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Technical Note

Particulate Characterization of CNG Fuelled Public Transport Vehicles at Traffic Junctions

Avinash Kumar Agarwal[1*], Prakhar Bothra[1], Pravesh Chandra Shukla[2]

[1] *Engine Research Laboratory, Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur-208016, India*
[2] *Indian Institute of Technology Kanpur, Kanpur-208016, India*

ABSTRACT

Compressed natural gas (CNG) is considered as cleaner fuel compared to gasoline and has emerged as an important alternate transport fuel in view of its abundant availability globally. CNG has been implemented in mass transport sector globally. This study explores the emission characteristics of two different classes of CNG operated vehicles used for public transportation in Indian Cities. One is a heavy-duty CNG bus and the other one is a light-duty CNG tempo. Both are very popular commuting vehicles in Indian cities. The number of such CNG vehicles is quite large therefore their emissions affect the health of traffic policemen, who are responsible for regulating the traffic during their long duty-hours. They are continuously exposed to harmful regulated and unregulated pollutants from such vehicles. Regulated gaseous emissions and particulate bound polyaromatic hydrocarbons (PAHs) were determined for both vehicles at different engine speeds at no load, which simulates typical traffic junction scenario. For the heavy-duty CNG operated bus, particulate number-size distribution and mass-size distributions were also evaluated. Carbon monoxide (CO), Hydrocarbons (HC) and nitric oxide (NO) emissions were found to be higher for the CNG operated bus compared to the CNG tempo. Particle bound PAHs were quite significant for CNG fuelled vehicles however they reduced at higher engine speeds. Particulate number emissions increased with increasing engine speed, especially in the accumulation mode (50–250 nm) for the heavy-duty CNG bus. Despite moderate increase in particle number emissions, particulate mass contributions of the accumulation mode particles increased significantly with increasing engine speed.

Keywords: Compressed natural gas; Particle number-size distribution; Particle mass-size distribution; Particulate bound PAHs; Regulated gaseous emissions.

INTRODUCTION

Liquid fuels such as diesel and gasoline have limited reserves and use of gaseous fuels such as natural gas (NG) is inevitable because it is an important alternative fuel candidate for global mobility. According to a study, enough reserves (approximately 6,845.6 trillion cubic feet) of NG are available to sustain global transport sector for next few decades (USEIA, 2013). NG mainly contains methane (minimum 87%), in addition to traces of ethane (Narain and Krupnick, 2007). Compressed natural gas (CNG) is an odorless, colorless and tasteless gas, which is an excellent alternative fuel for displacing gasoline from spark ignition (SI) engines with some engine hardware modifications. It has superior emission characteristics compared to gasoline. According to a report by Environmental Protection Agency (EPA), use of CNG in vehicles results in 90–97% reduction in carbon monoxide (CO), 35–60% reduction in oxides of nitrogen (NO_x), and 50–75% reduction in unburned hydrocarbons (HC) (EPA, 2002). It also results in lesser toxic emissions such as PAHs and particulate however the toxic potential of the smaller nano-particles generated by CNG is not investigated thoroughly. Unlike gasoline and diesel, it does not have issues such as evaporative emissions (ETSAP, 2010). CNG has significantly higher octane number compared to gasoline therefore the engine noise is also lower. But methane is a very strong greenhouse gas and its global warming potential is 21 times higher than carbon dioxide (CO_2) (IPCC, 1995). Therefore, any leakage of gas from CNG operated vehicles would be environmentally detrimental. Such leakages can take place from storage, fuel systems, during cylinder filling process etc. These methane emissions have the potential to offset the benefits offered by CNG. CNG offers quite low CO_2 emission per unit power produced compared to other hydrocarbon fuels.

* Corresponding author.
E-mail address: akag@iitk.ac.in

According to data from the Mauna Loa Observatory in Hawaii, CO_2 concentration in the atmosphere has crossed 400 ppm (NOAA Report, 2014), raising concerns of accelerated global warming and climate changes and it is blamed on transport sector related CO_2 emissions.

Aslam *et al.* (2003) performed comparative analysis of emission and performance parameters for gasoline and CNG in a 1.5 *l*, 4-cylinder SI engine. They modified a gasoline engine so that it can be operated on gasoline as well as CNG. CNG delivered lower brake mean effective pressure (BMEP), lower brake specific energy consumption (BSEC), but higher brake thermal efficiency (BTE). CO, CO_2, HC and NO_x emissions were relatively lower for CNG. Machacan *et al.* (2000) studied CNG operation of a two-stroke, two-cylinder engine. They varied the compression ratio of the engine from 8.6 to 14.5 and observed that self-ignition, akin to HCCI was possible under certain operating conditions, while using CNG. Their study revealed that self-ignited combustion of CNG in SI engine resulted in lower brake specific fuel consumption (BSFC), HC and NO_x emissions. Liu *et al.* (2013) investigated the effects of pilot injection of diesel in a CNG/diesel dual-fuel engine. They reported 30% reduction in NO_x emissions in dual-fuel mode compared to diesel mode. However, HC emissions were higher for CNG-diesel dual-fuel mode compared to diesel mode. Several studies focused on laboratory test-bed CNG engines however there are only a few studies on emission characterization of CNG vehicles in the field conditions in open literature. Therefore in this study, experiment were performed on two different CNG vehicles used for mass transport in simulated traffic junction conditions, where the emissions from CNG vehicles have most direct impact on the occupants of other vehicles at the intersection and on the traffic policemen regulating the traffic for long hours. As the vehicles approach the traffic junction, they decelerate/idle. Therefore idling condition or high idling conditions of the engine are adequate representation of the engine operating condition at the traffic junctions. When these vehicles leave the traffic junction, they operate for few seconds (maximum 5 seconds) at low engine torques at and low engine speed to cross the traffic junction, which is relatively smaller compared to their waiting time at the traffic junction for the light to turn green. This time may be anywhere from 60 to 120 seconds or even higher at times. Therefore, for the impact assessment, it is appropriate to carry out tests at different engine speeds at no load and this will essentially simulate the traffic junction situation. Guo *et al.* (2014) measured and compared the on-road emissions of regulated pollutants from diesel and CNG buses. They observed that using selective catalytic reduction (SCR) in CNG vehicles results in significantly lower NO_x emissions. CNG buses also emits lower particle numbers. Thiruvengadam *et al.* (2014) reported that a large fraction of particulates from CNG buses contain traces of lubricating oil and wear debris. This showed that lubricating oil and wear debris are major fraction of particulates from CNG vehicles. In India, large variety of public transport vehicles has been converted to operate on CNG because of its cleaner emission characteristics. There are few studies carried out to investigate some of these aspects however comprehensive investigations need to be carried out in order to assess actual impact of CNG emissions on the environment. Therefore, in the present study, experiments were carried out for emission characterization of two different classes of CNG vehicles.

EXPERIMENTAL SETUP

In this study, two CNG vehicles were characterized for emissions. Vehicles used were heavy-duty bus (Tata Motors; CNG Star Bus) and a CNG Tempo (Scooters India, Vikram). Both these vehicles are common means used for inter-city as well as intra-city transport in Indian cities. The Tempo is represented as 3C1 and the bus is represented as 4C1 in the present study. Regulated gaseous emissions and particle bound PAH emissions were measured for both vehicles. For CNG bus, particle number-size distributions were also measured. Measurements were taken at four engine speeds (1500, 2000, 2500 and 3000 rpm) at no load, in order to simulate typical traffic junction situation. The vehicles were driven for some time and then brought to a standstill before measurement. This was done in order to more closely simulate actual vehicle condition and to make correct measurements in closely simulated environment. Exhaust samples were drawn into various emission measuring instruments from these CNG vehicles at different engine operating conditions. Fig. 1 shows the schematic of the experimental setup.

Engine exhaust particle sizer (EEPS) spectrometer (3090, TSI Inc.) was used for online measurement of particle size-number distribution. EEPS measures the nuclei as well as accumulation mode particles (50–250 nm) with high concentration (upto 10^8 particles cc^{-1}). It measures particle sizes ranging from 5.6 to 560 nanometers with a size resolution of 16 channels per decade (a total of 32 channels). Each data point is an average of 60 readings and corresponding standard deviation is shown in every graph. For measurement, a fraction of engine exhaust was drawn from the exhaust pipe, which was diluted using rotating disc thermo-diluter (Matter Engineering; 379020) in order to lower the particle concentration and bring it in the measurement range of the EEPS. Rotating disk thermo-diluter dilutes the exhaust gas with a treated pre-conditioned air upto 3000 times. Dilution ratio is a very important factor in terms of particle number emission because dilution ratio affects the particle morphology significantly. Photo-Acoustic Sensor (PAS 2000, EcoChem Analytics) was used for measurement of total particle bound polyaromatic hydrocarbons (PAHs). It operates on the principle of photoelectric ionization of particle bound PAHs. For measuring the regulated gaseous emissions (CO, HC and NO), a raw exhaust gas emission analyzer was used (AVL, 444) was used. Table 1 shows the specifications of the emission measurement instruments and Table 2 shows the specifications of the test vehicles.

Procedure: Selected vehicles were tested in steady-state conditions for characterization of regulated gaseous emission components, particle bound PAHs and particle number-size distribution. Before taking the exhaust samples, vehicles were operated for 10 minutes on the road and they were brought to a stand-still immediately prior to measurements. Separate sampling probes were used for sampling exhaust into raw exhaust gas emission analyzer, EEPS and PAS analyzer. The experimental test matrix is shown in Table 3.

RESULTS AND DISCUSSION

A three wheeler CNG tempo (Seating capacity 10) and a heavy-duty CNG bus (Seating Capacity: 40) were used for

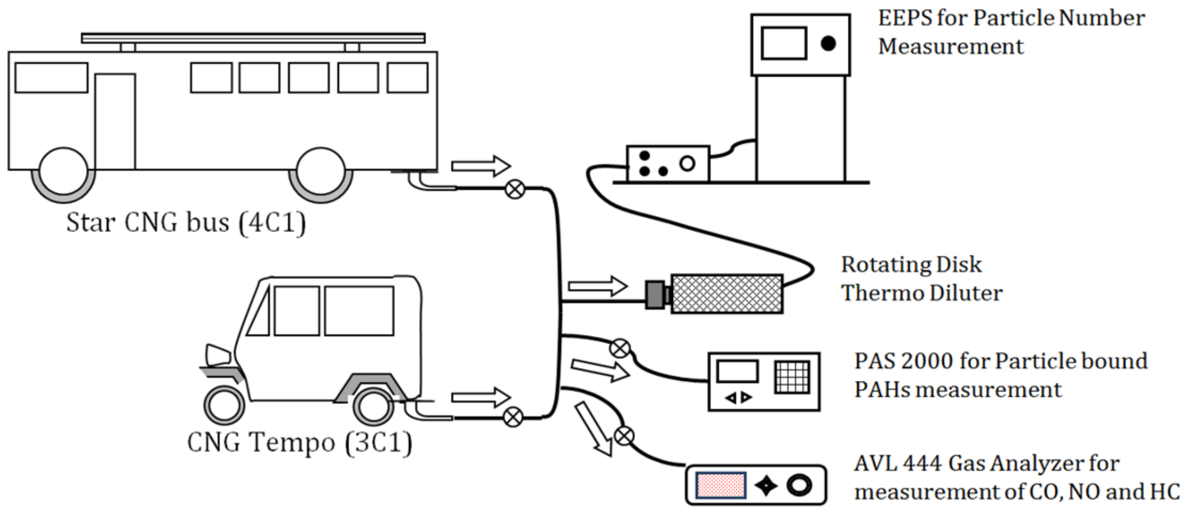

Fig. 1. Experimental setup for emission measurement from CNG fuelled vehicles.

Table 1. Specifications of the emission measurement instruments.

Engine Exhaust Particle Sizer (EEPS)	
Particle size range	5.6 to 560 nm
Particle size resolution	16 channels per decade (32 total)
Electrometer channels	22
Charger mode of operation	Unipolar diffusion charger
Inlet cyclone 50% cut-point	1 µm
Maximum data rate	10 Hz
Photo Acoustic Sensor (PAS)	
Range	0 to 100 pico amp
Sensitivity	~0.3–1 g m^{-3} PAHs per pico amp
Response time	< 10 s
Operating temp	5 to 40°C
Raw Exhaust Gas Emission Analyzer Measurement Ranges	
NO_x	1 ppm
CO	0.01% (v v^{-1})
HC	1 to 10 ppm
CO_2	0.1% (v v^{-1})

Table 2. Specifications of the test vehicles.

CNG operated Vikram	
Manufacturer	Scooter India Limited
Engine	2 stroke, single-cylinder, air cooled engine
Bore × stroke	85 mm × 90 mm
Displacement	510 cc
Output	9.8 BHP @ 3000 rpm
Maximum RPM	4800
Ignition	By electronics device & HT coil
CNG operated Bus	
Manufacturer/Model	TATA/Star Bus 24
Maximum power	92 kW @ 2400 rpm
Maximum torque	400 Nm @ 1300–1500 rpm

Table 3. Test matrix for experiments on CNG vehicles.

	Vikram three wheeler	Tata Star Bus
Representation	3C1	4C1
Engine speeds	1500, 2000, 2500 and 3000 rpm	1500, 2000, 2500 and 3000 rpm
CO	√	√
HC	√	√
NO	√	√
Particle bound PAHs	√	√
Particle number emissions	×	√

the study of regulated gaseous emissions (CO, HC and NO), particle bound PAHs, particle number-size distribution and particle mass-size distribution. The results of the raw exhaust gas emissions at varying engine speeds at no load for both vehicles are shown in Fig. 2. Every data point shown in Fig. 2 is an average of five readings and corresponding standard deviations are shown as error bars in each data point of the graphs.

The emissions of CO and HC were quite high from both vehicles because both vehicles have stoichiometric engines, which are prone to incomplete combustion in field conditions. CO, HC and NO emissions increased with increased engine speed for both vehicles. Higher engine speed leads to availability of shorter in-cylinder combustion duration in terms of time. Shorter combustion duration results in incomplete combustion of hydrocarbons (primarily methane in this case), therefore higher CO and HC emissions were observed with increasing engine speed. NO emission also showed an increasing trend with increasing engine speed from both vehicles. There may be a possibility of having more NO emissions at elevated engine speeds because of higher CNG quantity induction in every engine cycle. This leads to higher peak in-cylinder temperature, therefore high NO_x formation. As far as vehicles are concerned, heavy-duty CNG bus emitted relatively higher CO, HC and NO amongst the two vehicles. CNG combustion phenomenon is similar to gasoline combustion and homogeneous combustible charge is ignited by a spark plug. Once spark is generated, flame front propagates towards the combustion chamber walls. In case of heavy-duty CNG bus, flame-front takes longer time to reach piston bowl surface due to deeper bowl. This phenomenon possibly leads to emission of higher HC emissions. This also increases the knocking tendency of the engine. Knocking is a phenomenon, in which unburned charge explodes spontaneously towards the end of combustion in a SI engine. As a result, local in-cylinder temperature increases dramatically, which leads to higher NO_x formation. NO_x formation takes place when peak in-cylinder temperature reaches above 2000 K in certain zones of the combustion chamber. NO_x formation increases exponentially with any further increase in peak in-cylinder temperature. It is important to note that both vehicles have two-way catalytic converter but their effectiveness is rather poor.

Fig. 2 also shows the total particle bound PAH emissions from the two CNG vehicles at four different engine speeds at no load. Particle bound PAH emissions were relatively higher for CNG bus compared to CNG Tempo. PAHs slightly decreased at the highest engine speed tested for both vehicles. At higher engine speed, it is possible that the lower particulate emission occurred, which resulted in lower particle bound PAH emissions in the exhaust. However it is possible that a large fraction of PAHs are present in gas phase (in the form of gaseous HC). Also, higher in-cylinder temperature may oxidize a fraction of PAHs. Higher temperature exhaust may also restrict the condensation of HC, which may result in increased HC emission at highest speed. This is an opposite trend to the trend observed for emission of particle bound PAHs.

Fig. 3 shows the comparison of particle number-size distribution and particle mass-size distribution for the heavy-duty CNG bus at four engine speeds. It was observed that accumulation mode (~100 nm) particle number concentration increased with increasing engine speed. However there was no change in the nuclei mode (< 50 nm) particle number concentration at all four engine speeds. Coarse mode (> 250 nm) particle concentration was higher at lower engine speeds. Significant nuclei mode particles were present in the exhaust. Combustion results in several semi-volatile compounds, which may act as precursor for nuclei mode particle formation. On the other hand, lubricating oil also plays an important role and unburned or partially burned volatile compounds generated from lubricating oil come in contact with high temperature gases in the combustion chamber.

Corresponding particle mass-size distributions are shown in each figure. The density of particles is assumed to be 1 g cc^{-1} for calculation of mass-size distribution in these graphs. The density of the engine particulates may vary according to engine load, speed, fuel composition etc. however these artifacts are ignored in the calculations in this study. Particle mass-size distribution attains a peak close to 100 nm size. This peak rises further with increasing engine speed. Nuclei mode particles had negligible mass contribution in the mass-size distribution and it maximum mass was contributed by accumulation mode particles close to 100 nm diameter. CNG is a gaseous fuel and does not contribute significantly to the particulate formation. Therefore, the main sources for particulate formation are semi-volatile organics, lubricating oil and wear debris generated in the combustion chamber. In recent years, particle number emissions have come under severe scrutiny because of their adverse effects on human health. Higher particle number emissions provide greater surface area for absorption of higher volatile organic species such as PAHs present in the engine exhaust, making them more toxic.

CONCLUSIONS

We have investigated the regulated gaseous emissions and particulate bound PAHs from two CNG vehicles used for public mass transport, under simulated traffic junction conditions. Particle number-size distributions were also

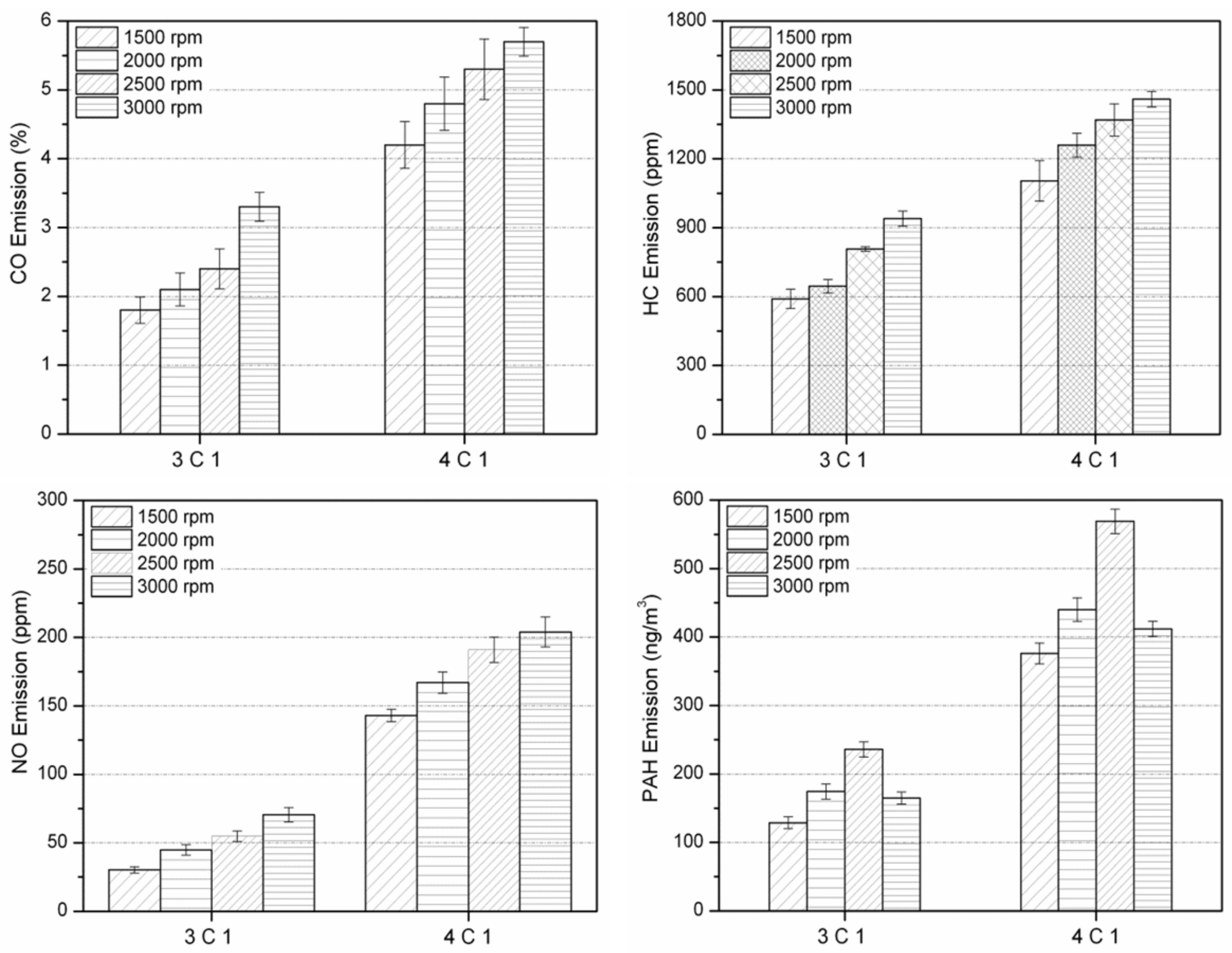

Fig. 2. Emissions of CO, HC, NO and particle bound PAHs from the CNG Tempo and CNG bus.

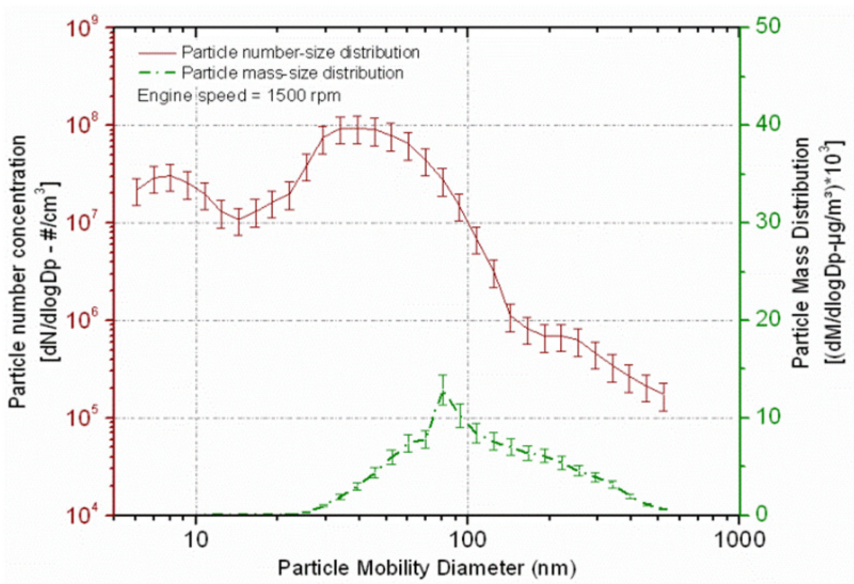

Fig. 3. Particle number-size distribution and particle mass-size distribution for heavy-duty CNG bus.

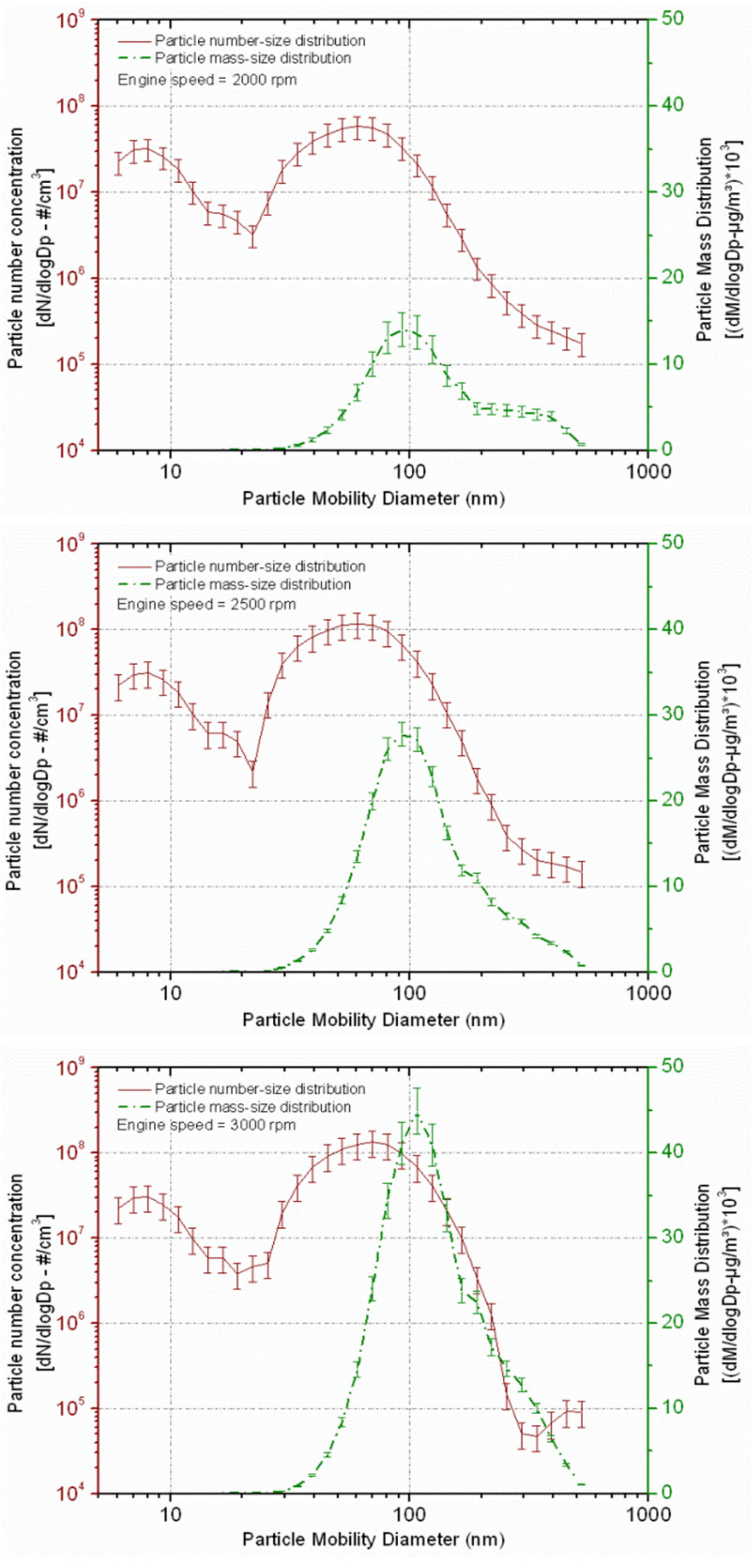

Fig. 3. *(continued).*

measured. The following main conclusions were drawn from this experimental study:

1. Heavy duty CNG vehicle showed significantly higher concentration of CO, HC and NO emissions. Higher gaseous emissions were emitted at higher engine speeds. Performance of after-treatment devices was rather inferior in controlling regulated gaseous emissions.
2. Particle bound PAHs showed an increasing trend with increased engine speed however they slightly decreased at the highest engine speed tested. A possible reason for the reduction in the particle bound PAHs may be increased relatively higher in-cylinder temperature at higher engine speeds. Higher in-cylinder temperature leads to further oxidation of organics produced in the combustion chamber.
3. For heavy-duty CNG bus, there was moderate increase in the particle number concentration in accumulation mode with increased engine speed. On the other hand, there was drastic increase in particle mass near 100 nm diameter with increased engine speed.

Overall, it is known that CNG vehicles are excellent in terms of lower particulate mass emissions however this study demonstrated that these vehicles are prone to emit higher level of particle numbers particularly at traffic junctions, which could have serious health effects to the exposed people. Also regulated gaseous emissions are on higher side compared to conventional vehicles fuelled with gasoline or diesel. Based on these findings, it can be concluded that vehicles based on old engine designs perform sub-optimally when these are modified to operate on CNG and do not offer expected environmental benefits.

REFERENCES

Aslam, M., Masjuki, H., Kalam, M., Abdesselam, H., Mahlia, T. and Amalina, M. (2006). An Experimental Investigation of CNG as an Alternative Fuel for a Retrofitted Gasoline Vehicle. *Fuel* 85: 717–24.

Energy Technology Systems Analysis Programme (ETSAP) (2010). Automotive LPG and Natural Gas Engines. IEA ETSAP - Technology Brief T03 – April 2010.

Environmental Protection Agency (EPA) (2002). Transportation and Air Quality, Transportation and Regional Programs Division, EPA420-f-00-033.

Guo, J., Ge, Y., Hao, L., Tan, J., Li, J. and Feng, X. (2014). On-road Measurement of Regulated Pollutants from Diesel and CNG Buses with Urea Selective Catalytic Reduction Systems. *Atmos. Environ.* 99: 1–9.

IPCC (1995). Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Vol. 2. Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. and Maskell, K. (Eds.), Cambridge University Press, Cambridge, UK. pp. 22.

Liu, J., Yang, F., Wang, H., Ouyang, M. and Hao, S. (2013). Effects of Pilot Fuel Quantity on the Emissions Characteristics of a CNG/Diesel Dual Fuel Engine with Optimized Pilot Injection Timing. *Appl. Energy* 110: 201–206.

Machacon, H.T., Yamagata, T., Sekita, H., Uchiyama, K., Shiga, S., Karasawa, T. and Nakamura, H. (2000). CNG Operation of a Two-stroke, Two-cylinder Marine SI Engine and Its Characteristics of Self-ignition Combustion. *JSAE Rev.* 21: 567–572.

Narain, U. and Krupnick, A. (2007). The Impact of Delhi's CNG Program on Air Quality. Resources of for the Future, Washington, DC, SSRN 969727.

National Oceanic and Atmospheric Administration (NOAA) (2014). Green House Gas Reference Network. Earth System Research Laboratory, Global Monitoring Division, National Oceanic and Atmospheric Administration.

Thiruvengadam, A., Besch, M.C., Yoon, S., Collins, J., Kappanna, H., Carder, D.K. and Gautam, M. (2014). Characterization of Particulate Matter Emissions from a Current Technology Natural Gas Engine. *Environ. Sci. Technol.* 8: 8235–8242.

United States Energy Information Administration (USEIA) (2013). International Energy Statistics, Natural Gas Proved Reserves, http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=3&pid=3&aid=6&cid=ww,&syid=2011&eyid=2014&unit=TCF.

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