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An Experimental Investigation of PAH Emissions from a Heavy Duty Diesel Engine Fuelled with Biodiesel and its Blend

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Abstract. For the comparison of emissions of polycyclic aromatic hydrocarbons (PAHs) from diesel, biodiesel and its 20% blend with diesel, and their carcinogenic potencies, an experimental study has been conducted on a turbocharged, intercooled and direct injection diesel engine. Total PAHs (solid and gas) from diesel, B20 and B100 at low load were more than those at high loads. Total PAH emissions from the test fuels at the rated speed were more than those at maximum torque speed. Benzo[a] pyrene (BaP) brake specific emission of biodiesel is less than that of diesel. LMW-PAH emissions for the test fuels are all higher than those of MMW and HMW PAH. Biodiesel and B20 reduce both the total Benzo[a]pyrene equivalent concentration (BaP$_{eq}$) and the total mean–PAHs as compared to commercial diesel fuel. BSFC of the engine increased but its brake power decreased in the cases of B20 and biodiesel.

Keywords: diesel engines, biodiesel, polycyclic aromatic hydrocarbons, carcinogenic potencies

Introduction

Diesel engines due to their high fuel efficiency, out put power and fuel economy are widely used in heavy duty trucks, buses, generators, construction and agricultural machinery, in the face of the dwindling sources of conventional fossil fuels, their ever increasing demand and prices and stringent emission regulations. Among a number of alternative fuels like methanol, ethanol, LPG, LNG, CNG and vegetable oils, biodiesel consisting of alkyl monoesters of fatty acids from vegetable oils or animal fats can be used in unmodified diesel engines in pure or blended forms (Meher *et al*., 2006; Graboski and McCormick, 1998). It is a non-toxic, eco-friendly and biodegradable fuel (Lapinskiene *et al*., 2006). Use of biodiesel as an alternative fuel reduces the regulated air pollutants, including particulate matter, HC, CO and SO$_x$ (Labeckas and Slavinskas, 2006; Sinha and Agarwal, 2005; Usta, 2005; Senda *et al*., 2004; Turrio-Baldassarri *et al*., 2004; Monyem and Van Gerpen, 2001). Global use of biodiesel can curtail green house gas emissions as compared to mineral diesel (Gerpan, 2006; Carraretto *et al*., 2004; Tan *et al*., 2004; Peterson and Hustruid, 1998). It has higher cetane number, ultra-low sulphur concentration, higher flash point, high oxygen content and improved lubricating efficiency (Ebiura *et al*., 2005; Agarwal *et al*., 2003; Fukuda *et al*., 2001). Biodiesel has less adverse effect on human health as compared to diesel (Schroder *et al*., 1999) and mutagenicity of biodiesel particulate emissions is much lower than that of petroleum-based diesel fuel (McDonald *et al*., 1995). To encourage the use of biodiesel fuel, Austria,

Germany and United States, Governments have announced tax benefits for the people (Raneses *et al*., 1999; Krawczyk, 1996).

Although biodiesel has widely been investigated as an alternative fuel in diesel engines for performance, regulated and somewhat unregulated emissions, however polycyclic aromatic hydrocarbons (PAHs) and their carcinogenic potencies still need to be addressed comprehensively. This study is an effort to determine PAHs and their corresponding carcinogenic potencies from the exhaust of a diesel engine alternately fuelled with biodiesel and its 20% blend with commercial diesel fuel.

PAHs are formed by incomplete combustion or high temperature pyrolytic process involving organic matter (Khalili *et al*., 1995). PAHs are semi volatile substances at atmospheric conditions and occur both in vapour-phase and as attached to particles depending on vapour pressure of each PAH component (Basheer *et al*., 2003). Lighter PAHs are in vapour phase, while those having four or more rings are found mainly adsorbed in particulate material (Park *et al*., 2002). Although lighter PAHs have weaker carcinogenic properties, they are the most abundant in the urban atmosphere and react with other pollutants to form more toxic derivatives (Ho *et al*., 2002). PAHs specially benzo (a) pyrene injure the respiratory and immune system, and is responsible for cell mutation and can cause skin and lung cancers (Grevenynghe *et al*., 2003; Yousef *et al*., 2002). PAHs are mainly contributed by the mobile sources like diesel and gasoline engines; the contribution of total PAHs from mobile sources to ambient air is 91.8% (Yang *et al*., 1999).

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Materials and Methods

Engine specifications. The engine under study is a turbo-charged, direct injection and intercooled, which runs on an electrical dynamometer (SCHENCK HT 350). The engine specifications are given in detail in Table 1. No modification or alteration has been made in the engine. The schematic diagram of the experimental set up is given in Fig. 1.

Table 1. Engine specifications

Items	Value
Number of cylinders	4
Bore (mm)	110
Stroke (mm)	125
Displacement (litre)	4.752
Compression ratio	16.8
Rated power (kW@ r/min)	117/2300
Maximum torque (N.m@ r/min)	580/1400
Nozzle hole diameter (mm)	0.23
Number of nozzle holes	6

Test fuels. Three fuels were used in this study namely D (commercial diesel), B100 (biodiesel), B20 (a blend of 20% biodiesel and 80% diesel). Biodiesel is provided by Zhenghe Bioenergy Co. Ltd., Hainan, China. Main properties of the test fuels are given in Table 2.

Sampling methodology and PAH analysis. An ejector-diluter (Dekati Ltd., Finland) was used to obtain the emission directly from the exhaust pipe by inserting a J-shaped stainless-steel sample probe into the exhaust pipe as shown in Fig. 1. The ejector-diluter consists of a set of filters, a dryer, a temperature controller, a pressurized air heater and two diluters. Dry, particle-free and pressurized air was introduced into the
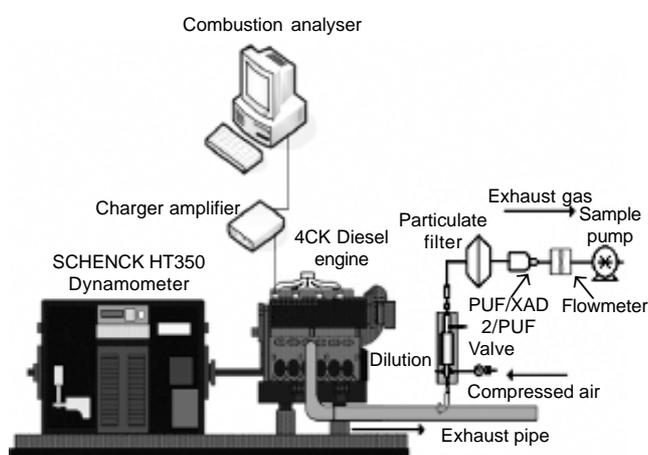
Table 2. Properties of fuels

Properties	B100	B20	D	Standards
Density (kg/m³)	886.4	845.1	834.8	SH/T 0604
Viscosity (mm²/s) at 20 ºC	8.067	4.020	3.393	GB/T 265
Lower heating value (MJ/kg)	37.3	41.57	42.8	GB/T 384
Sulphur content (mg/l)	25	-	264	SH/T 0253-92
Cetane number	60.1	-	51.1	GB/T 386-91
Carbon content (%)	76.83	-	86.92	SH/T 0656-98
Hydrogen content (%)	11.91	-	13.08	SH/T 0656-98
Oxygen content (%)	11.33	-	0	Element analysis

primary diluter and was heated up to the exhaust gaseous temperature. The diluted sample was then introduced into the secondary diluter for further dilution. The dilution ratio of the primary and secondary diluters was 8, so the over all dilution ratio of the instrument was about 64. Before sampling, the calibration was made by using two concentrations of CO_2 which were measured before and after the dilution instrument. The total residence time was about 0.1 seconds for the primary and the secondary diluters as delineated by Dekati Ltd.

Sampling of PAHs was performed by two distinct ways: one for the particulate phase and another for the vapour phase. Particulate phase PAHs were collected on a glass-fibre filter. Before sampling, filters were placed in an oven at about 450 °C for 8 h to avoid the possibility of presence of any organic compound. Cleaned filters were stored in a desiccator for 8 h to achieve moisture equilibrium and then were weighed. After the tests, filters were put again in a desiccator for 8 h to remove moisture, and were weighed to determine the net mass of the trapped particles. Gaseous phase PAHs were collected in a glass cartridge PUF/XAD-2/PUF, Sopelco USA, (Fig. 2), connected in series with particulate filters (Fig. 1). PUF is poly-urethane foam of density 0.022 g/cm³, having outside diameter

Fig. 1. Experimental setup.

Fig. 2. PUF/XAD-2/PUF cartridges.

(O.D) and length of 22 mm and 30 mm, respectively. XAD-2 resin sandwiched between PUF plugs is an aromatic polymer (styrene-divinyl benzene polymer) which can capture the gaseous phase PAHs. The diluted exhaust was sampled with the help of a constant volume pump, Air Chek 2000, SKC, USA (Fig. 3), at a constant rate of 5 ml/min. The flow rate was controlled using a flow-meter installed down stream of the pump.

Fig. 3. Constant volume sampling pumps.

The collected sample was extracted in an ultrasonic extractor (for 30 min) for the solid-phase PAH emissions and in Soxhlet extractor (for 24 h) for gaseous phase PAHs, with 250 ml dichloromethane (DCM). The extracted liquid was collected in a flask of 500 ml, and was concentrated by a rotary evaporator (Kuderna-Danish evaporator) to 1.0 ml. The concentrated sample was cleaned by passing it through a silica gel column at a speed of $2 \sim 3$ ml/min, which was installed to solid-phase extraction (SPE) device and was activated with 3 ml n-hexane. In order to wash the PAHs staying on the silica gel column, 15 ml mixture of n-hexane and DCM (volume ratio, 1:1) was added to the sample. At last PAHs-washing liquid was concentrated by evaporator (K-D) exactly to 1.0 ml, and was refrigerated until analysis.

For PM-phase PAHs extraction, fibre-glass filter was cut into several pieces which were put into a flask and then DCM was poured into the flask. The sample was extracted by ultrasonic agitation thrice (30 min each time), and was volatilized with water bath to 10 ml. The residues were filtered by core filter. Other aspects of the treatment procedure for the sample were identical to those described above.

After the sampling, the identification and quantification of PAHs were made by using a gas chromatograph (GC) Agilent 6890N) and mass spectrometer (MS) Agilent 5795C) according to the compendiun method TO-13A (US/EPA, 1999). The specifications of GC/MS are given in Table 3.

Table 3. GC/MS specifications

Gas chromatograph (GC)	Capillary column: HP-5MS (30 m x 0.25 mm x 0.25 μm); carrier gas: helium (99.999%); oven temperature programme: from 80 ℃ (2 min)-(20 ℃/min)-160 ℃-(5 ℃/min)-280 ℃ (10 min)
Mass spectrometer (MS)	Transfer line to MS: 250 ℃; ion source: electron impact (EI); ion source temperature: 200 ℃; acquisition mode: selected ion monitoring (SIM)

Compounds were identified from their mass spectral data, using U.S National Institute of Standards and Technology (NIST) library. After the identification, compounds were quantified by using the external standard methods to make the linear standard curves. The GC/MS was calibrated with a standard solution of 16 PAH compounds (EPA 610 PAHs Mixture, Supelco, Bellefonte, PA, USA). The standard samples, diluted 10, 50, 100, 500, 1000 and 2000 times, were injected into GC/MS as 1 μl liquid of each concentration with the help of micro-injector to get the standard ion flow graph, and hence the peak area of the 16 PAHs. The retention time, quantitative and reference ions, curve equations, R (correlation coefficient) and RSD (relative standard deviation) of different compounds are depicted in Table 4.

PAH emissions and statistical analysis. According to the number of rings, the PAH homologues have been grouped as under: Naphthalene (Nap) with 2-rings; acenaphthylene (AcPy), acenaphthene (Acp), fluorene (Flu), phenanthrene (PA) and anthracene (Ant) with 3-rings; fluoranthene (FL), pyrene (Pyr), benzo[a]anthracene (BaA) and chrysene (CHR) with 4-rings; benzo[b]fluoranthene (BbF), benzo[k] fluoranthene (BkF), benzo[a]pyrene (BaP) and dibenzo [a,h]anthracene (DBA) with 5-rings; and, indeno[1,2,3-cd] pyrene (IND) and benzo[g,h,i]perylene (BghiP) with 6-rings.

Total PAH concentration is the sum of the individual concentration of the 16 compounds. In order to analyze the PAH homologous distribution, the total PAHs have further been divided into three groups on the basis of their molecular weight, which are low molecular weight (LMW), medium molecular weight (MMW) and high molecular weight (HMW) PAHs. LMW-PAHs have two and three-ringed PAHs, MMW-PAHs have four-ringed PAHs and HMW-PAHs have five and six-ringed PAHs. In this way, first six PAHs are LMW-PAHs, next four are MMW-PAHs and last six are HMW-PAHs of the 16 compounds. Among these PAHs, several are known as

Table 4. PAHs with their equations of standardization curve, correlation coefficients and RSD

Compound	Retention time (min)	Quantitative ion	Reference ion	Standard curve	Correlation coefficient	RSD (%)
Nap	5.76	128	127, 129	y = 4.19345e+006x	0.9941	2.85
AcPy	8.33	152	153, 154	y = 2.48049e+006x	0.9927	6.26
Acp	8.70	154	153, 152	y = 1.97297e+006x	0.9993	5.73
Flu	9.97	166	167	y = 1.87257e+006x	0.9949	6.28
PA	12.92	178	176	y = 2.13584e+006x	0.9910	2.58
Ant	13.11	178	176	y = 2.10768e+006x	0.9927	6.39
FL	17.56	202	201	y = 1.86261e+006x	0.9944	1.64
Pyr	18.47	202	201	y = 2.21573e+006x	0.9924	3.33
BaA	23.93	228	226, 229	y = 1.58855e+006x	0.9910	5.99
CHR	24.08	228	226, 229	y =1.35516e+006x	0.9920	6.66
BbF	28.59	252	250	y =1.21176e+006x	0.9935	6.53
BkF	28.70	252	250	y =1.11217e+006x	0.9949	7.39
BaP	29.84	252	250	y = 1.03983e+006x	0.9982	2.62
IND	35.19	276	274	y = 849205x	0.9955	2.99
DBA	35.52	278	276	y = 380247x	0.9973	11.34
BghiP	36.68	276	274	y = 476422x	0.9928	14.53

human carcinogens. The carcinogenic potency of a certain PAH compound is, generally, evaluated on the basis of its Benzo[a]pyrene equivalent concentration (BaP_{eq}) which is determined by the corresponding toxic equivalent factor (TEF) (Nisbet and LaGoy, 1992). For the assessment of carcinogenic potency of total PAHs, each individual BaP_{eq} is added to get the total BaP_{eq} of all the 16-PAHs.

Engine conditions. The experimental conditions of the engine, basing on speed-load characteristics, are given in the Table 5.

Table 5. Engine conditions

	Speed (r/min)	Load (%)
Engine condition 1	1400	75
Engine condition 2	2300	25
Engine condition 3	2300	75

Results and Discussion

Brake specific emission of PAHs. Brake specific emission (BSE) is defined as the PAH mass emitted per kilowatt power, developed in the engine in one hour. Table 6, 7 and 8 show BSE of PAHs both in PM and gas phases for engine conditions 1, 2 and 3, respectively. It is clear from Table 7 and 8 that total PAHs (solid and gas) from diesel, B20 and B100 at engine condition 2 are more than the corresponding PAHs at engine conditions 3. This finding is consistent with the previous studies that fuel PAHs survival is highest at low engine loads (Collier *et al*., 1995; Barbella *et al*., 1989; Williams *et al*., 1986). Low engine load gives rise to emissions by quenching of the

flame front in the clearance between the piston top and the cylinder head near top dead center (Collier *et al*., 1995). Furthermore, at low load, oxidation rate of fuels may decrease due to increase in over-lean mixture area, which may result in incomplete combustion and hence may increase PAH emissions.

It is elucidated from the Tables 6 and 8 that total PAHs for the fuels at rated speed are more than the corresponding PAHs at maximum torque speed. Since engine speed can affect the swirl characteristics, injection timing and combustion temperature of the engine (Collier *et al*., 1995; Rao *et al*., 1993; Gomes and Yates, 1992), so, the possible reason for increased PAHs at higher speed may be the increase in turbulence in the combustion chamber of the engine at higher speed, which may

Table 6. PAH brake specific emission at engine condition 1 (μg/kW•h)

Compound	D		B20		B100	
	PM-PAHs	Gas-PAHs	PM-PAHs	Gas-PAHs	PM-PAHs	Gas-PAHs
Nap	6.603	123.198	1.893	188.028	8.575	143.606
AcPy	0.749	1.559	0.123	3.869	0.251	3.406
Acp	0.562	0.778	0.052	1.781	0.139	2.505
Flu	1.617	1.946	0.791	7.096	0.581	13.627
PA	2.436	17.393	4.171	13.769	4.546	18.152
Ant	0.324	1.253	0.155	1.487	0.543	1.153
FL	3.688	0.556	0.810	2.361	3.090	1.416
Pyr	6.095	0.680	3.531	1.990	1.737	5.158
BaA	1.651	1.845	0.110	0.488	0.243	0.694
CHR	1.228	0.544	0.362	1.603	2.293	0.348
BbF	0.401	0.356	0.077	0.031	1.153	0.133
BkF	0.254	0.293	0.351	0.027	1.094	0.067
BaP	0.566	0.363	0.157	0.014	0.145	0.225
IND	0.160	0.046	0.290	0.001	0.591	0.047
DBA	1.883	0.638	0.133	0.009	0.707	0.003
BghiP	1.685	0.624	0.464	0.014	1.727	0.049
Σ Total	181.975		236.032		218.001	

increase the heat losses to the combustion chamber walls, and hence may decrease the combustion temperature. The low temperature in the combustion chamber decreases the oxidation rate and hence increases the PAH emissions.

From the Table 6, 7 and 8, it is obvious that after the naphthalene, phenanthrene is prominent in PAH emissions from the test fuels. The BSE of phenanthrene from diesel, B20 and B100 are 9.2%, 53.1% and 18.1% more, respectively, at low load (condition 2) as compared to high load (condition 3). This is in good agreement with the previous finding that percentage recovery of phenanthrene, in case of diesel fuel, is more at low load as compared to that at high load (Collier *et al.*, 1995).

The BSE of total PAHs (sum of BSE of all PAHs at the three conditions) for B100, B20 and diesel is 1325.740, 1224.974 and

Table 7. PAH brake specific emission at engine condition 2 (μg/kW•h)

Compound	D		B20		B100	
	PM-PAHs	Gas-PAHs	PM-PAHs	Gas-PAHs	PM-PAHs	Gas-PAHs
Nap	27.015	638.157	28.292	377.885	35.233	361.275
AcPy	0.896	3.459	0.707	8.905	0.868	6.033
Acp	0.773	1.351	0.576	4.969	0.521	6.447
Flu	3.494	5.295	3.377	15.053	2.233	32.030
PA	15.293	42.726	35.746	61.124	15.621	32.230
Ant	2.364	1.046	1.616	7.487	1.951	2.338
FL	6.672	1.304	5.100	20.595	5.025	6.399
Pyr	14.219	1.579	11.067	28.642	11.810	6.305
BaA	0.786	1.955	6.011	0.746	0.929	1.941
CHR	2.091	1.434	11.686	2.008	1.359	6.155
BbF	0.754	0.387	21.138	0.560	2.272	0.632
BkF	0.197	0.204	13.420	0.215	2.329	0.333
BaP	2.854	0.998	4.475	0.180	1.281	0.840
IND	0.838	0.028	4.507	0.035	0.871	0.218
DBA	1.712	0.327	1.426	0.027	0.418	0.208
BghiP	4.022	0.823	3.382	0.204	0.749	0.345
Σ Total	785.049		681.162		547.200	

Table 8: PAH brake specific emission at engine condition 3 (μg/kW•h)

Compound	D		B20		B100	
	PM-PAHs	Gas-PAHs	PM-PAHs	Gas-PAHs	PM-PAHs	Gas-PAHs
Nap	31.130	390.330	2.521	181.380	23.769	394.023
AcPy	0.691	2.345	0.377	2.669	0.937	9.309
Acp	0.428	1.709	0.146	1.873	0.537	9.358
Flu	2.138	10.015	1.189	6.473	1.664	27.321
PA	12.220	40.466	20.736	24.629	11.048	28.139
Ant	1.353	2.758	1.992	3.373	1.542	2.405
FL	6.613	3.342	6.335	8.375	5.053	5.041
Pyr	14.365	8.702	14.170	12.351	5.213	10.195
BaA	2.670	0.986	0.529	2.355	1.634	1.058
CHR	1.995	2.561	3.584	2.307	2.012	3.350
BbF	0.202	1.289	0.203	1.952	2.631	1.623
BkF	1.266	0.143	0.134	1.676	1.436	1.600
BaP	1.297	0.884	1.797	0.148	1.479	0.068
IND	0.939	0.021	1.341	0.034	1.344	0.032
DBA	2.729	0.439	1.064	0.151	2.314	0.227
BghiP	3.424	0.016	1.789	0.130	3.249	0.928
Σ Total	549.464		307.780		560.539	

1516.488 μg/kW•h, respectively which reveals that biodiesel and its blends reduce the PAH emissions. This is consistent with other results (Lin *et al.*, 2006a, Cardone *et al.*, 2002).

Benzo[a]pyrene (BaP), the most carcinogenic compound, shows less BSE in case of B100 as compared to diesel for all the engine conditions. Although B20 shows less BSE in terms of Benzo[a]pyrene at engine conditions 1 and 3, its BaP emission improves surprisingly at engine condition 2 compared to diesel fuel.

Total LMW, MMW and HMW- PAHs. Fig. 4 shows the comparison of total lower, medium and higher molecular weight PAHs. ΣLMW-PAHs show higher BSE as compared to ΣMMW-PAHs and ΣHMW-PAHs, while the least BSE is depicted for ΣHMW-PAHs at the three engine conditions for all the test fuels. For diesel fuel, ΣLMW-PAHs is 87.1%, 94.5% and 90.2% of total PAH emissions at engine conditions 1, 2 and 3, respectively. Similarly, ΣLMW-PAHs is 94.5%, 80.1% and 80.4% of the total PAH emissions from B20 at conditions 1,2 and 3, respectively, and 90.4%, 90.8% and 91% of the total PAHs from B100 at the engine conditions 1, 2 and 3, respectively. This finding is in good agreement with the previous studies that two and three ring PAHs contribute a large fraction of the total PAH emissions (Lin *et al.*, 2006b, c).

Mean brake specific emission and corresponding carcinogenic potencies. Table 9 illustrates the mean specific emission of total (solid and gas) PAHs for the test fuels at the three engine conditions, with their corresponding toxic equivalent factors (TEFs). Each individual PAH was multiplied with its corresponding TEF to get its BaP$_{eq}$ factor. So, total BaP$_{eq}$ of all

Table 9. Mean brake specific emission of test fuels

Compound	Mean brake specific emission (μg/kW•h)			TEF
	D	B20	B100	
Naphthalene	405.478	259.999	322.161	0.001
Acenapthylene	3.233	5.550	6.935	0.001
Acenaphthene	1.867	3.132	6.502	0.001
Fluorene	8.168	11.326	25.819	0.001
Phenanthrene	43.511	53.392	36.578	0.001
Anthracene	3.033	5.370	3.310	0.01
Fluoranthene	7.391	14.525	8.675	0.001
Pyrene	15.213	23.915	13.473	0.001
Benz[a]anthracene	3.297	3.413	2.166	0.1
Chrysene	3.285	7.183	5.172	0.01
Benzo[b]fluoranthene	1.129	7.987	2.815	0.1
Benzo[k]fluoranthene	0.786	5.274	2.286	0.1
Benzo[a]pyrene	2.321	2.257	1.346	1
Indeno[1, 2, 3-cd]pyrene	0.677	2.069	1.034	0.1
Dibenzo [a, h] anthracene	2.576	0.937	1.292	1
Benzo[ghi]perylene	3.531	1.995	2.349	0.01
Total Mean BSE	505.496	408.325	442.117	
Total BaP$_{eq}$	6.069	5.586	3.997	

the 16-PAHs was calculated by the following formula:

$$BaP_{eq} = \Sigma(M_i \cdot TEF_i) \tag{1}$$

Where M is mean BSE in (μg/kW•h); $i = 1 \sim 16$

It is clear from the Table 9 that total BaP_{eq} and total mean BSE (sum of mean BSEs) for the three fuels follow the order
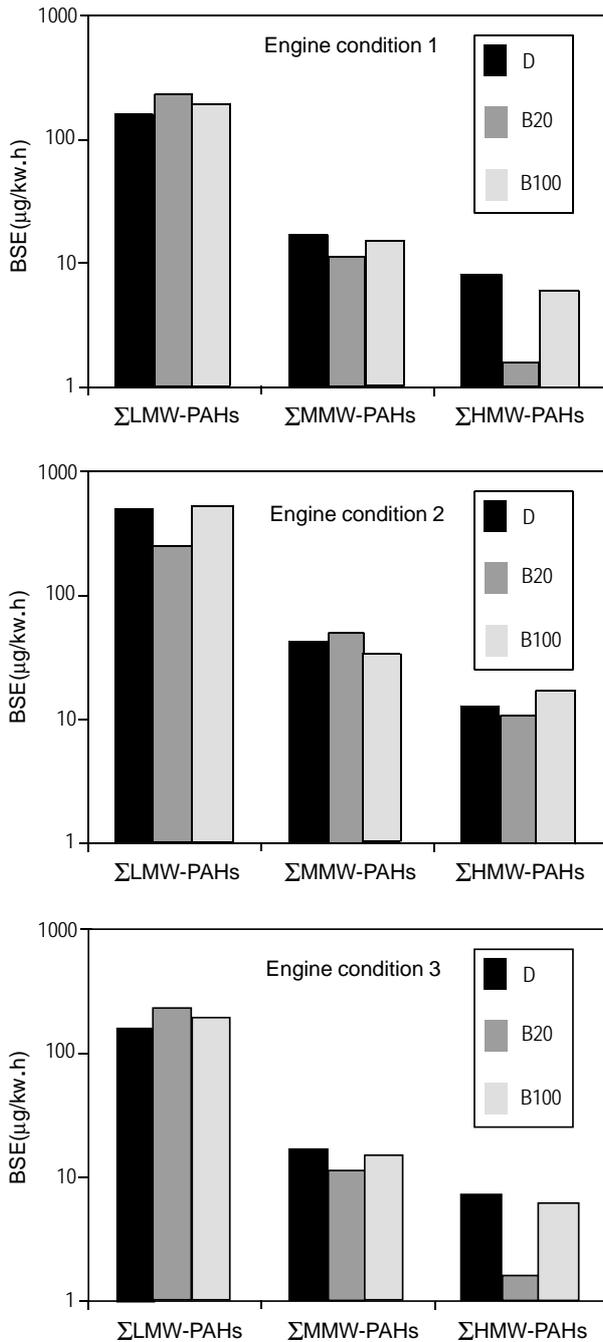
Fig. 4. Total LMW, MMW and HMW-PAH emissions (on logarithmic scale) from test fuels at different engine conditions.

B100 < B20 < D. The above results reveal that use of biodiesel and its 20% blend decreases both the total- BaP_{eq} and the total mean- PAH emissions. This finding is consistent with the data quoted in other literature (Lin *et al*., 2006a, b).

Brake specific fuel consumption and brake power. Fig. 5 shows comparison of the brake specific fuel consumption (BSFC) of the test fuels at different engine conditions. The increase in BSFC of the engine in the cases of B20 and B100 is 6.4% and 13.9%; 2.5% and 13.8%, and 1.2% and 13.2%, respectively at conditions 1, 2 and 3, respectively.

Fig. 6 depicts the effect of biodiesel and its blend on brake power of the engine at the three different conditions. The percentage decrease in power of B20 and B100 compared to diesel is of the order of 3.3% and 0%; 9.8% and 7.5%, and 12% and 11.7%, at engine conditions 1, 2 and 3, respectively.

The possible reasons for higher BSFC but lower power, in the cases of B20 and B100, are lower heating value and more
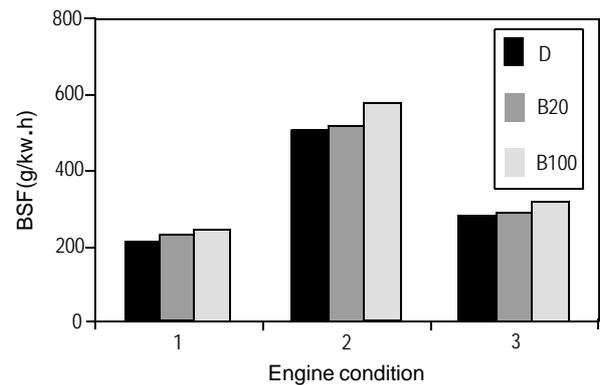
Fig. 5. Brake specific fuels consumption of test fuels at different engine conditions.
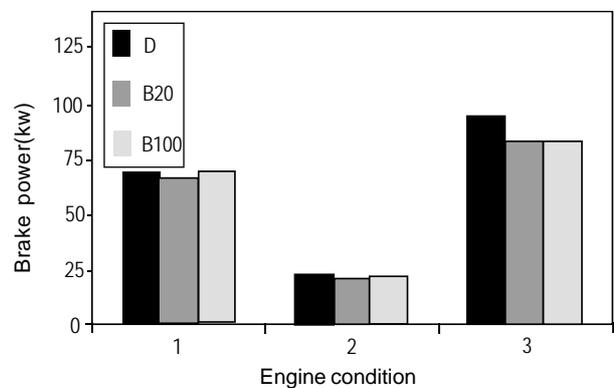
Fig. 6. Brake power of the engine for the test fuels at different engine conditions.

density of biodiesel as compared to those of diesel. Furthermore, at the same degree of crank angle, more mass is injected in case of biodiesel due to its earlier injection start with raised pressure and rate, as compared to diesel.

Conclusion

The current study aims at the comparative assessment of PAHs in terms of brake specific emissions and their corresponding carcinogenic potencies from a heavy duty diesel engine alternatively fuelled with biodiesel and its 20% blend with diesel. The main findings are as follows:

- BSE of total PAHs of diesel, B20 and B100 is more at low load than that at high load.
- BSE of total PAHs emitted from diesel, B20 and B100 is more at rated speed compared to that at maximum torque speed.
- Naphthalene and phenanthrene emissions for the test fuels are all dominant to other PAHs and the phenanthrene BSE for diesel, B20 and B100 is 9.2%, 53.1% and 18.1% more, respectively, at low load as compared to high load.
- The BSE of total PAHs for B100, B20 and diesel follows the order B20 < B100 < D.
- Benzo[a]pyrene (BaP)- BSE is less for biodiesel as compared to diesel for all the engine conditions.
- LMW-PAH emissions for the test fuels are all higher than those of MMW and HMW PAH, but HMW-PAHs are least among the three major categories of PAHs for all the engine conditions.
- Total BaP_{eq} for the three test fuels follows the order as B100 < B20 < D.
- BSFC of the engine increases following the decrease in its brake power in the cases of biodiesel and B20 for all the engine conditions used in this study except condition 2 where diesel and B100 show almost the same brake power.

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