Defence Science Journal, Vol. 68, No. 6, November 2018, pp. 533-539, DOI : 10.14429/dsj.68.12701

Study and Analysis of Exhaust Emission of Diesel Vehicles using Thermal IR Imagers

Ajay Jain[#,*], Amit Sharma[#], S.L Borana[#], B. Ravindra[@], and J.P. Mangalhara[#]

[#]DRDO-Defence Laboratory, Jodhpur - 342 011, India
[@]Indian Institute of Technology Jodhpur, Jodhpur - 342 011, India
[*]E-mail: ajay.jain@dl.drdo.in

ABSTRACT

Exhaust emission analysis from diesel vehicles has received a lot of attention in recent times in the context of implementation of Bharat Stage-IV norms and thermal signature analysis for civil and military applications. The exhaust emission thermal IR signatures of military diesel vehicles such as truck and bus using a gas analyser and thermal imager under idling and accelerating conditions of these vehicles is investigated. Concentration and temperature of diesel exhaust emission CO, NOx, and HC remains almost constant during engine running in idle condition and varies with the engine acceleration. Exhaust gases maximum temperature reaches in the range of 240 °C - 270 °C during engine acceleration. A detailed investigation of thermal signature in mid wave infrared, 3 µm - 5 µm waveband and long wave infrared, 8 µm - 14 µm waveband is also presented under the same engine running conditions. Thermal image analysis exhibited that the area of thermal IR image of diesel vehicles truck and bus has been increased 0.077 per cent and 0.594 per cent, respectively with the engine acceleration. It has been observed that thermal signature of exhaust gases is a good tool for vehicle exhaust emission visualisation and analysis.

Keywords: Vehicle exhausts emission; Thermal IR signature; Gas analyser; Thermal imagers

1. INTRODUCTION

Diesel engines are used widely in vehicles as well as other general purpose civil and defence applications such as loading trucks, cranes, dosers, etc. Thermal signature study and analysis of diesel vehicles exhaust will be useful for testing of engine function, exhaust emission control and development of thermal signature simulated targets[1]. Thermal signature study, analysis and visualisation of exhaust emissions of diesel engines using thermal imaging techniques is an important area of research[2-3]. Thermal signature of diesel exhaust emission will help in detection and identification of engine characteristics as well as taking preventive measures for vehicles maintenance and surveillance from enemy's thermal sensor. Infrared radiometric thermal imaging camera in mid wave infrared (MWIR) 3 µm - 5 µm region of EM spectrum may detect apparent temperature and radiance of exhaust emission species. Thermal imager in LWIR 8 µm - 14 µm region also detects thermal signature of some gases[4-5]. However, determination of concentration and wavelength of specific gas are not possible using wide band based thermal imager in MWIR and LWIR. Hence, attempt was made to measure exhaust emission compositions such as CO, HC, NO, and NO_2 of selected two diesel vehicles using portable gas analyser. Thermal signature[6-7] of diesel exhaust depends on many factors such as ambient condition, gas concentration, gas temperature, thermal contrast and thermal imager performance.

Received : 12 February 2018, Revised : 26 September 2018
Accepted : 09 October 2018, Online published : 31 October 2018

In defence, diesel vehicle exhaust may reveal vital information to thermal imager which will be vulnerable target for detection and heat seeking weapons[8-9]. In this paper efforts are made by the authors to analyse diesel exhaust thermal images and simultaneously analyse exhaust gases concentration and temperature.

2. EXPERIMENTAL SETUP AND METHODOLOGY

An experimental setup was planned for carrying out measurement of diesel engine exhaust species by gas analyser and thermal signature to be recorded using a radiometric thermal imager[10]. Details of equipment used for measurement are as follows:

(a) Radiometric thermal imaging system- nake- Cedip
(b) Hand held thermal imager-nake –Fluke
(c) Portable gas analyser-nake –Sitron
(d) Thermocouple PT-100

Thermal imager was interconnected with the computer system for data transmission and recording[11]. Vehicles were parked about 50 m distance from thermal imager. Vehicles were run for 3 min in idle condition and subsequently accelerating static condition. Thermal imaging system was turned on for recording thermal video acquisition and simultaneously exhaust species concentration along with temperature was measured using portable gas analyser[12]. Same procedures were carried out for obtaining thermal images and taking measurement of temperature and species concentration for bus. Engine of both the vehicles were running for same time duration in static conditions in similar ambient environments. Ambient parameters such as temperature, wind velocity and humidity were also recorded using weather station installed at Defence Laboratory, Jodhpur.

2.1 Vehicles Specifications

Two type of vehicle were selected for diesel exhaust emission concentration measurement and thermal IR signature analysis. Specifications of the selected test vehicles are as given in Table 1.

Table 1. Vehicles Specifications

Parameter	Truck	Bus
Model and Make	1210E, TATA	T3500, SWRAJ MAZDA
Type	Six cylinders, water cooled diesel engine	Four cylinders, overhead valve engine
Bore and stroke	92 mm and 120 mm	100 mm and 110 mm
Engine	4788 cc	3455 cc
Compression ratio	17:1	18: 1
Engine Power	73.5 kW at 2800 rpm	66.2 kW at 3000 rpm
Torque max	294.3 N-m at 1800 rpm	227 N-m at 2000 rpm

2.2 Diesel Fuel Specifications

Diesel fuel used in selected vehicles follows the BS-IV norms and conforms to BIS: 1460:2000 specifications. Fuel specification details are as given in Table 2.

Table 2. Specifications for automotive diesel fuel (BS-IV)

Parameter	Specification value
Density@15 °C	825 kg/m^3
Kinematic viscocity@40 °C	3.0 cSt
Pour point	-10 °C
Flash Point	40 °C
Cetane number	53
Total sulphur	40 mg / kg

3. DIESEL EXHAUST GAS SPECIES DATA FOR TRUCK

Diesel exhaust gas emissions measurement of Truck was carried out in field conditions at Defence Laboratory and simultaneously thermal IR video recording was also carried out for gas species visualisation using thermal imager in MWIR (3 μm - 5 μm).

3.1 Truck in Idle Engine Running Condition

Engine of Truck was started for three minutes in static condition. Measurement of exhaust gas species of the vehicle was carried out in time gap of 15 s and thermal images were also recorded simultaneously using radiometric thermal imager. Weather parameters recorded such as ambient temperature Ta = 26.32 °C, wind v = 0.43 m/s and RH = 14.8 %.

Gas species concentration and temperature variation with time was analysed and it was observed that concentration and temperature variations in gas species are very less with the time during idle running condition of engine.

3.2 Truck in Accelerating Engine Running Condition

Gas species concentration and temperature variation with time was plotted and shown in Figs. 1 and 2. It was observed that concentration of CO reduces with engine acceleration time and concentration of NO , NOx and HC marginally increases with the acceleration time. It is due to rich burning ratio of fuel and air during engine accelerating condition.

It was also observed from Fig. 2 that temperature of gas species mixture and thermal contrast (temperature difference, T_{gas} -T_a) gradually increases with engine acceleration time. Thermal contrast plays an important role in process of detection and identification of the exhaust emissions. Higher thermal contrast provides better visibility by thermal imager.

3.3 Thermal Images of Diesel Exhaust Gas Species of Truck

Thermal images were captured with radiometric thermal imager in 3 μm - 5 μm EM spectrum range in different running condition of engine. It was observed that gas species visualisation is not very prominent in idle engine running condition. This may be attributed to the fact that exhaust concentration of gas emission and temperature of exhaust gas species are lower side than accelerating engine condition.

In acceleration condition, the exhaust gas temperature and gas concentration increase with accelerating time period which provides better visibility of exhaust gas emissions in thermal IR image as shown in Fig. 3 at full acceleration condition of the vehicle.

3.4 Thermal Image Analysis of Truck using ENVI Software

Environment for visualising images (ENVI) is commercially available software used for image processing and analysis of digital images. Thermal image analysis using ENVI 4.1 software during engine idle running and acceleration of truck is carried out. Statistics of exhaust thermal images area is as given in Table 3**.**

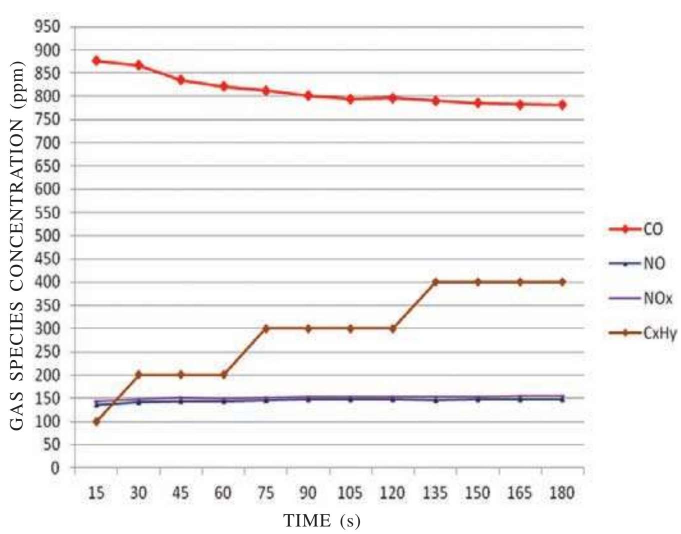

Figure 1. Exhaust gas species concentration of Truck during engine accelerating condition.

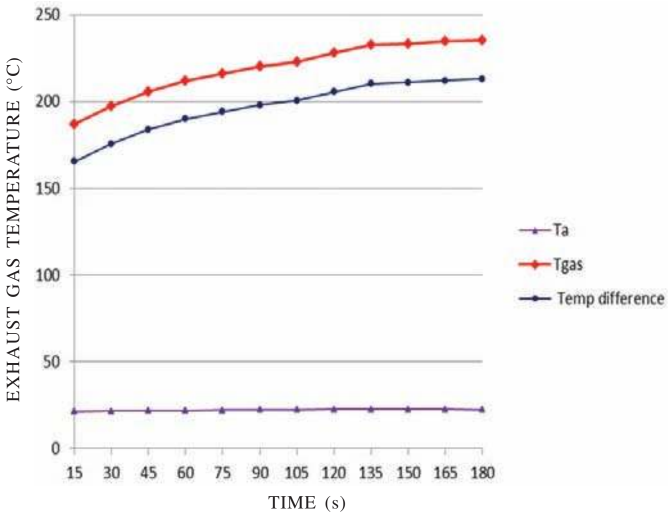

Figure 2. Exhaust gas temperature of truck during engine accelerating condition.

Table 3. Statistics of truck exhaust thermal images area

Truck (Exhaust thermal image)	Area (percentage)	Change in area
Idle state	0.056	-
Acceleration state	0.060	0.004
Full acceleration state	0.077	0.017

Thermal image area rise during idle and acceleration engine condition of truck is mentioned in Table 3. It is evident from Table 3 that area of exhaust thermal image has increased during acceleration.

3.5 Thermal Image Analysis of Truck using Altair software

Altair is radiometric image analysis software provided by M/s Cedip Infrared System, France along with radiometric thermal imager. Thermal IR images were analysed using Altair software. It was observed that temperature of gas mixture emission does not appreciably vary in idle engine running condition. Maximum, mean and minimum temperatures of gas species mixture are plotted with time as shown in Fig. 4.

Figure 3. Thermal IR image (3 µm - 5 µm) of truck exhausts in full accelerating engine condition.

It was observed that temperature of gas emission mixture vary significantly in accelerating engine condition. Maximum, mean, and minimum temperatures of gas species mixture are plotted over a period of time as shown in Fig. 5. It confirms from thermal IR images and gas species details that visualisation of gas mixture is very prominent with increasing concentration of gas species during full acceleration condition of the vehicle. It is also observed that apparent temperature of the exhaust gas mixture recorded by the thermal imager as shown in Fig. 5 is less than that measured by the thermocouple probe of gas analyser as shown in Fig. 2. It is due to loss of thermal radiation between object and sensor of thermal imager and emissivity value used.

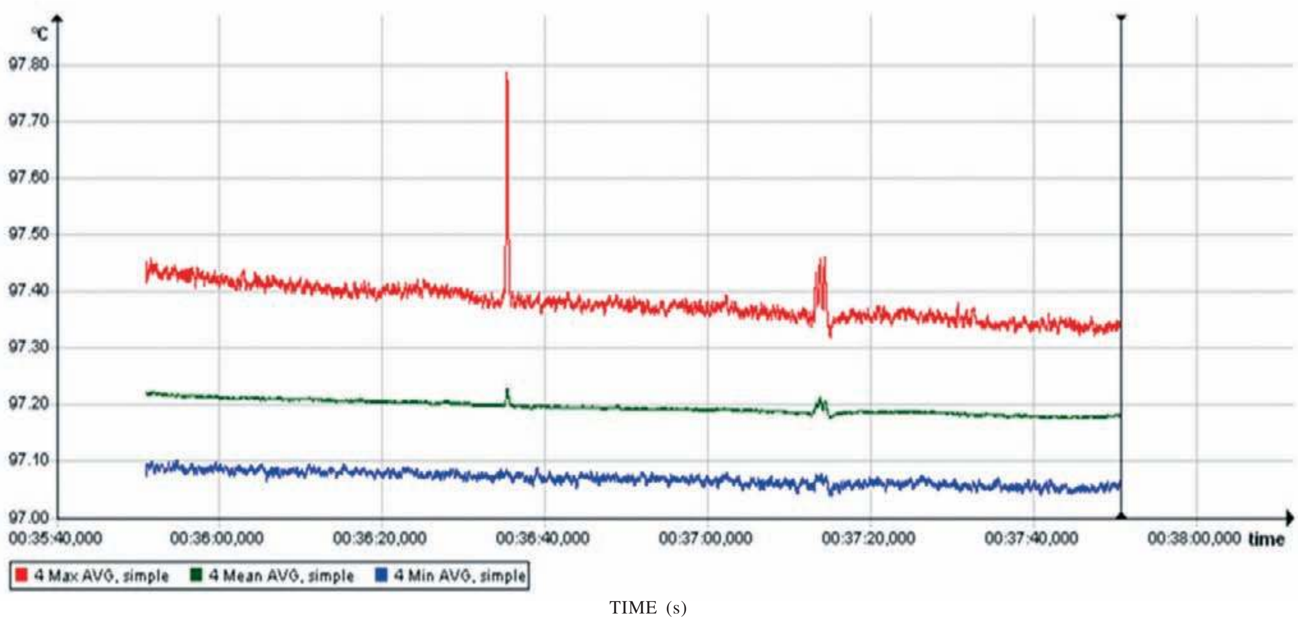

Figure 4. Truck exhaust gas apparent temperature recorded during engine idle running condition.

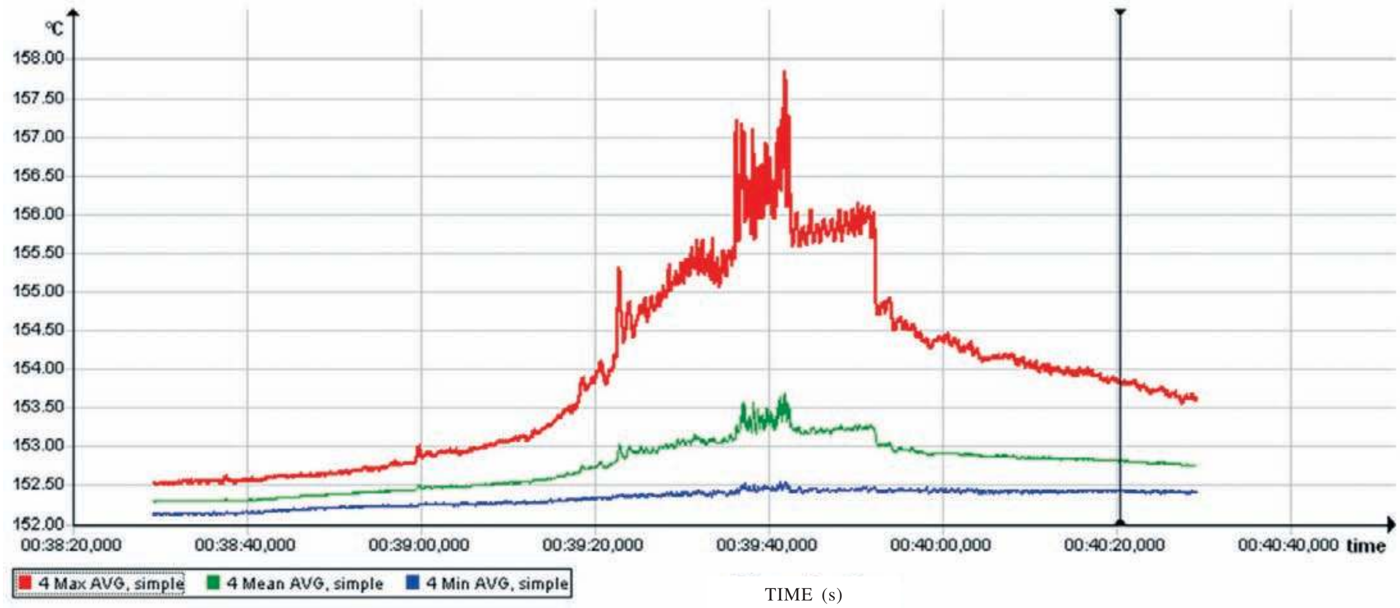

Figure 5. Truck exhaust gas apparent temperature recorded during engine accelerating condition.

4. DIESEL EXHAUST GAS SPECIES DATA FOR BUS

Diesel exhaust gas emissions measurement of bus was carried out for same duration as truck in trial field of the laboratory.

4.1 Bus in Idle Engine Running Condition

Weather parameters recorded such as ambient temperature, Ta = 20.63 °C, wind velocity = 0.2 m/s and RH= 31.62 per cent.

Gas species concentration and temperature variation was observed and found that concentration and temperature variations of gas species are very less with the time during idle running condition of engine.

4.2 Bus in Accelerating Engine Running Condition

Gas species concentration variation and temperature with time was plotted and shown in Figs. 6 and 7. It was observed that concentration of gas species have been varying with the time in similar pattern of Truck during engine accelerating condition of vehicle.

It was also noted that temperature and thermal contrast of gas species mixture increased with engine acceleration time as illustrated in Fig. 7.

4.3 Thermal Images of Diesel Exhaust Gas Species of Bus

In acceleration condition, the exhaust gas temperature and gas concentration increase with accelerating time period which provides better visibility of exhaust gas emissions in thermal IR image as shown in Fig. 8 at full acceleration condition of the vehicle.

4.4 Thermal Image Analysis of Bus using ENVI Software

Thermal image analysis using ENVI 4.1 software during engine idle running and acceleration of Bus was carried out.

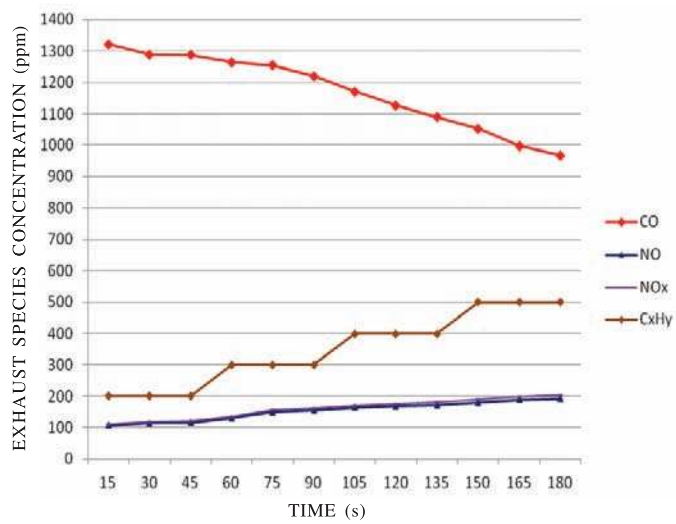

Figure 6. Exhaust gas species concentration of Bus during idle engine running condition.

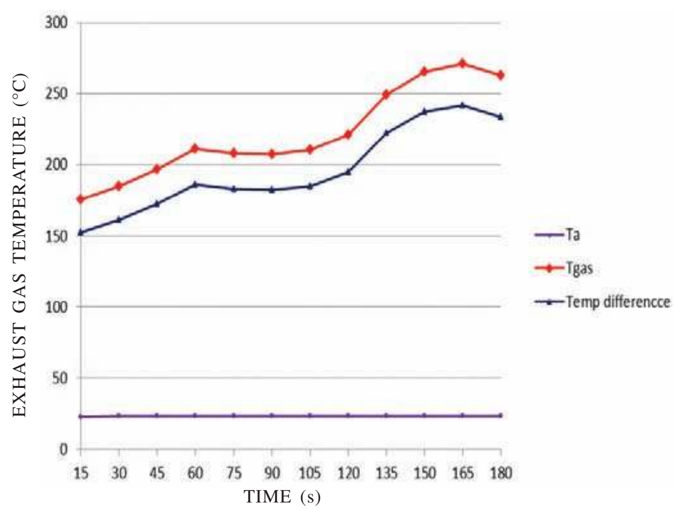

Figure 7. Exhaust gas temperature of Bus during accelerated engine condition.

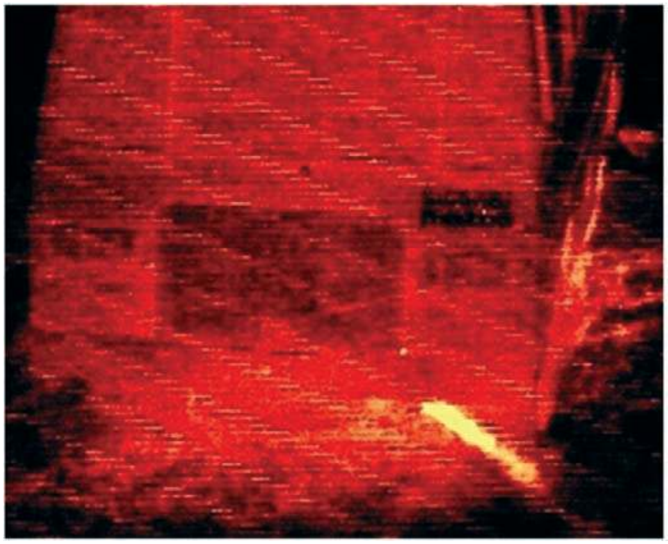

Figure 8. Thermal IR images of Bus exhaust in full accelerated engine condition.

Statistics of exhaust thermal images area of bus is given in Table 4.

Table 4. Statistics of Bus exhaust thermal images area

Truck (Exhaust thermal image)	Area (percentage)	Change in area
Idle state	0.192	-
Acceleration state	0.300	0.0108
Full acceleration state	0.594	0.294

Thermal image area rise during idle and acceleration engine condition of truck is as mentioned in Table 4. It is evident from Table 4 that area of exhaust thermal image has been increased during acceleration.

4.5 Thermal image analysis of Bus using Altair software

Thermal images were analysed using Altair software. The temperature of gas mixture emission does not vary appreciably in idle engine running condition. Maximum, mean and minimum temperatures of gas species mixture are plotted with time as shown in Fig. 9.

The temperature of gas emission mixture vary significantly in accelerating engine condition. Maximum, mean and minimum temperatures of gas species mixture are plotted over a period of time as shown in Fig. 10. It confirms from thermal IR images and gas species details that visualisation of gas mixture is very prominent with increasing concentration of gas species during full acceleration condition of the vehicle.

5. THERMAL IR IMAGES IN LWIR

Thermal IR image of diesel exhaust gas species was also visualised by using hand held thermal imager (HHTI)[13] which captured thermal IR image of certain gas species. A radiometric thermal imager is required for quantitative analysis of thermal images in terms of radiance and temperature. It is known that most of the exhaust gases species CO, NO, NOx, and water particle H_2O radiation are absorbed in MWIR 3 µm - 5 µm wavelength. However, exhaust emission HC unburned gases and particulate matter radiation can be visualised in LWIR 8 µm - 14 µm wavelength by using HHTI.

6. RESULTS AND DISCUSSIONS

A methodology has been established for exhaust gas species thermal signature measurement and analysis. Thermal signature visualisation of diesel vehicles exhaust gas species is possible using thermal imagers in MWIR (3 µm - 5 µm) and LWIR (8 µm - 14 µm). It has been observed that vehicles exhaust gas species concentration and temperature variation is more significant in accelerating engine running condition than idle engine running condition. It is also observed from

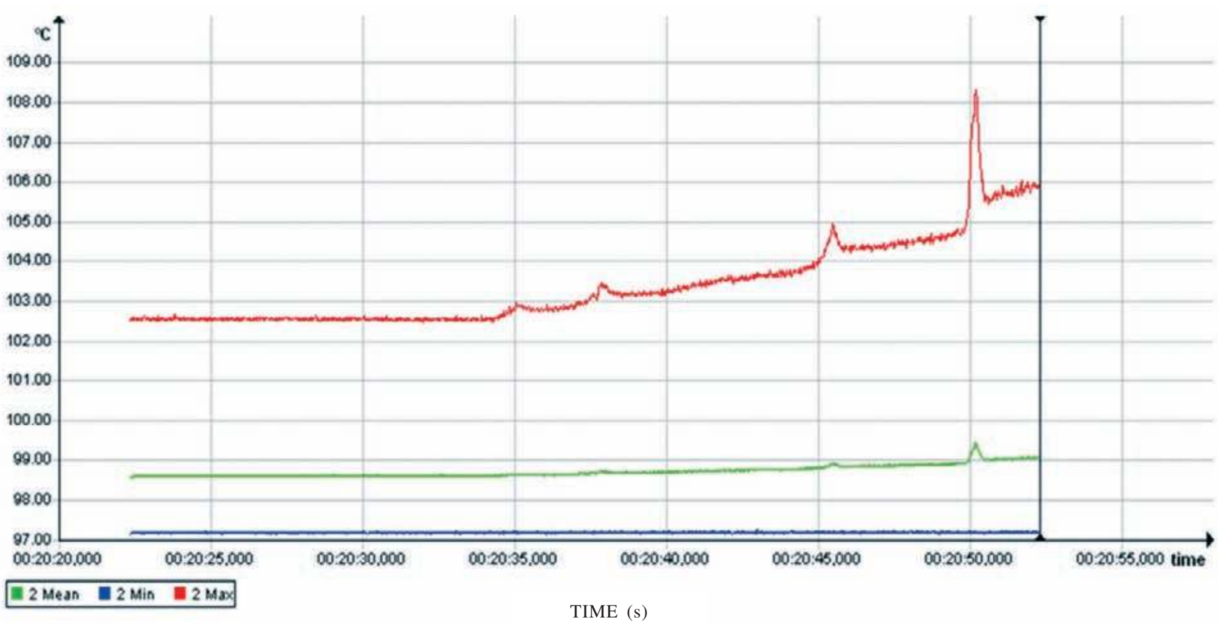

Figure 9. Bus exhaust gas apparent temperature recorded during engine idle running condition.

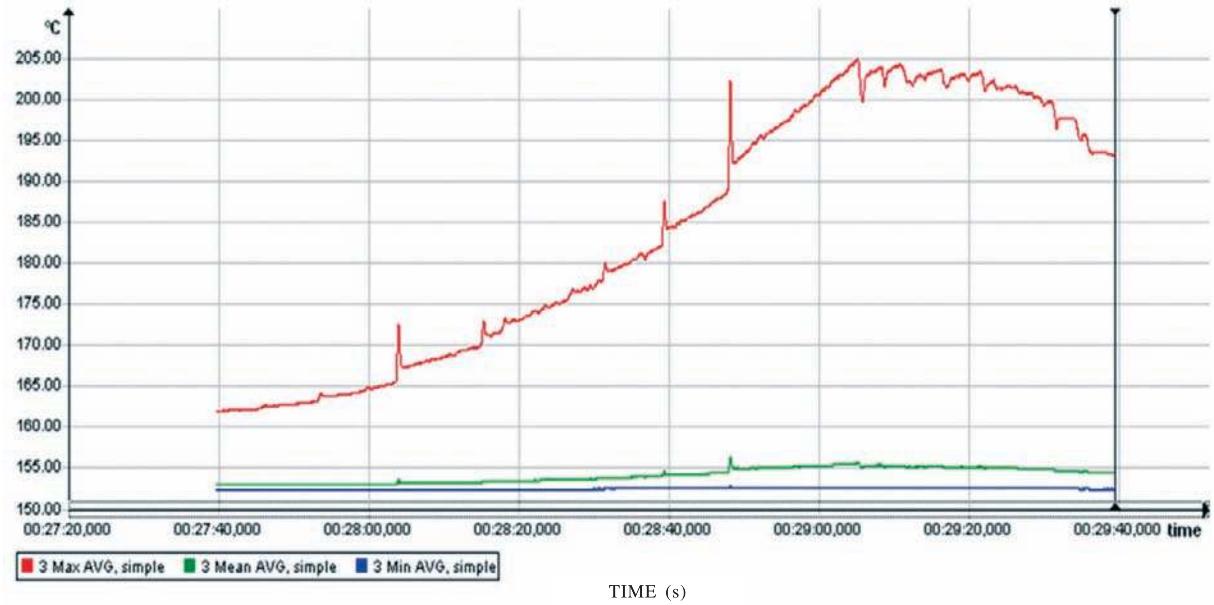

Figure 10. Bus exhaust gas apparent temperature recorded during engine accelerating condition.

image analysis that thermal IR image area of truck and bus exhaust emission is also increased 0.077 per cent and 0.594 per cent, respectively with engine acceleration of vehicle. Thermal signature of measured exhaust gas species is more prominently visible in MWIR in comparison to LWIR due to more exhaust gases such as CO, HC, and NOx, absorption and emission falls in this range.

7. CONCLUSIONS

Vehicle exhaust thermal signature measurement becomes very complicated due to varying nature of exhaust emission concentration, temperature and changing atmospheric conditions such as ambient temperature, wind velocity, pressure and humidity. Experimental measurement is carried out in about one hour duration so that effects of environmental factors are assumed to be negligible. Thermal signature of diesel vehicle exhaust gases are mainly function of temperature and concentration of gases. Exhaust thermal image area increases with the increase of exhaust gas concentration and temperature. It is concluded that thermal IR images of diesel vehicles exhaust gases are more prominently visible with the increase of exhaust gas concentration and temperature during acceleration of engine. In view of the military threat perception, vehicles need not be transported in convoy and speed of vehicles is also to be kept minimum as far as possible. It will reduce the vehicle exhaust emission and its temperature consequently probability of vehicle detection will be reduced using thermal imager.

REFRENCES

1. Shirsath, Vivek & Kulkarni, V.S. Review on thermal analysis of exhaust gas of variable compression ratio CI Engine using diesel-Biodiesel blend. *Int. Res. J. Eng. Technol.,* 2018, **5**(5), 312-314.
2. LV Shi-gui; Yang Li & Yang Qian. Research on the application of infrared technique in the prediction of diesel engine exhaust fault. *J. Thermal Sci.,* 2011, **20**(2), 189-194.
   doi: 10.1007/s11630-011-0456-7.
3. Chullang, Wei; Zhuang, Zemin; Xin, Qin; AI-Shammaá, A.I. & Shaw. A. Sensing of diesel vehicle exhaust gases under vibration condition. *Procedia Environ. Sci.,* 2011, **11**, 1100-1107.
   doi: 10.1016/J. proenv.2011.12.166.
4. Kyung, Joo Yi; Seung, Wook Baek; Bonchan, Gu; Sung, Nam Lee; Man, Young Kim & Won, Cheol Kim. Infrared signature study of aircraft exhaust plume. *In* the 15th International symposium on transport phenomena and dynamics of rotating machinery ISROMAC-15, Feb 24-28, 2014, Honolulu, HI, USA, pp. 1-2.
5. Jozef Rohacs; Istvan Jankovics; Istran Gal; Jerzy Bakunowicz; Giuseppe Mingione & Antonio, Carozza. Small Aircraft Infrared radiation measurement supporting the engine airframe aero-thermal integration. *Periodica Polytech. Transp. Eng.*, 2018, pp. 1-13.
   doi : 10.3311/P Ptr:11514.
6. Paszko, M. Cooling of exhaust gases as a possibility to increase stealth properties of military Helicopters. *J. KONES Powertrain Transport*, 2017, **24**(1), 281-290.
   doi: 10.5604 /01.3001.0010.2828.
7. Barreiros M. Vulnerability assessment of surface to air missile system. *In* the Remote sensing Laboratory, RTO SCI symposia*.,* 22-24 May 2000, Valencia, Spain, RTO MP-063.
8. Bushlin, Y.; Lessin A. & Reinov, A. Comparison of thermal modeling and experimental results of a generic model for ground vehicles. *Proceeding of SPIE.,* 2006, **6239**, 62390 P-1.
   doi: 10.1177/12.665256.
9. US Environment Protection Agency. EPA Handbook, Optical Remote Sensing for measurement and monitoring of emission flux. US Environment Protection Agency, 2011, North Carolina, 27711.
10. Chelsea, Jenkins; Stefanie, Bourne; Matthew, Rowley

& Jonathan, Miles. Development and implementation of thermal signature testing protocol of auxiliary power unit and diesel tractor. *Proceeding of SPIE*. 2004, **5405.** doi:10.1177/12.547500.

11. User's manual. Cedip thermal imaging system, France.
12. Use and Maintenance manual. Portable gas analyser, Seitron, (2015), bassano del grappa (vi) - Italy.
13. User's Manual. Hand Held Thermal Imager (HHTI), Fluke, USA.

ACKNOWLEDGEMENTS

The authors of this paper are very thankful to Dr S.R. Vadera, Director, Defence Laboratory, Jodhpur, Mr Ravindra Kumar, Group Director, ESG and Ms Anjali Bhatia, Head Camouflage Division for providing opportunity and support during this work.

CONTRIBUTORS

Mr Ajay Jain obtained his MTech (Thermal Engineering) from NIT, Bhopal. He is presently working as Scientist 'F' at Defence Laboratory, Jodhpur. His research area includes design and development of mock-up of military equipment, thermal signature simulation and analysis.
In present study, he designed and performed the experiments for exhaust emission measurements, analysed data and drafted the manuscript.

Mr Amit Sharma received his MSc (Physics) from University of Rajasthan. He is presently working as Scientist 'E' at Defence Laboratory, Jodhpur. His research area includes : Thermal IR signature study, measurement and analysis of military vehicles.
His contribution in the current study is thermal IR signature measurement and analysis of exhaust emission of vehicles.

Dr S.L. Borana received ME (Electronics & Communication) and PhD from JNV University, Jodhpur. Presently working as Scientist 'D' at Defence Laboratory, Jodhpur. His research area includes remote sensing, GIS and image analysis.
His contribution in the current study is thermal IR image analysis of exhaust emission using ENVI software.

Dr B. Ravindra obtained his MTech and PhD from IIT Kanpur, in 1989 and 1994, respectively. He is presently working as Associate professor and Head Mechanical Engineering Department at Indian Institute of Technology Jodhpur, Jodhpur. His research area is design, dynamics, vibration, and control.
In the present study, he contributed in experiment design, data analysis and finalisation of manuscript.

Dr J.P. Mangalhara did his MSc and PhD in Physics from IIT Delhi. Presently working as Scientist 'G' at Defence Laboratory, Jodhpur. His research area of interest is IR signature studies, IR camouflage system development and thermal target system development.
In the present study, he contributed in data analysis and finalisation of manuscript.