Indian Journal of Chemical Technology
Vol. 29, September 2022, pp. 572-577
DOI: 10.56042/ijct.v29i5.63251

# Analysis of emissions trapped on energy balance variables for spark-ignition engine modifying a commercial diesel engine

Velmurugan Kulanthaivel*[,1], Arunprasad Jayaraman[1], Arif Senol Sener[2] & Thirugnanasambantham Rajamanickam[1]
[1]Department of Mechanical Engineering, Dhanalakshmi Srinivasan Engineering College, Perambalur, India
[2]Department of Mechanical Engineering, Engineering and Architecture Faculty, Nisantasi University, Istanbul/Turkey
E-mail: sugumardsec@gmail.com

*Received 13 May 2022; accepted 21 June 2022*

Several approaches in the context of a high-compression-ratio, spark-ignition engine made by modifying a commercial diesel engine have been examined. The accuracy of calculating the equivalency ratio from exhaust gas analysis and determining the commencement of combustion from the mass fraction burned has been tested. The effect of trapped mass on the energy balance inside the cylinder has been studied. This study evaluates the estimation of the relative dosing from the emission composition as a verification criterion for the calculation of this parameter from the air and fuel flows, and the effect of the residual mass on the mass of the fuel is also analysed.The results suggest that the approaches for determining equivalency ratio, starting combustion, and trapped are useful tools for assessing data quality and investigating spark-ignition engines with high compression ratios.

**Keywords:** Equivalence ratio, High compression ratio, Residual mass, Spark-ignition engines

Heat release analysis or combustion diagnostic based on the pressure signal is one of the approaches for researching alternative internal combustion engines. The in-cylinder pressure data is used to conduct an energy balance, which offers an estimate of how combustion occurs using theoretical-experimental techniques[1].These models' degree of approximation is determined by the phenomena considered and the simplifications applied. The precise measurement of numerous factors involved in energy and mass balance calculations is required for the study of combustion performance and combustion diagnostics. Based on an investigation of the species of pollutant emissions from the engine, the presents an indirect assessment of relative dosage with acceptable accuracy. In cyclic dispersion analysis, waste gases play a crucial role, but their direct measurement necessitates the use of advanced equipment[2].This parameter may be approximated using a variety of approaches based on factors such as chamber pressure and instantaneous volume. A technique for estimating the mass of waste gases was discovered to be a superior approximation to simulations used to quantify this parameter. Given that the estimated temperature in the cylinder is dependent on these variables and other factors that interfere with the balance, an accurate estimate of the total mass trapped in the cylinder allows for technically correct conclusions about the energy balance[3]. The heat transported to the walls, which is normally estimated using an average heat transfer coefficient based on correlations discovered, is one of the most unpredictable quantities in combustion diagnostics calculations[4]. The empirical constants derived to relate the fluid dynamics of the load with the average piston speed, a theory that does not apply to all kinds of engines. In comparison to conventional engines, ignition engines with high compression ratios exhibit changes in operational characteristics such as relative metering, combustion temperatures, pressure losses in the intake, and residual mass of exhaust gases[5]. For the study of traditional technologies, theoretical-experimental tools and data quality criteria have been adjusted; however, for emerging or modified technologies, such as high compression ratio spark-ignition engines, quality criteria, and parameter sensitivity analysis must be defined for the optimal design of these engines[6]. There has been much research on the performance and combustion analysis of high compression ratio ignition engines, but the validity of the traditional analytical approaches employed in these engines has not yet been investigated, to the best of the authors' knowledge. This study assesses the estimation of relative dosing from emission composition as a verification criterion for calculating this parameter from air and fuel flows, as well as the impact of residual mass on fuel mass, and the effect of trapped emissions on energy balance variables such as average temperature and percentage of fuel burned.

## Experimental Section

### Experimental Set-up

The technical features of the engine are shown in Table 1. For load management, its compression ratio is linked to a generator and an electrical resistance cell. Electrical resistors wasted the power as heat. The fuel utilised in the testing was natural gas for automobiles sold in Chennai, which had a volumetric composition of roughly 98% $CH_4$ - 0.30% $CO_2$ - 1.70% $N_2$ employing species measurement under the concept. A Coriolis meter was used to measure the fuel flow. An orifice plate meter coupled to a differential pressure transducer was used to monitor the incoming airflow. For $CH_4$, $CO_2$, and CO, the exhaust gas composition was determined on a dry basis, and for $O_2$, the paramagnetic approach was used. The chemiluminescent approach was used to determine the NO content. A transducer was used to measure the pressure in the chamber. A piezoelectric sensor and the angular location of the crankshaft were measured with 3600 pulses per revolution resolution using an encoder linked to a pulse multiplier. For chamber pressure reference, a piezoresistive transducer was utilised. The instruments' signals were recorded on a computer and read out using an acquisition card that takes data at a rate of 250 kHz with a 32-bit resolution.

### Mass balance in the cylinder

In addition to the mass of incoming air and fuel, the difference in pressures between the cylinder and the intake and exhaust manifolds as well as with the crankcase generates a fluid movement through the exhaust duct and piston rings as well as a mass remaining after each cycle, which can generate noticeable differences between the mass admitted and the mass participating in the combustion process. In the study, the short-circuit and leakage masses were not considered due to the lack of parameters for their calculation, therefore the mass balance can be seen in Eq. 1.[7]

$$m = m_f + m_a + m_c \quad \text{... (1)}$$

where $m_f$ is the mass of fuel, $m_a$ is the mass of air and $m_c$ is the mass of waste gases.

### Indirect verification of air and fuel mass by relative dosing by emission analysis Relative dosing

The quotient between absolute and stoichiometric dosing allows for the ratio between the absolute and stoichiometric dosage, giving an idea of the composition of the composition of the charge being fed to the engine. Relative metering is defined in Eq. 2

$$\varphi = \frac{1}{\varphi stq}\frac{m_f}{m_a} \quad \text{... (2)}$$

As air is the most present flow during the combustion process, the correct measurement of this parameter is associated with the quality of information on the energy balances developed. However, this parameter is not measured near the intake manifold, which allows air infiltration and therefore an overestimation of this parameter. To verify the correct measurement of this flow and to guarantee reliable analyses of engine operation and performance, the calculation of the relative dosing from the pollutant emissions was incorporated. For the calculation, an equivalent molar composition of the incoming fuel is defined. Eq. (3) shows the overall mass balance for the emissions measured in the cell and the elements present in the gaseous fuel[7].

$$\mathrm{N}C_nH_mO_rN_s + \frac{nO_2}{\varphi_e}(O_2 + 3.775N_2) \rightarrow \mathrm{np}(\mathrm{y}\ c_aH_bC_aH_b + \ldots\ldots + \mathrm{ycoCO} + \mathrm{yco_2CO_2} + \mathrm{yo_2O_2} + \mathrm{y_{N2}N_2} + \ldots\ldots + \mathrm{yNo\ NO} + \mathrm{yNo_2\ NO_2} + \ldots\ldots \mathrm{yH_2oH_2O} + \mathrm{yH_2H_2} \quad \text{... (3)}$$

Where $n_p$ are the moles of products, $NO_2$ are the stoichiometric moles of air, φe is the relative dosage determined by pollutant emissions. The solution to this balance involves the balance of the species C, H, N, and O, however, the analyzers deliver the composition on a dry basis. From Eq (4) we obtain the

Table 1—Technical characteristics of the engine

| | |
|---|---|
| Manufacturer | Kirloskar |
| Injection type | Direct injection |
| Number of cylinders | 2 |
| | Air-cooled aspiration natural |
| Displacement | 1550 $cm^3$ |
| Compression ratio | 15: 1 |
| Diameter × Stroke | 98.6 × 101 mm |
| Rated power | 17.6 kW @ 2500 rpm |
| Rated torque | 76 .5 N-m @ 1500 rpm |

ratio between the composition on a dry and wet basis, and i and y¯i, respectively. To solve the system of equations in1, the dissociation reaction for hydrogen, Eq (5), is proposed, taking a chemical equilibrium constant K of 3.5, which is appropriate for the temperature ranges reached at MCIA[7].

$$y_i = (1 - yH_2O, e)\overline{y_i} \quad \text{... (4)}$$

$$K = 3.5\ \frac{y_{co}yH_2O}{y_{co_2}yH_2} \quad \text{... (5)}$$

Finally, a relationship can be obtained for the relative dosage shown in Eq (6)

$$\varphi_e = \frac{nO_2}{n_p yH_2O + n_p(1 - yH_2O)(\overline{y}CO\ +\ 2\overline{y}CO2\ +\ 2\overline{y}O2\ +\ \overline{y}NO)\ -\ r)} \quad \text{... (6)}$$

**Residual mass estimation**

Residual mass is the gases that fail to be evacuated during the exhaust stroke. In the designed methodology, the method was used, which assumes that the combustion gases undergo an isentropic process during the exhaust stroke, so that the mass at the instant of exhaust valve closure (EVC) can be determined from the ideal gas correlations for this type of process between

$$m_r = m_{EVC} = m_{EVO}\left(\frac{V_{EVC}}{V_{EVO}}\right)\left(\frac{p_{EVC}}{p_{EVO}}\right)^{\frac{1}{\gamma}} \quad \text{... (7)}$$

where γ¯ is the ratio of average specific heats, from the temperatures at EVO and EVC. m, V and p are the mass, volume and pressure, respectively, at the point of interest during the cycle. The implementation of this method requires an iterative process to determine initial conditions at EVC, for which the Ideal Gas Equation of State was used, assuming that the temperature at this point is approximately equal to the exhaust gas temperature. A tolerance equal to the uncertainty of the Coriolis type meter was used in the process. The residual mass is usually presented as a percentage relative to the total trapped mass (TTR) during the period of closed valves, Eq. 8.[7]

$$RGF = \frac{m_f}{m} \quad \text{... (8)}$$

**Energy balance in the cylinder**

Since the Heat Release Analysis diagnostic methodology is applied, only the terms of the change in internal energy, boundary work, and heat transfer to the walls are taken into account in the balance, resulting in Eq.2.

$$\frac{dQ_{ch}}{d\theta} = mc_v\frac{dT}{d\theta} + P\frac{dv}{d\theta} + h_cA_s\,(T - T_{CW})\frac{1}{6N} \quad \text{... (9)}$$

Where $\frac{dQ_{ch}}{d\theta}$ is the heat release rate,
$c_v$ is the specific heat at constant volume,
N is the engine speed, and
$T_{CW}$ is the cylinder wall temperature.
$h_c$ is the average convective coefficient

$$h_c = 3.26\,B^{-0.2}p^{0.8}w^{0.8}T^{-0.55} \quad \text{... (10)}$$

Where w is an adjustment factor relating different kinematic and thermodynamic properties of the fluid during the compression and expansion processes.[7]

***Duration of combustion***

The combustion process only lasts for a small fraction of the thermodynamic cycle, so it is necessary to define the instants at which combustion starts and ends. There are different techniques to estimate these instants from the value of chamber pressure gradients or variables such as the heat release rate. In the methodology, the start of combustion was defined as CA05, Eq.(11), since this criterion does not depend on the type of technology but on the temporal development of the combustion process itself and is robust to the effects of noise in the pressure signal.

$$x_b(\theta = CA05) = \frac{\int_{\theta_i}^{\theta_{05}} dQ(\theta)d\theta}{\int_{\theta_i}^{\theta_F} dQ_{ch}(\theta)d\theta} = 0.05 \quad \text{... (11)}$$

Where $\theta_i$ and $\theta_F$ are the integration intervals equivalent to the analysis period of $dQ_{ch}/d\theta$.

The end of combustion was defined as the angle at which 95 % of the energy (CA95) was released. To account for the validity of the results obtained from InEq 9, we implemented the use of a variable called the percentage of fuel burned, Eq 12, which relates the heat released during combustion and the energy input to the fuel.[7]

$$C_q = \frac{\int_{\theta_i}^{\theta_f} dQ_{ch}(\theta)d\theta}{m_f PCI_f} \leq 1 \quad \text{... (12)}$$

Where $C_q$ is the percentage of fuel burnt and $LHV_f$ is the lower calorific value of the fuel.

## Results and Discussion

**Relative dosage and residual mass analysis**

The results obtained from the proposed method for directly verifying the relative dosage are presented in Fig. 1, in which for the loads evaluated there is a proximity between the way of calculating and estimating the relative dosage, with the estimated dosage always having a higher value. This difference is associated with several phenomena that are not taken into account when estimating the relative dosage, such as the mass of combustion gases remaining in the cylinder, which, because it contains significant concentrations of oxygen and carbon dioxide, can easily lead to changes in the dosage, and the mass that is not involved in the combustion process can have a significant influence on the dosage estimates from the emissions. The results in Fig. 1 indicate that for high levels of dilution or gas recirculation (EGR), the implementation of the method requires an adjustment due to the concentrations one instant after the IVC[8].

The estimation of the residual mass was incorporated into the diagnostic model to evaluate its influence on the energy balance; in addition, this variable allows us to understand trends in the combustion process, given that the presence of this mass can increase the resistance to ignition of the inlet mixture or the formation of pollutant species.[9]

The results obtained in the estimation of the residual mass are presented in Fig. 2, in which it can be seen that it tends to increase with the advance of the spark[10]. As can be seen in Eq. 7, the residual mass is directly proportional to the quotient between the pressure in the EVC and the EVO, so the trend found in the right-hand graph is due to the increase in pressure as the spark advance increases[11]. The increase in pressure with load for a given advance and its effect on leakage and the out gassing process can help to understand the trends in the left graph. It is important to note that the method used to estimate the residual mass presents results in line with those found experimentally for a diesel engine of similar operating characteristics to the one used in the test cell[12].

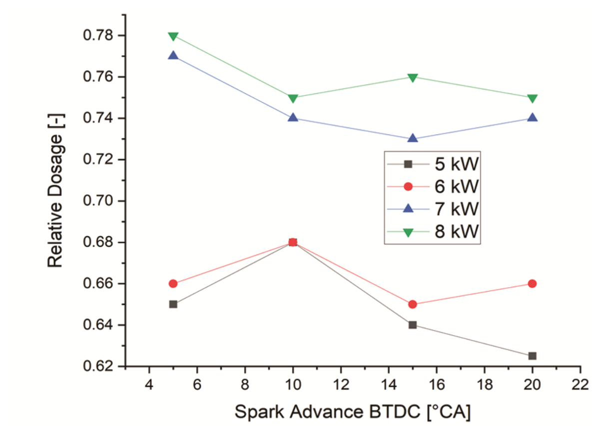


Fig. 1— Comparison of relative dosing by flow measurement.

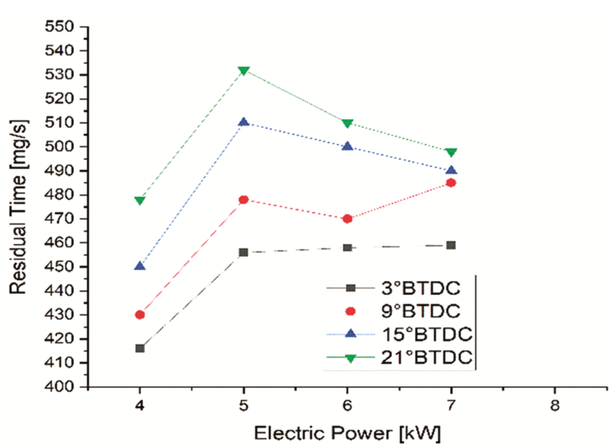


Fig. 2 — Estimated residual mass and its percentage

**Combustion initiation values**

The results obtained by the diagnostic software for combustion initiation are shown in Fig. 3, which shows the results obtained to calculate this variable from two methods widely used in diagnostic methodologies and which are enabled in DICOMOTOR Off-line.

It can be seen how the values obtained from the dP/dθ method show inconsistencies for several points evaluated, where the start of combustion occurs before the jump of the spark, this being associated with the noise thatCriteria for the processing and evaluation of experimental data for a high compression ratio ignition[13]. The pressure signal is accompanied by the pressure signal, which generates pressure gradients that do not correspond to those of the process carried

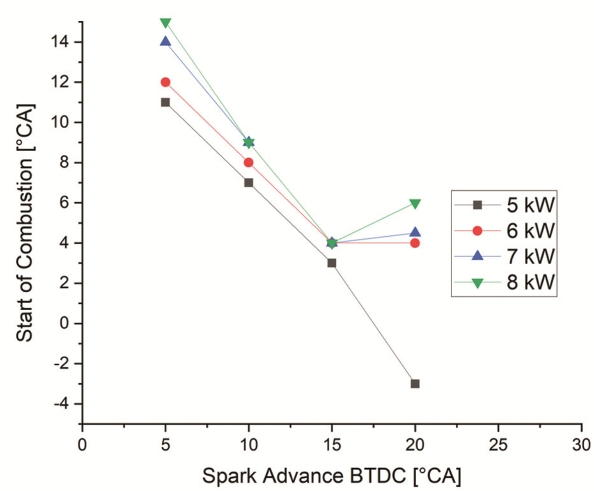


Fig. 3 —Variation of combustion initiation (CA05) in a high compression ratio spark ignition engine.

out in the engine. For the CA05 method, physically valid results were obtained with clear tendencies, which makes it a recommendable method that allows good results to be obtained without the need to apply severe filtering that could eliminate valuable information from the pressure signal[14].

**Analysis of energy balance parameters**

The importance of performing a mass balance lies in the effect it has on the average temperature calculations and the variables in Eq. 9, and since the average temperature is inversely proportional to the trapped mass, an underestimation of the mass leads to temperatures outside the range normally obtained in MCIA. Fig. 4 shows the influence of incorporating residual mass into the temperature calculations[14].

It is remarkable how low orders of magnitude of residual mass, as observed in Fig. 2, generate differences of the order of 100 K in temperature during the combustion duration interval[15]. This difference generates important changes in the results of the overall energy balance as shown in Fig. 5, in which there are differences of up to 4 % in the percentage of fuel burned, because higher temperatures are equivalent to higher energy released[16].

However, residual mass can affect only the change in internal energy and heat transfer to the walls, as seen in Eq 9. Looking at the change in magnitude of these balance elements with the inclusion of residual mass, it was found that for most points[17-18], the energy estimated by the heat transfer model is the element that is affected the most, Fig. 6. It can also be observed that at 6 kW there are notable increases in the heat transferred to the walls for higher spark advance, in which there is a considerable increase in the percentage of fuel burned as shown in Fig. 6, thus demonstrating the effect of the transfer model on the overall energy balance and the importance of adjusting existing models to the engine where the

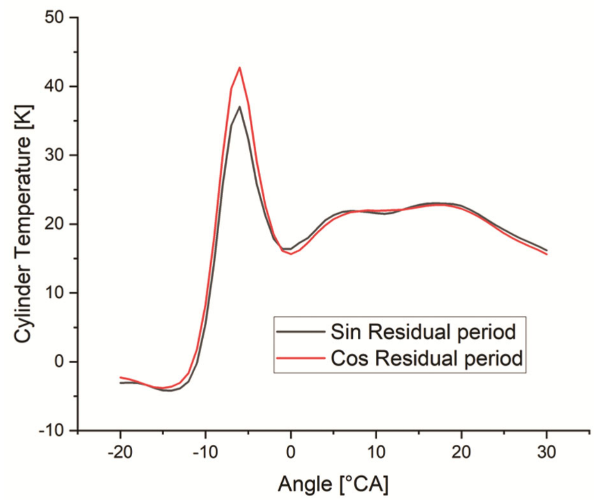


Fig. 4 — Cycle temperature during the period of closed valves

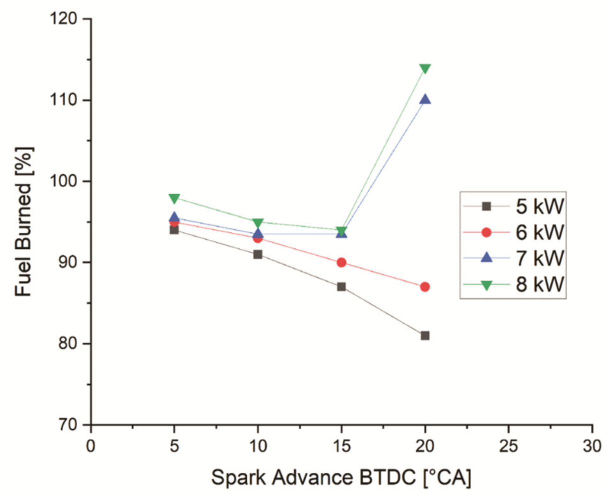


Fig. 5 — Comparison of the percentage of mass burned with the determination of the residual mass.

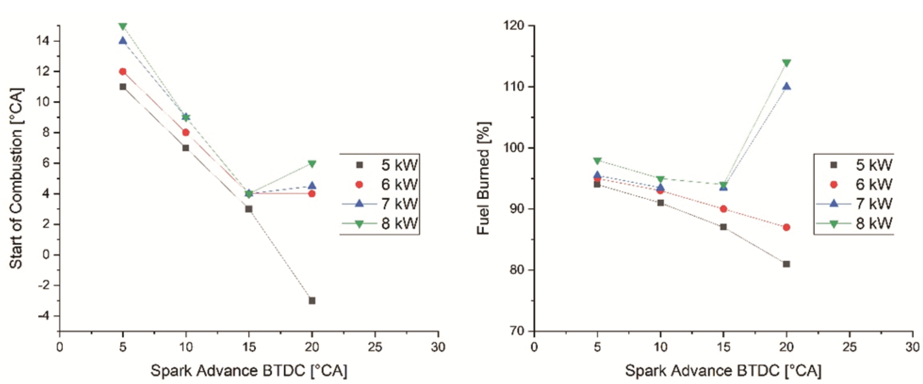


Fig. 6 — Comparison of the percentage of mass burned and of the heat transferred to walls with the determination of the residual mass.

studies are being carried out, especially if its operation differs for the technologies on which the correlations were based[19-21].

## Conclusion

The results show that estimating relative dosing by analysing pollutant emissions is a good approach for verifying the engine's fuel-air ratio in real time; however, its accuracy may be enhanced by incorporating flows that are not normally monitored, such as residual mass and leaky mass. The latter, under the technology assessed, must be measured due to the engine changes and increased chamber pressure. Since determined by the residual mass calculation technique, the engine conversion has no influence on this variable's magnitude. Likewise, the requirement to include it in the energy balance is clear, as fractions of up to 8% cause changes of up to 4% in the global balance. The initial pressure derivative approach had abnormal trends and erroneous readings when estimating the commencement of combustion. The CA05 approach produces excellent results, demonstrating that not all methodologies for calculating combustion time are effective for the technology studied. The proportion of fuel burned may be used to validate the energy balance findings. However, lower results may be affected by combustion instabilities and fuel type at the doses used in the tests, as well as combustion instabilities and fuel type at the dosages used in the testing.

## References


1 Fattah I M R, Ong H C, Mahlia T M I, Mofijur M, Silitonga A S, Rahman S M A & Ahmad A, *Front Energy Res*, 8 (2020) 1.

2 Ong H C, Milano J, Silitonga A S, Hassan M H, Shamsuddin A H, Wang C T, Indra Mahlia T M, Siswantoro J, Kusumo F & Sutrisno J, *J Clean Prod*, 219 (2019) 183.

3 Silitonga A, Shamsuddin A, Mahlia T, Milano J, Kusumo F, Siswantoro J, Dharma S, Sebayang A, Masjuki H & Ong H C, *Renew Energy*, 146 (2020) 1278.

4 Gad M S & Jayaraj S, *Fuel*, 267 (2020) 117168.

5 Mahlia T M I, Syazmi Z A H S, Mofijur M, Abas A E P, Bilad M R, Ong H C & Silitonga A S, *Renew Sust Energy Rev*,118 (2020) 109526.

6 Imtenan S, Masjuki H H, Varman M, Rizwanul Fattah I M, Sajjad H & Arbab M I, *Energy Convers Manag*, 94 (2015) 84.

7 Castaño Mesa Edisson S, Quintana Sebastian H, Bedoya Iván D & Arrieta Andrés A, *Ing Cienc*, 12 (2020) 107.

8 Fangsuwannarak K & Triratanasirichai K, *Am J Appl Sci*, 10 (2013) 1201.

9 Sajith V, Sobhan C B & Peterson G P, *Corp Adv Mech Eng*, (2010) Article ID 581407, 6 pages.

10 Sathiyamoorthi R, Puviyarasan M, Bhuvanesh Kumar B & Breslin Joshua D, *Int J Chem Sci*, 14 (2016) 473.

11 Jayanthi P & Srinivasa Rao M, *Int J Adv Eng Technol*, 9 (2016) 689.

12 Anbarasu A, Karthikeyan A & Balaji M, *J Energy Resour Technol*, 138 (2016) 022203.

13 Nantha Gopal K & Thundil Karupparaj R, *Ain Shams Eng J*, 6 (2015) 297.

14 Rastogi P M, Kumar N, Sharma A, Vyas D & Gajbhiye A, *Pollution*,6 (2020) 25.

15 Radhakrishnan S, Munuswamy D B, Devarajan & Mahalingam A, *Utilization Environ Effects*, 40 (2018) 2485.

16 Kilic B, *Int J Renew Energy Res*, 1 (2012) 259.

17 Ubwa S T, Oshido B A & Malu S P, *Int J Renew Energy Res*, 4 (2014) 73

18 Bayindir R, Hossain E, Kabalci E & Perez R, *Int J Renew Energy Res*, 4 (2014), 1094.

19 Kularathne I W, Gunathilake C A, Rathneweera A C, Kalpage C S & Rajapakse S, *Int J Renew Energy Res*, 9 (2019) 1355.

20 Fetni S, Boubahri C, Lassoued I & Said R, *Int J Renew Energy Res*, 9 (2019) 542.

21 Ubwa S T, Oshido B A & Malu S P, *Int J Renew Energy Res*, 4 (2014) 73.