

A new method for estimation of automobile fuel adulteration

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1. Introduction

Since the beginning of the industrial revolution, the air pollution has been on the rise due to fast increasing use of fossil fuels. In particular, the automobile sector has emerged as a major consumer of fuel oil and a major contributor to air pollution. In developing countries like India, China, Brazil the automobile industry is expected to grow at a faster rate in coming years (Velooso, Kumar 2002) accompanied by proportional increase in the air pollution. The problem is essentially global in nature as the tail pipe emissions of automobiles result in an increase in the greenhouse gases in the atmosphere leading to global warming.

Adulteration of automobile fuels i.e. gasoline and diesel, leads to increased tailpipe emission and the consequent ill effects on public health. The primary cause of adulteration is the greed fueled by differential tax system (World Bank reports July 2002, September 2001, December 2001, CSE India report March 2002). For example, in south Asia, gasoline is taxed most heavily, followed by diesel, kerosene, industrial solvents and recycled lubricants, in that order. The fact that adulteration of gasoline by diesel and that of diesel by kerosene, is difficult to detect, combined with the differential tax structure makes such adulteration financially alluring, even though it is illegal. Mixing kerosene with diesel does not lead to an increase in tailpipe emission, but contributes to air pollution indirectly in South Asia. The diversion of kerosene for adulteration drastically brings down its availability, to the poor households, who turn to bio-mass for the purpose of cooking. This leads to an increase in the indoor air pollution and consequent ill effects on health. For the prevention of adulteration, monitoring of fuel quality at the distribution point, therefore, is highly essential.

In the Indian context, the gasoline is adulterated by mixing diesel and diesel is adulterated by mixing kerosene. This is because these types of adulterations when limited to small volume percent are difficult to detect by the automobile user. The expected adulteration percentage is 10 % to 30 % by volume in both the cases. Less than (10%) adulteration is financially unattractive, while more than 30% adulteration is likely to be easily detected by the user from the degradation of the engine performance caused by the adulterated fuel.

To check the adulteration effectively, it is necessary to monitor the fuel quality at the distribution point itself. The equipment for this purpose should be portable and the measurement method should be quick, capable of providing test result within a very short

time. The measuring equipment should also be preferably inexpensive (as a large number of such units would need be simultaneously deployed) and easy to use.

2. Methods for estimation of Fuel Adulteration

The American Society for Testing and Materials International (ASTM International) has developed and documented the test methods for most of the widely used materials including petroleum products. Many ASTM tests for the gasoline and diesel have been standardized and documented. Some of these tests involve determination of physical and chemical properties while others provide a measure of suitability of the fuel for use in automobiles from the point of engine performance / air pollution generated. Though no test is specifically designed to measure the adulteration of petrol by mixing diesel or diesel by mixing kerosene, some tests namely Density test, Evaporation test, Distillation test, Chemical Marker test, Gas Chromatography may be used to determine the adulteration of fuel also. However, none of these methods are suitable for adulteration test in the context mentioned in section-1, as pointed out below.

Density Test (ASTM D4052):

Hydrometers and digital densitometers are used to measure the density of the fuel sample. The reported densities of gasoline, diesel and kerosene at 15°C are in the ranges 0.74-0.75 Kg./L, 0.835-0.855 Kg./L and 0.79-0.80Kg./L respectively. The adulteration causes a change in the density which can be correlated with the adulteration. The method has the advantage that densitometer provides very good accuracy but suffers from the disadvantages that (i) densitometers are expensive and need a controlled environment (for correct operation) which is unlikely to be available in the field at the distribution point and (ii) the change in density is very small even for high level of adulteration as reported in the literature and reproduced below.

No.	Diesel and Kerosene Proportions (v/v)	Density at 15°C (g/ml)	Kinematic Viscosity at 40°C (Cst)
1	Pure Diesel	0.8456	2.63
2	Prescribed Level	0.82-0.86	2 to 3
3	85:15	0.8400	2.33
4	75:25	0.8390	2.16
5	65:35	0.8321	1.89
6	50:50	0.8304	1.83
7	25:75	0.8234	1.5

Table 1. Density and kinematic viscosity of diesel fuel and adulterant kerosene at different proportions (reprinted from Sh. R. Yadav, et.al, 2005).

Similar results for density variation in gasoline and diesel as a function of % adulteration by diesel and kerosene respectively has also been reported by Sharma and Gupta-2007. Therefore the overall sensitivity of this method is rather poor if the change in density is used

as an indicator of extent of adulteration. However as evident from Table 1, the viscosity of the fuel shows a considerably stronger dependence on the % adulteration and therefore should be a preferred parameter to be calibrated against % adulteration.

Evaporation Test (ASTM D3810):

The evaporation techniques are capable of detecting very low concentrations (1-2%) of diesel in gasoline and fairly low concentrations (5%) of kerosene in gasoline. However this is basically a laboratory technique and is not suitable for field use.

Distillation Test (ASTM D86):

This technique exploits the difference in the boiling points of different liquids comprising the fuel sample. Accurate distillation data for uncontaminated fuel is essential for comparison and precise results. The technique, however, is not suitable for field use as the measurement set up is generally bulky and measurement process is time consuming.

Gas Chromatography (GC):

GC is powerful laboratory tool which can be used to detect hydrocarbon based adulterants. However it requires an experienced technician to operate the equipment and interpret the results. It is an effective method for detection of adulterants in gasoline and diesel but would require easily portable, robust and user friendly equipment which may be operated by an inexperienced operator also.

Adulteration Estimation/Detection using Optical Fiber Sensor:

A technique for detection/estimation of adulteration of petrol/ diesel by kerosene using optical fiber sensor has been reported by Roy S. (1999). The technique exploits the change in refractive index and therefore the evanescent absorption of monochromatic light in petrol/ diesel when the same is adulterated by mixing kerosene.

Optical fiber acts as a wave guide for light if the cladding has a lower refractive index than that of fiber material. When the light is reflected from the interface of the fiber and the cladding (or any other material surrounding the fiber), the field associated with the light wave extends beyond the interface into the surrounding medium. The amplitude of this field decreases exponentially with distance from the interface. If the surrounding material absorbs some part of the light propagating through the fiber, the power received at the other end of the fiber would be less by the amount absorbed by the surrounding medium. This idea has been implemented in the experimental set up shown below (Roy S. 1999).

The light source in fig. 1 is a He-Ne laser which is coupled with the optical fiber through a lens. The length of the fiber within the vessel containing the fuel under test is unclad so that the fiber is directly in contact with the absorbing medium that is, the fuel under test. The received power is measured by the power meter.

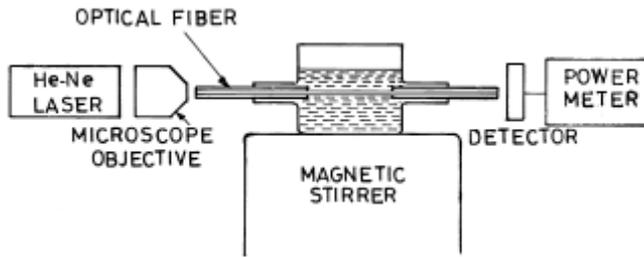


Fig. 1. Optical Fiber Sensor and associated experimental Set up (Reprinted from Roy S., 1999).

The power received by the power meter is reduced by the amount that is absorbed by the fuel through evanescent absorption. The received power at the detector is given by the expression,

$$P(L) = P_0 \cdot \exp(-\alpha \cdot L) \quad (1)$$

where 'L' is length of the unclad optical fiber and 'P₀' is the power transmitted from the laser source end. The parameter 'α' is evanescent absorption coefficient of the fuel and the factor 'exp(-α.L)' accounts for the power absorbed by the fuel through evanescent absorption. The power P(L) is a sensitive function of 'α' which itself depends upon the refractive index of the fuel.

The dependence of P(L) and 'α' (also refractive index of the fuel) have been experimentally investigated by Roy S. (1999) for petrol and diesel adulterated with kerosene. The method is particularly suitable for adulteration detection in petrol as its refractive index (< 1.42) remains lower than that of core of the optical fiber i.e. silica (refractive index =1.457) even after mixing with 50% kerosene which results in smooth (and almost linear) variation of received power with % adulteration. The received power normalized with respect to 'P₀', as observed for petrol adulterated with kerosene are shown in Fig.2. The similar experimental results for diesel adulterated with kerosene are not consistent with the theory and so are not reproduced here.

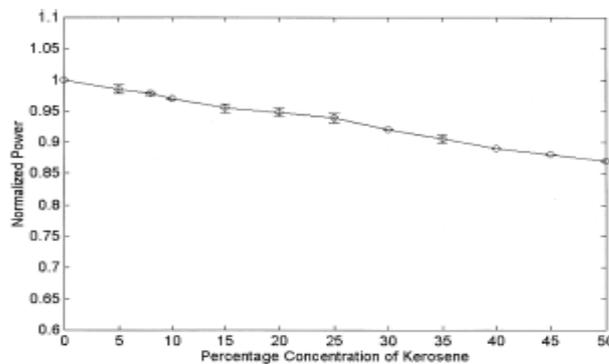


Fig. 2. Normalized power as a function of volume% concentration of kerosene in petrol (Reprinted from Roy S., 1999).

The note worthy feature of this method is that the sensitivity of the sensor can be effectively varied by changing the 'L', the length of unclad fiber because the received power P (L) varies exponentially with 'L'.

3. Adulteration Detection using Sound/Ultrasound-A New Method

As mentioned in the previous section, the adulteration leads to the change in density as well as viscosity of the fuel. Since both these parameters influence the speed of sound in a fluid, it is expected that the speed of sound in the adulterated fuel would be different from that in un-adulterated fuel (Thomas K V et.al. 2004). The effect of adulteration of petrol by diesel and diesel by kerosene on the speed of sound in the fuel sample has been investigated by the authors. The experimental method followed is described in following sub-sections.

Working Principle:

For determination of speed of sound, the time taken by the sound to travel a known distance (commonly termed as Time of Flight or TOF) is to be determined. There are two basic methods for determination of TOF.

(A) Pulse-Echo (PE) Method:

The schematic of the basic experimental set up for this method is shown in Fig. 3. The transmitter TX, excited by an electrical signal of sonic/ultrasonic frequency, emits a pulse of acoustic energy of a short duration.

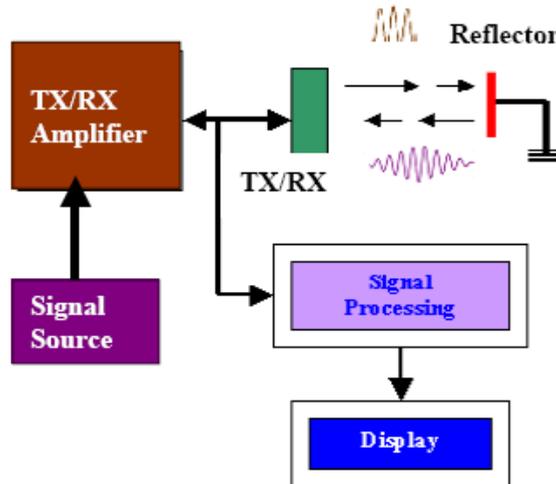


Fig. 3. Basic experimental setup for Pulse-echo method

In general, the transmitting transducer TX also serves as receiving transducer RX (converting received acoustic pulse into electrical signal). The time delay T_D between the transmitted and the received pulse (after reflection from a target) is measured. The value of T_D is related with the speed of sound by the equation,

$$\text{Speed of sound, } V_s = 2d / T_D \quad (2)$$

where 'd' is the distance between the TX/TR and the reflector.

This simple principle of measurement gets considerably complicated due to the following:

- The transducer TX / RX (generally ultrasonic piezoelectric crystals) has narrow bandwidth, which causes the long ringing tails in the emitted pulse. So there is no sharply defined start and end point of the pulse emitted.
- The emitted acoustic pulse gets attenuated in the medium. The attenuation is proportional to the square of the frequency. Therefore, the higher frequency components of the pulse get more attenuated than its lower frequency components. As a result, the received pulse is broadened more as compared to the transmitted one.
- Noise also corrupts the received pulse.
- Echoes from other objects make it difficult to identify the echo from the object under study.
- The resolution (for distance measurement) is limited by the width of the acoustic pulse.

Simple threshold technique, for measurement of T_D , leads to low accuracy in the measurements. Digital Signal Processing (DSP) techniques have been developed to measure T_D more accurately (Parrilla et.al. 1991). In these techniques, the envelopes of the echoes from a reference object and other echo signals, are extracted and a value of T_D , for which there is maximum similarity between the reference and echo signals, is determined, using DSP algorithms. The algorithms used for the purpose are norms L1, L2 and correlation. The procedure is computation intensive and requires considerable dedicated hardware. However, the development of FPGAs has made it easy and cost effective to design correlation detector required for the purpose (Urena J et.al 1999). Cross correlation between the transmitted and the received signals has also been used to determine T_D . More recently the use of wavelet networks, for more accurate measurement of T_D has been reported (Grimaldi D 2006). An interesting method using self-interference of transmitted pulses has been proposed for accurate measurement of Time of Flight (Cai C et.al. 1993). In this method, transmitter emits two pulse trains which interfere with each other in such a way that the wave envelope becomes zero at certain time instant. The time interval between the two pulse trains is so chosen that the envelope zero is halfway between the two waves. The time instants of zero envelope amplitudes are detected and used for determination of TOF. Analysis of sonar pulses emitted by bats has shown that emissions from each bat are uniquely frequency modulated which enables the bat in distinguishing its own emissions from those of other bats. This principle has been implemented in digital polarity correlation detection method. The cross correlation function for clipped transmitted and received signals has been used for measurement of TOF in digital polarity correlation detection method (Nakahira K et.al 2001). A variation of conventional pulse echo method uses Binary-Frequency- Shift- Keyed (BFSK) signal. The time instant where the transition between each frequency occurs is detected and used for determination of TOF (Webster D 1994). This method offers significant improvement in respect of reduction of measurement errors as compared to correlation-based methods.

(B) Continuous Wave (CW) Method:

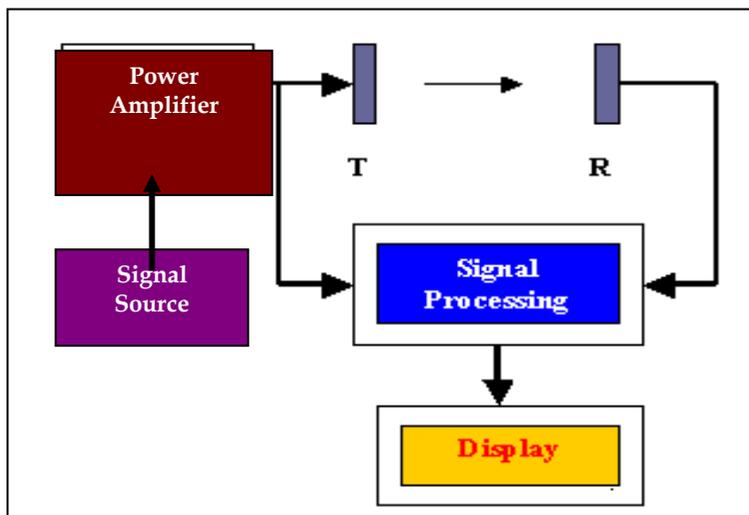


Fig. 4a. Basic Experimental Setup (Continuous Wave Method)

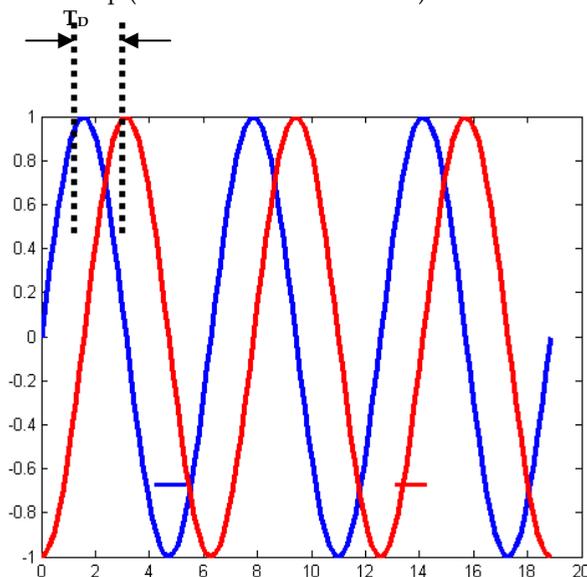


Fig. 4b. Transmitted () and Received () Signals

The typical setup is shown in Fig.4a. The acoustic vibrations of the signal frequency are excited in the medium. The received signal is processed to recover the time-delayed replica of the transmitted signal. The time delay T_D in Fig.4b is the sum of the transit time of the sound (or TOF) of acoustic radiations and the delay caused by the electronic circuits (including transducers).

The measurement of phase difference between the transmitted and received signal gives transit time (i.e. TOF), if the delay due to electronic circuits is negligible or the necessary correction in the measurement of T_D has been made. The CW method has found application in fluid flow velocity measurements. This method however does not seem to have attracted much effort possibly because the measurements are more sensitive to external noise, even though it has potential to lead to more accurate measurements.

Experimental Setup for Estimation of Adulteration using Sound Waves:

The authors have studied the effect of adulteration on speed of sound in petrol/diesel, using Continuous Wave (CW) method, with an objective to explore the feasibility of detection/estimation of adulteration of petrol and diesel. The experimental setup (including the electronics part used) is shown in Fig.5. It consists of a 30 cm long metallic cylinder, with inner diameter of 7.62 cm and a base of thin copper foil. The cylinder has a valve-controlled nozzle near its base for controlled removal of fuel contained in the cylinder. The cylinder is placed and locked on a wooden platform which has a circular hole of 3 inch diameter, covered by a speaker (the transmitter- TX) which is fixed on the wooden platform. This ensures that the vibrations of the frame of the speaker do not excite sound waves in the liquid. The pressure waves in the liquid column are excited only by the sound emitted by the speaker, through the copper foil at the base. A glass tube containing the microphone (the receiver- RX) is held vertically inside the cylinder along its axis. The liquid / fuel sample to be tested is contained in the cylinder.

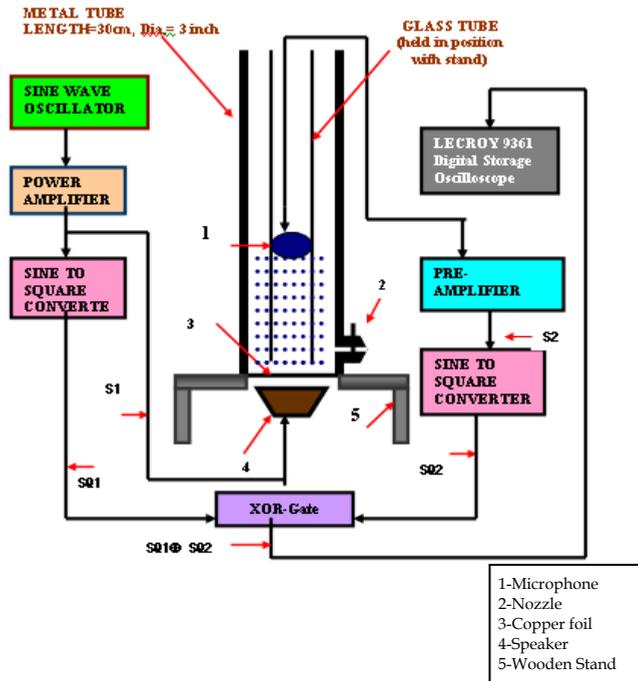


Fig. 5. Experimental setup for measurement of speed of sound in a medium using CW method

Note: The waveforms of the signals S1, S2, SQ1, and SQ2 in Fig. 5 are shown in Fig. 6.

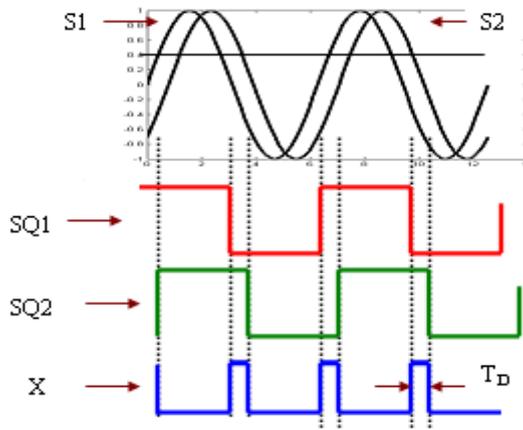


Fig. 6. Signal waveforms

The signal X is Exclusive-OR of signals SQ1 and SQ2 ($SQ1 \oplus SQ2$). The pulse width of 'X', T_D , is the time delay of the received signal and it is equal to the sum of time taken by the sound to travel through the liquid column of known height plus the delay caused by the circuit.

$$T_D = T_d(\text{circuit}) + \text{TOF} \tag{3}$$

If T_{D1} and T_{D2} are measured for path lengths h_1 and h_2 in the medium, then

$$T_{D1} = T_d(\text{circuit}) + \text{TOF}_{h1} \tag{4}$$

$$T_{D2} = T_d(\text{circuit}) + \text{TOF}_{h2} \tag{5}$$

Because the $T_d(\text{circuit})$ is independent of path length h_1 and h_2 in the medium, therefore

$$\begin{aligned} T_{D1} - T_{D2} &= \text{TOF}_{h1} - \text{TOF}_{h2} \\ &= \text{TOF of sound for path length } h_1 - h_2 \\ &= (h_1 - h_2)/V_s \end{aligned} \tag{6}$$

Or

$$V_s = (h_1 - h_2) / (T_{D1} - T_{D2})$$

Thus, the speed of sound can be determined by measuring the ON- time of signal X (see Fig. 6) for two path lengths h_1 and h_2 in the medium.

In the above experiment, the correct measurement of TOF requires that the received signal S2 is exact replica of transmitted signal S1 because any phase distortion in received signal will lead to shifting of zero crossing point and consequent change in measured value of T_D .

It was determined experimentally that the preamplifier output remains sinusoidal only in the frequency range 80 Hz to 390 Hz. This was possibly due to the mismatch of acoustic impedance at the speaker output since the speaker output is coupled to the metal diaphragm through air, which provides for rather poor coupling. To ensure accurate measurement of T_D , all the measurements were taken at 90 Hz. The measurement of time delay T_D (i.e. ON- time of signal X pulses) was done using digital storage oscilloscope LeCroy 9361A. An average width of signal X in ten successive measurements for the same sample was determined using the built in provision for the same in the oscilloscope.

To test the accuracy of the measurement system described above, the speed of sound in air and water was determined. The average value of speed of sound in air, $V_s(\text{air})$, determined using equation (6) is 344.03 m/sec at 23°C which is in very close agreement to the expected value of 344.824 m/sec on the basis of the values of $V_s(\text{air})$ reported in literature (William M. H 1998). The speed of sound in water at 22°C was determined to be 1486.76 m/sec. The reported value of speed of sound in distilled water is 1482 m/s at 20°C (Benedetto G et.al. 2003). The temperature co-efficient in water being 2.87 m/s/°C, the expected speed of sound in water at 22°C, therefore, is 1488m/s. The value for speed of sound in water determined in our experiment, therefore, is in close agreement with the corresponding reported value (within 1.3 m/sec.).

4. Experimental Results

Speed Of Sound In Gasoline And Diesel

The samples of gasoline and diesel used in the experiments (along with the respective test reports) were collected from the local depot of Indian Oil Corporation Limited. The kerosene was obtained from a retail outlet of the public distribution system regulated by Government of India.

The values of T_{D1} and T_{D2} in unadulterated gasoline and intentionally adulterated (with diesel) gasoline samples were measured using the experimental setup of Fig. 5 for two different volumes V_1 (= 500ml) and V_2 (= 400ml) contained in the metal cylinder. The corresponding column heights (path lengths) h_1 and h_2 were computed using the equation,

$$h = (\text{Net volume of fuel}) / (\text{Area of cross section}) . \quad (7)$$

The speed of sound was computed using equation (6). The volume percent of diesel in gasoline (i.e. % adulteration) has been plotted against measured speed of sound (in gasoline) in Fig. 7 (labeled as CW).

The experiments, as performed with gasoline, were also carried out with unadulterated diesel and intentionally adulterated (with kerosene) diesel for V_1 (= 500ml) and V_2 (= 300ml). The volume percent of Kerosene in diesel (i.e. % adulteration) has been plotted against measured speed of sound (in diesel) in Fig. 8. (Labeled as CW).

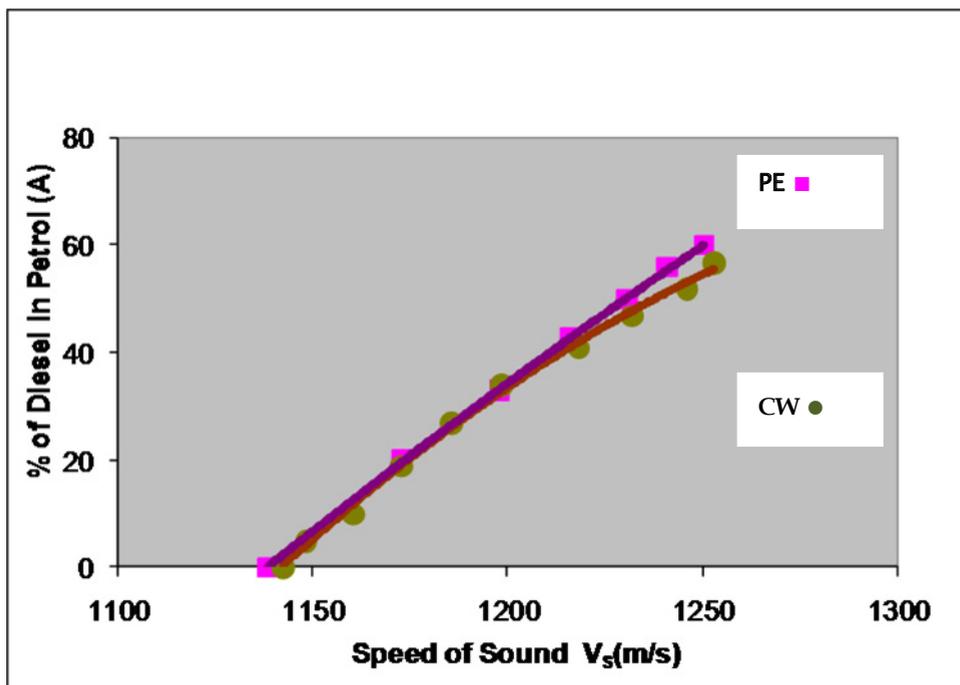


Fig. 7. Speed of Sound in Gasoline Mixed with Diesel

Verification of Experimental Results

An extensive search in literature for the speed of sound in gasoline and diesel yielded no result. Therefore to verify the results shown in Figs.7 and 8 (labeled as CW), the speed of sound in gasoline and diesel samples was also determined using equipment, namely NUSONIC model 6080 Concentration Analyzer (manufactured by MAPCO INC. ITALY). The equipment measures the speed of ultrasound (of frequency 4 MHz) in liquids and is based on pulse echo method. The % adulterations vs. speed of sound as measured using this equipment are plotted in Figs. 7 and 8 (labeled as PE). As can be seen, the measured speed of sound by the two methods is in good agreement. In case of gasoline samples the maximum difference between the speeds of sound measured using the two methods is 7.14 m/sec while the same for diesel samples, it is 5.9 m/sec.

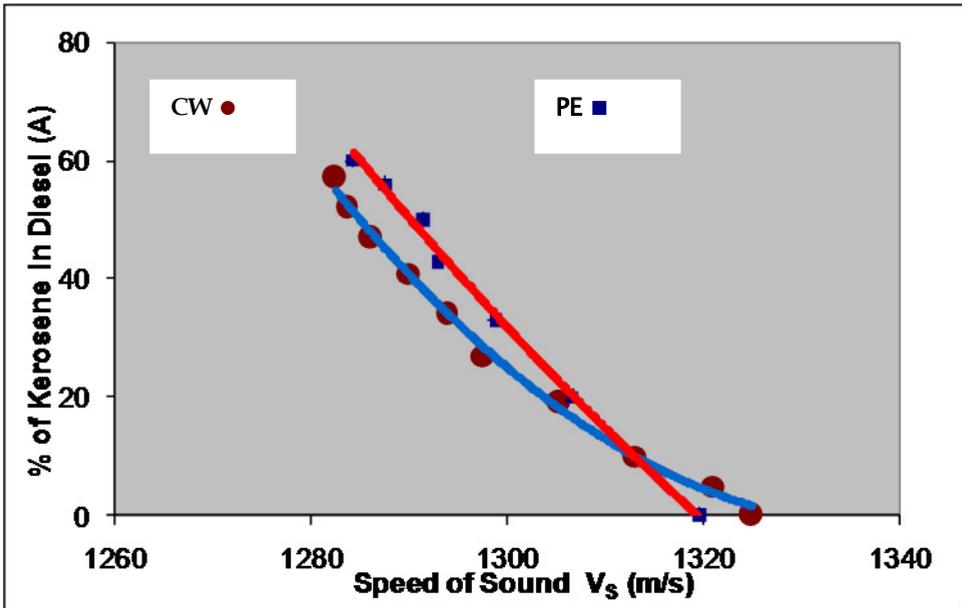


Fig. 8. Speed of Sound in Diesel Mixed with Kerosene

A significant and measurable change in speed of sound in gasoline/diesel samples with change in level of adulteration is seen in Figs. 7 and Fig. 8. This indicates towards the feasibility of calibrating the speed of sound in gasoline/diesel samples in terms of percent adulteration. From the plots of Figs. 7 and 8, the equations of the curves that are the least square fit to the experimental data, have been determined to be:

$$A = -0.0004 * V_s^2 + 1.5014 * V_s - 1184.8 \quad (8)$$

(for gasoline samples using Pulse-echo method)

$$A = -0.001 * V_s^2 + 3.9493 * V_s - 2631.4 \quad (9)$$

(for gasoline samples using CW method)

$$A = 0.0072 * V_s^2 - 20.397 * V_s + 14441 \quad (10)$$

(for diesel samples using Pulse-echo method)

$$A = 0.0184 * V_s^2 - 49.306 * V_s + 32984 \quad (11)$$

(for diesel samples using CW method)

where

V_s = Speed of sound (m/sec) in fuel under test, and

A = Percent adulteration (by Volume) in the fuel under test.

The equations (8) to (11) can be used for computing percent adulteration when speed of sound in the sample under test is known. Such computations can be easily performed by a micro controller based system with coefficients of the equations stored in its memory. Since the composition and, therefore, the physical properties such as density, viscosity of the gasoline, diesel, and kerosene are not constant and may vary significantly, depending upon the supplier company; the above equations would need to be updated as required. Alternatively, a look-up table of measured speed of sound vs. percent adulteration data for known samples can be used to estimate percent adulteration in the samples under test, by interpolation. However, no attempt has been made to design such a micro controller based system because the commercial equipments (based on Pulse Echo principle) for the purpose are already available for measurement of speed of sound in liquids and these equipments can easily be programmed for detection / estimation of adulteration in gasoline/ diesel using the experimental results obtained in this work.

5. Conclusion

The problem of increasing urban air pollution due to fast increasing number of auto mobiles and adulteration of automobile fuel has been pointed out in the context of developing countries. For prevention of the adulteration, the monitoring of fuel quality at the distribution point is essential. For the detection/estimation of the commonly used adulterants (i.e. diesel in petrol and kerosene in diesel), a number of possible methods have been reviewed.

As such there is no standard method/equipment for detection of adulterants. The authors have explored the feasibility of using the speed of sound in the fuel under test to detect/estimate the volume percentage of commonly used adulterants in automobile fuel and have concluded that it is feasible to develop a cheap and easy to operate equipment which measures and uses the measured speed of sound to estimate the adulterants in fuel. A NUSONIC model 6080 Concentration Analyzer (manufactured by MAPCO INC. ITALY), commercially available equipment namely NUSONIC model 6080 Concentration Analyzer (manufactured by MAPCO INC. ITALY) may be used for the purpose with a small modification.

Besides the sound/ultrasound based method proposed by the authors, optical fiber sensor based method needs to be given more research effort. The method of measurement has great advantage of being relatively more insensitive to a number of external disturbances such as acoustic noise, temperature variation etc. and the required measuring equipment can be easily designed at low cost with large sensitivity to adulteration leading to more accurate measurements.

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