

Review of Literature

2.1 INTRODUCTION

In modern warfare, enemy employs different type of sensors to detect and identify the equipments and installations. Therefore, these days camouflage and deception plays a very important role to protect the defence equipments from enemy's surveillance devices. Thermal IR based heat seeking weapons is major threat to combat equipment and fighter Aircrafts. Thermal signature of exhaust emission of such military vehicles cannot be completely suppressed. Hence, decoy targets with simulated thermal signature are employed as an appropriate solution to fool the heat seeking weapons and thereby reduce the threat to the original combat equipment. Most of the research and development work pertaining to multispectral signature decoy are being carried out by the military Laboratories/ Establishments. Therefore, limited literature is available in open source related to military decoys.

Study of thermal signature and analysis of vehicle exhaust emission are important aspects to counter the threat from heat seeking weapons. Immense work has already been carried out for thermal signature study of Aircraft exhaust emission as stealth technology [Mahulikar S. *et al.*, 2007]. Similar study of thermal signature of ground vehicle is imperative to develop an appropriate decoy with comparable thermal signature. Thermal IR signature of vehicle exhaust emission plays an important role in air and ground surveillance, detection and recognition. Thermal IR images of vehicles vary with the temperature and composition of the exhaust emission.

In this chapter comprehensive literature survey is presented on relevant topics such as diesel exhaust emissions its measurement technique, exhaust emission analysis, thermal IR thermography of exhaust plume and thermal imaging of exhaust of diesel vehicles in MWIR and LWIR bands.

2.2 IR THERMOGRAPHY OF EXHAUST PLUME: A REVIEW

Thermal signature of an object is unique characteristic or pattern with respect to ambient condition, which is detected and identified by the thermal imaging sensor. Thermal signature of exhaust gas radiation depends on molecular concentration, gas temperature, optical path length, extinction coefficient, etc. The selection of spectral band 3-5 μ m or 8-12 μ m will depend on the type of gas and observation distance. [Plesa *et al.*, 2004].

IR signature theoretical modeling methods have been investigated based on radiation, heat transfer and atmospheric characteristics [Kim Y *et al.*, 2014]. In this paper, background thermal image captured using an IR camera. Target image is synthetically generated using RadTherm IR software. The IR target and IR background images synthesized as one image for a specific wavelength after adjusting its gray level and individual radiance corresponding to IR signature. The synthesized image can be used for the simulation of image for IR seeking weapons. Latest advancement in terms of sensitivity, resolution and detector material in infrared detector technologies was discussed in this paper [Rogalski A., 2011]. It is highlighted

that thermal contrast in the MWIR bands at 300K is 3.5- 4% as compared to 1.6% in LWIR band. Details on thermal imaging systems, operating wavelength windows and its application in military as well as civil sector are reported in this paper [Akula A. *et al.*, 2011]. Potential of high speed IR imaging was investigated as a diagnostics tool for internal combustion engines (ICEs). High speed infrared imaging using different waveband filter was carried out in the wavelength range of 3 - 5.5 μm and spectral radiance response of combustion gases CO_2 and hydrocarbon was recorded [Gagnon M. *et al.*, 2016].

The types and real time applications of thermal imaging system are explained in this paper [Rai M. *et al.*, 2017]. Thermal Camera or Imager may be classified on the basis of detector, spectral wave band, resolution, application etc. The classification of thermal imager on the basis of the spectral band are such as (i) MWIR (Mid wave infrared) imager operates in spectral range of 3 to 5 μm wave band (ii) LWIR (Long wave infrared) imager works in spectral range of 8-12 μm wave band (iii) SWIR (Short wave infrared) imager operates in spectral range of 1- 3 μm wave band. The comparison of the performance of MWIR and LWIR imagers for varying ambient temperature and humidity conditions were discussed in this paper [Dhar V. *et al.*, 2011]. The atmospheric transmission in MWIR and LWIR band depend on ambient temperature, relative humidity, thermal contrast, target signature and optical path length. MWIR thermal imager has higher thermal contrast, good performance in clear weather, better radiation transmittance in high humidity and high resolution due to less optical diffraction and molecular absorption of thermal radiation. LWIR thermal imager has better performance in fog and dust environment, winter haze, less sensitive to solar radiation and atmospheric turbulence. The range performance comparison of MWIR and LWIR thermal imaging system has been reported by the researchers in this paper [Khare S. *et al.*, 2018]. The radiation transmission window 8-12 μm for thermal imager is most suitable for short range 5- 6 km in most of the circumstances. The radiation transmission window 3 - 5 μm for thermal imager is most suitable for range more than 5- 6 km due to better atmospheric transmission in high humidity and visually clear weather.

The acquisition and analysis of thermal infrared images of military vehicle has been undertaken by various researchers. A paper documents the details of acquisition of thermal signature of auxiliary power unit (APU) and idling diesel engine by acquiring a series of thermal images from different viewing angle using radiometric infrared imaging system [Jenkins C. *et al.*, 2004]. This paper has reported the importance of hyperspectral IR imaging application in defence innovative research. Hyper Cam is an airborne hyperspectral imaging sensor which can be used in 3 to 5 μm and 8 to 11.5 μm wavelength range [Montembeault Y *et al.*, 2010]. An intelligent approach for fault diagnosis of cooling radiator based on thermal infrared image processing techniques is presented by the researchers [Garavand A. *et al.*, 2015]. Thermal signature acquisition mainly depends on type of vehicle, its thermal loading conditions & operation time, environment conditions and performance of the thermal imager [Barreiros M., 2000]. Thermal signature measurement of vehicle exhaust emission is feasible and effective in the diagnosis and prediction of diesel engine faults [Shi-gui *et al.*, 2010].

Some researchers reported the passive open-path fourier transform infrared spectroscopy (OP-FTIR) method for measuring atmospheric and process exhaust gases [Cieszczyks S., 2014]. Spectroscopic measurements of infrared molecular transitions in gas plume for determination of gas species was also reported [Jellison G., 2006]. Mid wave-infrared spectroscopy techniques have also been used for the detection and characterization of gases. The absorption spectrum of each gas species has unique pattern. Therefore, it can be used to identify and quantify specific gas species. The basic absorption lines for pollutant gases such as CO, NO, NO_2 are all located in the mid wave IR regions of EM spectrum (3 - 6 μm) [Mulrooney *et al.*, 2005]. CO_2 also has high absorption in the mid wave IR regions of the spectrum. Absorption lines for various gases have been identified through spectroscopy in the 0.3 to 10 μm region, for example, CO (4.6 μm), CO_2 (4.3 μm), NO (5.2 μm) and NO_2 (6.2 μm) [Modest Michael F, 2013].

2.3 RADIANCE AND SPECTRAL RADIANCE OF EXHAUST EMISSIONS: A REVIEW

Thermal signature analysis can be carried out quantitatively and qualitatively. In quantitative analysis thermal radiance and temperature are two important parameters by which prediction can be made about the thermal radiation and probable thermal object. In present research work a radiometric thermal imager is used for measurement of diesel exhaust emission of vehicles, which measures radiance and temperature. Spectral radiance is expressed in terms of specific wavelength of radiation at particular temperature. Spectral radiance of individual gas species can be calculated using HITRAN (High resolution transmission molecular absorption) database for gas transmittance.

HITRAN database is a computer model to predict atmospheric transmittance and background radiance. HITRAN data base was published in 1987 with the contributions from many researchers across the world. HITRAN is updated regularly and maintained by Harvard University [Rothman *et al.*, 2013]. The HITRAN database is not suitable for high temperature radiation of gas species. It was formulated for simulating transmission and emission of thermal radiation under atmospheric pressure at low temperature [Jae H. *et al.*, 2014]. The database HITRAN 2008 includes detailed information on 39 species with a total of about 2.7 million lines [Thomson J., 1997].

Some researchers have investigated IR spectra of exhaust emission from gas turbine engine using fourier transform (FT) spectroscopic technique. The HITRAN database of atmospheric species was used to calculate radiance and comparison with the measured radiance by FTIR spectrometer [Hitton M. *et al.*, 1997]. The scanning infrared gas imaging system (SIGIS) was used to determine composition of diesel powered aircraft exhaust emission CO, CO₂ and NO concentration, temperature and spectral radiance was calculated using HITRAN database [Jardines E. *et al.*, 2015].

Above research papers have provided good understanding on computation of spectral radiance intensity of gas species of diesel engine exhaust using HITRAN database. They also explain how to use HITRAN database for determining concentration of exhaust gases species along with the temperature for study and analysis of species radiation intensities.

2.4 IR Signature simulated decoys: A review

Decoy with thermal signature simulation plays a very crucial role as countermeasure in modern warfare. Thermal hot spots of any military equipment are most vulnerable targets of heat seeking weapons. Therefore, simulation of thermal radiation characteristics of exhaust is very important feature in a decoy.

Some researchers have reported about the importance and concept of decoy with IR signature simulation. A model of IR decoy's plume radiation characteristics was demonstrated considering the theoretical flow field of IR radiation combining with atmospheric radiation. The result of the analysis forms the basis for the infrared jamming and anti-jamming weapons, which is useful for survivability of the equipments [Yang C. *et al.*, 2015]. In this paper, the researcher described the particle system to realize visualization of infrared decoy, using mathematical model based on aerodynamics and statistics [Xiang H. *et al.*, 2010]. In this work, IR emission of clouds generated during combustion of process of pyrotechnic mixture was presented. An advancement of IR screening capability can be achieved when amount of soot in the combustion product and heat of combustion increases [Cudzilos S., 2001]. The experimental and theoretical research on pyrotechnic countermeasure (flare) was reported for prediction of

ignition delay [Woodley C., 2017]. Researcher in this paper developed a computer simulation model for movement characteristics of IR decoy based on aerodynamic theory [Chunling Y. *et al.*, 2011].

In military interest, it is extremely important to produce a recognizable thermal signature for decoy. Therefore, study is to be carried out to find out prominently detectable thermal signature of military equipments. Thermal signature simulation of exhaust emission for any combat vehicle decoy is very challenging and important feature in the field of military deception.

2.5 EXHAUST EMISSION OF DIESEL VEHICLE: A REVIEW

The exhaust emission generated by the internal combustion engine (ICE) both gasoline and diesel include nitrogen oxides (NO_x including NO and NO₂), hydrocarbons(HC), Carbon monoxide(CO) and particulate matters of size < 10 microns(PM₁₀) and <2.5 microns(PM_{2.5}) including black carbon (BC) [Winkler *et al.*, 2018].

Real World emission performance of heavy duty Euro VI diesel vehicles for truck and bus was reported by researchers [Grigoratos T. *et al.*, 2019]. In the reported study, exhaust emission was measured using Gas-PEMS (Portable emission measurement system) comprising various gas sensors manufactured by Sensors Inc. The obtained test results revealed that NO_x emission of a bus equipped with after treatment technology SCR is lower than conventional engine bus. However, NO_x emissions are higher at low speed of SCR equipped diesel vehicles consequently low exhaust emission temperature. All vehicles demonstrated low NO_x emission in the high speed driving condition. Higher CO emissions are reported at higher speed of test diesel vehicles due to lack of excess oxygen in the combustion chamber. [Guo *et al.*, 2014, Keramydes *et al.*, 2018]. Similarly, maximum total hydrocarbon (THC) emissions are observed at lower speed and higher THC at higher speed. In older technology heavy duty truck (Euro III) the exhaust emission was found to have almost double THC level [Vermeulen *et al.*, 2017]. Transport of London measured NO_x emission of four Euro VI heavy diesel vehicles (HDVs) and found higher NO_x value with decrease payload [Mayor of London and TfL., 2014]. In our present study, main focus is given on NO_x measurement and analysis of diesel vehicles.

2.5.1 Methods of measuring diesel exhaust

Measurement of exhaust emission is being carried out by various methods as discussed below [Marner B. *et al.*, 2016].

- i. Dynamometer test
- ii. Portable emission measurement systems (PEMS)
- iii. Smart emission measurement systems(SEMS)
- iv. Remote sensing

i. Dynamometer test

Light and medium duty vehicles such as passenger cars and loading vehicles are tested with chassis dynamometer test as per selected driving cycle. Heavy duty vehicle (HDVs) such as Bus and Truck, are bench tested with engine dynamometer in the laboratory. In chassis dynamometer test, vehicle engine is required to develop actual road power with respective to varying speed. Chassis dynamometer controller is simulated for the real life road driving condition of the vehicle.

ii. Portable emission measurement system (PEMS)

Portable emission measurement system (PEMS) test is carried out in open field area. Measurement can be planned on stationary vehicle as well as moving vehicle depending on the type of PEMS is available.

Measurement of diesel exhaust gases such as CO, NO, NO₂, HC and SO₂ and monitoring of the diesel engines of road vehicles are essentially required to control the concentration of exhaust emission gases and prevent its harmful effect. Exhaust emissions depends on engine speed, which varies as per vehicle loading condition and terrain. It is reported that diesel engine operation at various speeds discharges different level of harmful exhaust gases, and the measurement results of the gas sensors are not linked with the engine vibration. Vehicle exhaust gases are measured using a portable gas analyzer which has replaceable gas sensors. Simultaneously, four to six gas sensors may be used as per requirement. The gas analyzer has inbuilt PT 100 temperature sensor for gas temperature measurement and thermocouple probe for ambient temperature measurement [Wei *et al.*, 2011].

Portable Gas analyzer equipped with four gas sensors at a time was used for gas emission measurement of selected diesel vehicles in present study.

iii Smart emission measurement systems(SEMS)

Smart emission measurement system (SEMS) is generally used for smaller and low accuracy emission measurement.

iv. Remote sensing

In this method, exhaust of vehicle on move is imaged by optical imager and vehicle's speed and acceleration are recorded. Gas exhaust emission has been tested through optical analysis for the presence of NO, NO₂ and CO₂. This method has the advantage that large number of vehicles can be tested in short time [Ropkins K. *et al.*, 2015]. Some researchers have reported that most of the high emitting vehicles failed in the NO limit. No single vehicle failed in the HC limit. A few vehicles failed in CO limit in comparison with chassis dynamometer transient test [Huang Y. *et al.*, 2019]. However, remote sensing data does not provide details of complete cycle and driving condition. It provides information for specific driving pattern.

2.5.2 Exhaust emission test cycles

Our objective of thesis is to study and analysis thermal signature of exhaust gas emission of diesel vehicles in open field condition as required by the defence services. However, exhaust gas emissions study for pollution check and taking controlling measures requires testing of vehicles and engine on specified driving schedule of speeds and loads, which is not part of our study. India is following European test procedures & regulation with little modification as per our country traffic requirements [ARAI, 2011].

2.6 RESEARCH GAPS AND PROBLEM FORMULATION

In the light of the above discussions, it is evident that a lot of research work on exhaust plume of Aircraft was carried by the researchers. However, study and detailed thermal signature analysis of exhaust emission of diesel combat vehicles as well as diesel military vehicles are found missing. Therefore, literature review presented so far has clearly brought out the gaps in the previous research work. Diesel exhaust emissions of vehicles were not adequately studied and analyzed earlier along with the thermal IR signature visualization using

thermal imaging system in waveband of MWIR (3-5 μ m) and LWIR (8-14 μ m). Therefore, formulated research problem “Study and Analysis of Thermal IR Signature of exhaust emission of diesel engine based Vehicles” is extremely useful to fill the gap of previous researches as well as it will open a new, interesting and challenging research area for civil and defence application.

2.7 MOTIVATION AND APPROACH FOR WORK

The author has background in working on thermal IR signature generation and its evaluation under various ambient conditions. However, thermal signature study for gaseous emission with respect to its concentration was a new and challenging task. It has new research challenges, which will be helpful for both civil and defence sector. Gas species of diesel engine exhaust need to be measured using Portable gas analyzer. Simultaneously, Thermal imagers in MWIR & LWIR will be used for capturing thermal images. A new methodology has been formulated for measuring concentration of diesel engine exhaust gas species along with thermal IR signature visualization. Thermal IR imaging technique for exhaust emission visualization will provide the information about the thermal signature of exhausts of diesel vehicles. It will help in design and development of military decoy with thermal signature simulation and its evaluation. This work will be extremely useful to protect the crucial expensive military equipments from enemy’s IR seeking weapons by diverting them towards the decoy with simulated thermal signature. The steps adopted in the research work are discussed in **section 1.6**.

2.8 SUMMARY

Comprehensive literature survey has been carried out, which has provided useful information related to the area of research envisaged. The thermal signature study and analysis to be carried out on diesel exhaust emission will provide very crucial information for military application as well as vehicle conditioning. However, due to its relevance to defence sector, thermal IR signature study and analysis is a classified area of work and limited information is available in the open literature.

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