the estimated volume of the petroleum product was displayed on the PPVET screen once volume measurement was completed.

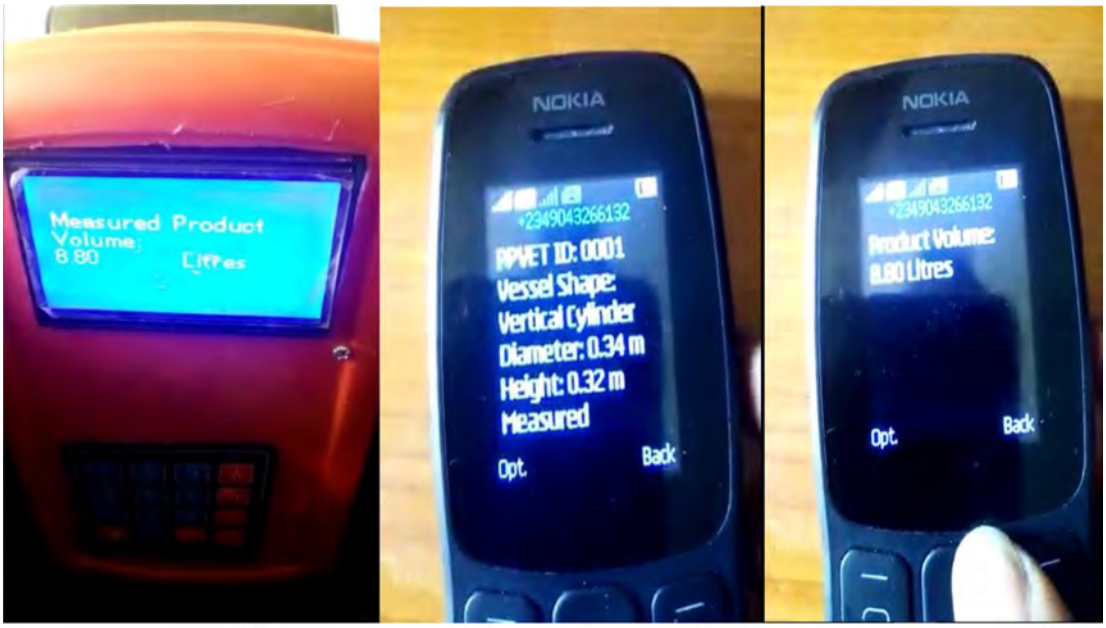

Figure 7—Automatic Volume Measurement by PPVET. (a) PPVET measuring 9L of Kerosene. PPVET sending Volume Alert message to authorized mobile number indicating PPVET ID, Vessel shape and size. (c) P)PVET Volume Alert message to authorized mobile number indicating estimated volume of petroleum product (8.80 L).

After estimation of volume, PPVET sent a Volume Measurement alert message to the authorized mobile phone number. This message contains the ID of the PPVET, as each PPVET is assigned a unique Identification Number. The ID of the PPVET that performed volume estimation for kerosene was 00001. The volume alert message also contains the shape of the receptacle containing the petroleum product (vertical

cylinder in this case), as well as the input size parameters utilized for volume estimation (see Figure 7b). PPVET then reports the estimated volume of the product (see Figure 7c).

PPVET was used to obtain the chemical signatures of crude oil, diesel, kerosene, and petrol. For each petroleum product, the concentration of benzene and formaldehyde, butane and propane, and natural gas for varying volumes ranging from 0.6 L - 3 L in an enclosed space of 5,097 cm^3. The results obtained from the vapor emission characterization of the four petroleum products are shown in Table 1. The output from the Gas Vapor Emission sensors indicate that pure volumes of crude oil, diesel, kerosene and petrol have distinct emission spectrums for natural gas. Kerosene has a distinct emission spectrum for Benzene and Formaldehyde, and diesel has a distinct emission spectrum for butane and propane. This chemical signature data has been utilized to develop an algorithm for detecting and distinguishing between pure crude oil, diesel, kerosene, and petrol in testing samples of 1 L.

Table 1—Measured Vapor Emission Characteristics of Crude Oil, Diesel, Kerosene and Petrol for 0.6 L - 3L.

Petroleum Product	Benzene & Formaldehyde (V)	Butane and Propane (V)	Natural Gas (V)
Crude Oil	1.68 - 2.00	0.45 - 0.65	1.22 - 1.32
Diesel	1.74 - 2.03	0.81 - 0.99	1.76 - 2.03
Kerosene	1.37 - 1.69	0.35 - 0.73	0.82 - 0.96
Petrol	1.70 - 2.45	0.98 - 1.40	2.67 - 3.60

For Product Tracking, a TEST ROUTE was defined at the Federal University of Petroleum Resources. It took approximately 15 minutes to walk this TEST ROUTE and Product Tracking was performed while transporting 9 L of a petroleum product along this route. Figure 8a shows PPVET estimating the volume of the petroleum product prior to departure. Figure 8b shows the PPVET in the petroleum product receptacle being transported along the TEST ROUTE. Figure 8c show PPVET displaying the results of its product tracking, verifying that the petroleum product is still being transported along the authorized route (TEST ROUTE).

Figure 8d shows the petroleum product receptacle being taken outside the authorized TEST ROUTE. PPVET detected the product diversion from the authorized route in 30 seconds (see Figure 8e). Figure 8f shows the diversion alert text message sent to the authorized mobile number indicating the PPVET ID (0001), and the selected authorized route for the transportation of the petroleum product. Figure 8g shows the diversion alert text message indicating the GPS location where the product diversion occurred. Figure 8h shows the diversion text alert message containing a web link to a google map, indicating where product diversion took place. The results indicate that PPVET can be used to detect petroleum product diversion during transportation.

Figure 8—Product Tracking by PPVET. (a) Petroleum Product Volume Estimation by PPVET prior to product departure. (b) Petroleum Product being transported along authorized route (TEST ROUTE). (c) PPVET indicating petroleum product is within authorized route. (d). Petroleum Product being diverted from authorized route (TEST ROUTE). (e) PPVET successfully detecting product diversion within 30 seconds. (f) PPVET diversion text message sent to authorized mobile number showing PPVET ID and authorized route (g) PPVET diversion text message showing GPS location where diversion occurred. (h) PPVET diversion text message with link to google map pinpointing diversion location.

Discussion

The utilization of PPVET as a potential replacement for manual tank gauging has been tested and explored. Since the unit is extremely portable and can be easily attached to the edge of any receptacle holding a petroleum product (see Figure 6 e& f) to conduct volume estimation. Since the unit allows the user to input the shape and size parameters of the receptacle, it can be used for automatic volume estimation for

virtually any kind of receptacle, from underground tanks to vehicle tankers used for petroleum product transportation. It can also be used to perform volume measurements for both calibrated and uncalibrated receptacles. Currently, PPVET can perform automatic volume estimation of horizontal cylinders, vertical cylinders, square tanks and rectangular tanks. Volume estimation tests conducted using the PPVET showed that the unit is capable of measuring volumes of petroleum product with a measurement error of 2.2%, which is reasonable. The unit also demonstrated the ability to transmit receptacle parameters and measured volume to designated mobile phone numbers. This information could also be sent to control centres. The ability to automatically conduct volume measurement of petroleum products and to produce electronic records of the measurements is an improvement to the current method used to generate gauge tickets for record keeping by the Department of Petroleum Resources [1]. This electronic volume estimation technique implemented by the PPVET prevents theft, manipulation, and inaccurate reporting, and can be used to accurately quantify the volume of crude or petroleum products at various stages or processes in the industry. PPVET can also replace the dip gauge used in petroleum filling stations in Nigeria to measure the depth and the volume of hydrocarbon left in the underground storage tanks. Future work includes testing the PPVET automated volume measurement capability on petrol tankers in Nigeria.

The Gas Vapor Emission Sensors of the PPVET were used to obtain and detect the chemical signatures of crude oil, diesel, kerosene, and petrol. The results obtained in Table 1, showed that in an enclosed space of 5,097 cm^3, pure volumes of crude oil, diesel, kerosene and petrol have distinct emission spectrums for natural gas, kerosene has a distinct emission spectrum for benzene and formaldehyde, and diesel has a distinct emission spectrum for butane and propane. This data has been incorporated into the PPVET so that the unit can distinguish and detect pure crude oil, diesel, kerosene, and petrol in testing samples of 1 L. If PPVET is enclosed in a receptacle containing 1 L of any of the four petroleum products, it now has the capability to identify the product, based on the chemical signature of the vapor emissions. This ability will prove useful to consumers purchasing petroleum products in Nigeria, and as this portable electronic device will enable them be able to quickly detect at point of sale terminals (POS), if the product they have purchased is a pure petroleum product or if it has been adulterated. Future work includes testing the PPVET's ability to detect adulterated petroleum products and to quantity the level of adulteration present in a given petroleum product.

PPVET demonstrated the ability to detect and alert authorities when a petroleum product is being diverted for product theft. PPVET successfully detected product diversion during transportation on a TEST ROUTE at the Federal University of Petroleum Resources. The GPS location of the diversion was transmitted to the authorized mobile phone number within 30 seconds. Because the PPVET is portable, it can be easily hooked unto any petroleum product tanker being used for product transportation. Once a tanker has been assigned to travel a certain route to deliver the product to a final destination, PPVET can be programmed to continuously track the movement of the petroleum product during transportation and to alert the appropriate authorities, if the product is diverted during transportation and to provide the GPS location of the diversion. The information can also be transmitted to control centre(s) using a dedicated 868 MHz communication network. This technology can be integrated into the oil and gas transportation system to address the problem of product diversion during transportation. Future work includes testing the PPVET product tracking capability on a petroleum tanker transporting petroleum products across the country.

Conclusion

A portable electronic device called the Petroleum Product Volume Estimator and Tracker (PPVET) has been designed, fabricated, and tested at the Federal University of Petroleum Resources (FUPRE). Results show that the unit is capable of conducting automated volume measurement for calibrated and uncalibrated receptacles, and has the potential to replace the manual tank gauging method. PPVET successfully measured 9 L of Kerosene contained in a vertical cylinder, with a measurement error of 2.2%. PPVET

also demonstrated the ability to distinguish between pure crude oil, diesel, petrol and kerosene, based on their chemical signatures from vapor emissions detected by the unit's gas vapor emission sensors. PPVET also demonstrated the ability to track a petroleum product during transportation and to alert the appropriate authorities when diversion occurs and to provide the GPS location of any and all product diversions.

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