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Study and Modelling of Effect of Tilt Angle on Thermal Signatures of Different Emissivity Surfaces

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ABSTRACT

The study and modelling of angular variation of thermal signatures are paramount for designing efficient thermal camouflage pattern painting schemes for military vehicles. To model and experimentally measure the effect of tilt angle on thermal signatures of different emissivity surfaces, a test panel was prepared with different emissivity paints ($\varepsilon = 0.4$ to 0.9). Thermal signatures (Apparent temperatures) of the test panel were measured in Middle Wave Infrared (MWIR, 3-5μm) and Long Wave Infrared (LWIR, 8-12μm) for variable tilt angles of surface normal to test panel concerning horizon ranging from -60° to 60° under different ambient conditions. The thermal signatures of the test panel were also simulated using thermal signature prediction software- TAITHERM IR. The simulated thermal signatures were compared with measured thermal signatures, and they agreed considerably. However, some deviations were observed, which may be attributed to using approximate assumed values of the Bi-directional Reflectivity Distribution Function (BRDF) of paints as input parameters in software. The paint of lower Emissivity (< 0.6) showed a larger variation in thermal signatures with tilt angle than the higher emissivity paint. Further, the variation of thermal signatures with tilt angle is more pronounced in LWIR (8-10°C reduction in apparent temperature) than in MWIR. This study may provide valuable inputs for developing and assessment new IR stealth techniques.

Keywords: Angular variation; Low emissivity; Viewing angle; TAITHERM IR; Sky radiance

1. INTRODUCTION

Thermal signatures are strongly dependent on various parameters like the optical properties of the surface, environmental parameters, performance parameters of the thermal camera, and several other parameters, such as surface orientation and tilt angle. The Emissivity of the surface, the camera's viewing angle, the surface-to-camera angle, the distance between the surface and the camera, etc., may be the sources of uncertainty in thermal signature measurement. These factors must be accounted for before thermal signature studies are taken up.

A lot of studies have been carried out to examine the effect of Emissivity, viewing angle, distance, angular variation of Emissivity, etc, on thermal signatures. Saunders first reported the angular measurement in thermal infrared region[1]. He discussed the angular variation in aerial measurement of sea surface temperature measurement. Based on Saunders's study, several other authors discussed the angular variation of thermal signatures until 1980. The study carried out by these authors was mainly focused on sea surface temperature measurement through aerial / satellite imagers[2-4].

The issue of angular variation of thermal infrared radiation of ground-based natural surfaces was first addressed by Rees and James[5]. They carried out a study of the angular variation of the infrared Emissivity of ice and water surfaces. Sobrino and Cuenca moved a step ahead, and they discussed the angular variation of thermal infrared Emissivity of some natural surfaces like sand, clay, water, slime, gravel and glass using an IR thermometer and Goniometer system[6]. These studies were related to the angular variation of Emissivity, which has a strong effect on the thermal signatures of surfaces.

The studies of angular variation of Infrared brightness temperature or apparent temperature were also carried out. In this series, Dozzier and Warren discussed the effect of viewing angle on the infrared brightness temperature of snow[7]. Friedl and Davis described the sources of variation in radiometric surface temperature over a tall grass prairie[8]. Lagouarde et al. conducted an experimental study of angular effects on surface temperature for various plant canopies and bare soils[9]. Mcatee et al. discussed the angular behaviour of emitted thermal infrared radiation (8μm-12μm) at a semi-arid site[10]. J Cuenca et al. also carried out an experimental study of angular variations of brightness surface temperature for some natural surfaces like sand, clay, water, slime, gravel, etc [11]. Although many studies have attempted to determine the angular behaviour of thermal infrared radiation, the effect of tilt angle and orientation of surface combined with Emissivity has yet to be reported to the best of our knowledge.

Surface tilt angle and orientation are two main factors, which may affect the temperature of a surface up to great extent[12-13]. This may attribute to the fact that the surface angle and orientation affect the amount of sky radiation, solar

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radiation and ground radiation reaching to the surface which in-turn affect the apparent temperature of the surface and hence the thermal signature of the same.

Recently, signature management has gained much importance as far as the survivability of military vehicles is concerned. Effective signature management may be achieved with the judicious application of different emissivity paints on differently tilted surfaces of military vehicles. This gives impetus to investigating the effect of the tilt angle of different emissivity surfaces on thermal signatures. This study is also necessary to predict the contribution of differently tilted surfaces to all thermal signatures of objects.

The objective of this paper is to investigate the effect of the tilt angle of different emissivity surfaces on thermal signatures through modelling and experiments.

2. THEORITICAL CONSIDERATIONS

The total radiance leaving from a surface may be written as the sum of emitted radiance as well as reflected radiance by the surface and given as

$$L_T = L + (L_{SKY} + L_{GR}) \quad (1)$$

where, L_T is the total radiance leaving the surface, L is the emitted radiance by the surface, L_{SKY} is the sky radiance reflected off the surface, L_{GR} is the ground radiance reflected off the surface. Here, it is essential to note that reflected sky radiance may be from the horizontal sky or zenith sky. Similarly, ground radiance may have two parts, i.e. vertical and horizontal ground radiation.

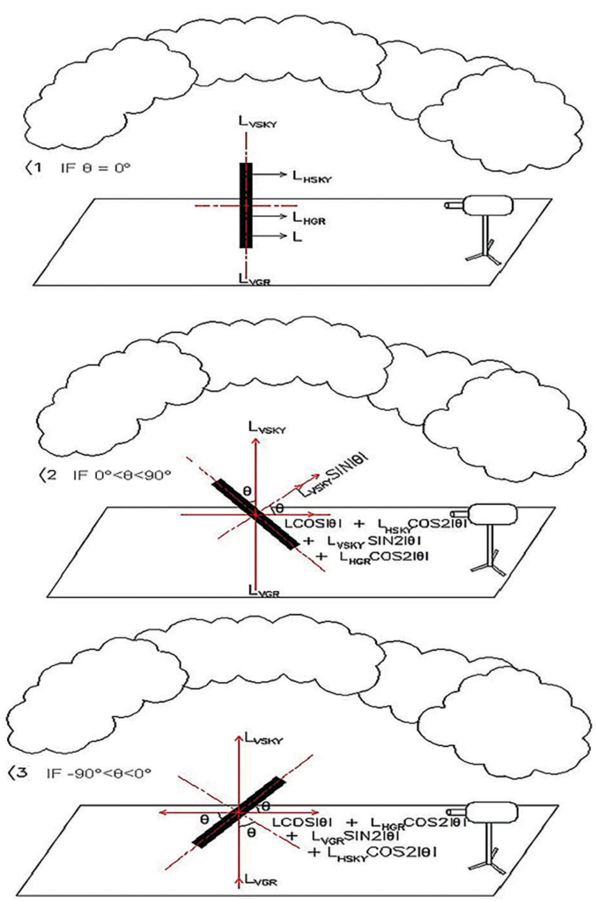

Figure 1. Considerations of tilt angle θ for the study.

To start the study, the tilt angle needs to be defined. Tilt angle Θ may be defined as the angle between the surface normal and the horizon. The orientation of the surface towards the sky is more if the tilt angle is more than 0˚and the orientation of the surface towards the ground is more if the tilt angle Θ is less than 0˚. These different conditions of tilt angle Θ are shown in Fig. 1.

If Θ= 0˚, then the total radiance leaving the surface is given as

$$L_T = L + L_{HSKY} + L_{HGR} \quad (2)$$

where, the horizontal component of sky radiance is reflected off the surface, and the horizontal component of ground radiance is reflected off the surface.

If Θ > 0˚ then total radiance leaving the surface is given as

$$L_T = LCos|\theta| + L_{HSKY}\,Cos\,2|\theta| + L_{VSKY}\,Sin\,2|\theta| + L_{HGR}\,Cos\,2|\theta| \quad (3)$$

where, is the zenith sky radiance reflected off the surface.

If < 0˚ then the total radiance leaving the surface is given by Eqn. (4)

$$LT = L\,Cos|\theta| + L_{HGR}\,Cos\,2|\theta| + L_{VGR}\,Sin\,2|\theta| + L_{HSKY}\,Cos\,2|\theta| \quad (4)$$

where, L_{VGR} is the vertical component of ground radiance reflected off the surface.

It is clear from Fig. 1 and also from Eqn. (2), Eqn. (3) and Eqn. (4) that if the surface tilt angle is different, then the total radiance leaving the surface will be different, which will, in turn, produce different IR temperatures to be sensed by a thermal camera.

3. EXPERIMENTAL

3.1 Instrumentation

The details of equipments and software used in this study are provided at Table1.

3.2 Test Panel

A special test panel consisting of supporting stands, a main supporting frame, an angular marker and an Aluminium Plate of Size 1.5m X 1m was designed for this study. The thickness of the plate was chosen to be 3mm. The angular marker was used to provide a specific angle to the test panel with respect to the horizon. The plate has been divided into five equal-sized regions coated with different emissivity paints. These five regions on the plate have been marked as 1 to 5. The schematic of the test panel is shown in Fig. 2. The details of the paints applied on regions 1 to 5 are given in Table 2. The Emissivity of the paints was measured using an emissometer, and the solar absorptivity of the samples was calculated based on the solar reflectance of the sample using an albedometer.

3.3 Measurement Methodology

The measurements for the study were carried out in the open field area of the Defence Laboratory, Jodhpur (Latitude: 26.24°N, Longitude: 73.02°E, Ground Elevation: 235 meters). The test panel was placed in the open field area in the direction of 180° relative to North (South Facing) with an elevation of 4°. The thermal cameras were placed at a distance of 30 mtr from the test panel at an angle of 0° relative to the North. The measurements were carried out for three different days of different seasons for 24 24-hour periods. During the

Table 1. Details of equipment and software used in the study

Long Wave Infrared (LWIR) thermal camera	Make: FLIR, Spectral Region: 8 µm - 9.4 µm, Detector: HgCdTe, Array Size: 640 X 512, Sensitivity: 10mk, Field of View (FOV): 12˚X10˚
Middle Wave Infrared (MWIR) cooled thermal camera	Make: Cedip-FLIR, Spectral Region: 3.7 µm – 4.8 µm, Detector: HgCdTe, Array Size: 320 X 240, Sensitivity:10mk, Field of View (FOV): 12˚X10˚
Field portable weather station	Make: NovaLynx, Model: 16-GE- 1610, Measured Parameters: Wind Speed, wind direction, air temperature, atmospheric pressure, solar radiation, relative humidity and visibility
Pyrgeometer	Make: Kipp & Zonn, Measured Parameter: Long Wave Sky Radiance in 4.2µm -42µm
Emissometer	Make: Surface optics, USA, Model: ET-100 Measures reflectance in Infrared Spectral band and calculates the directional thermal emissivity. Makes measurements at 02 incidence angles i.e. near normal 20° and near grazing 60°, Uncertainty: ±0.01
Albedometer	Make: EKO, Model: MS-80S It consists of 02 pyranometers and a special Albedo kit so as to measure Albedo (Surface Solar Reflectance). Irradiance Range: 0-4000 W/m^2, Wavelength Range: 285-3000nm, Uncertainty: ±0.01
TAITHERM IR software package	Make: Thermo analytics, Capability: Modelling of thermal signatures of surface at variable tilt angle under given weather conditions

Table 2. Details of paints over test panel

Paint number	Paint colour	Emissivity	Solar absorptivity
Paint 1	White	0.90	0.23
Paint 2	Light olive green	0.63	0.78
Paint 3	Military green	0.93	0.95
Paint 4	Tan	0.61	0.72
Paint 5	Aluminium	0.40	0.55

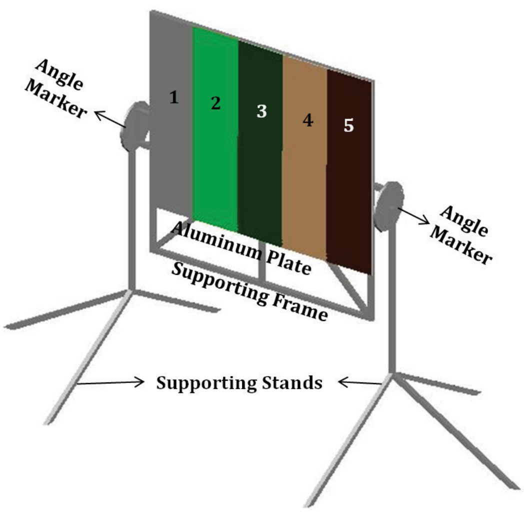

Figure 2. Schematic of test panel.

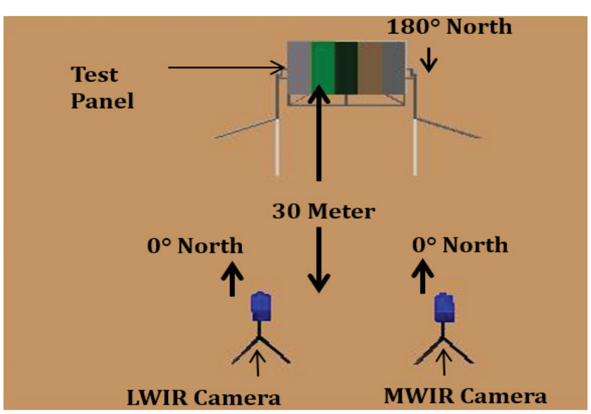

Figure 3. Schematic of experimental setup.

measurements, the angle of surface normal with respect to horizon of test panel was varied from - 60° to + 60° in a span of 10° and thermal images were acquired through factory calibrated MWIR and LWIR camera for each angular position of test panel. The acquired thermal images were analyzed using camera software FLIR RIR for apparent temperature estimation, and an average temperature value was estimated for each paint in the MWIR and LWIR bands. The schematic of the experimental setup is shown in Fig. 3.

During the measurements, the weather parameters were also recorded for every 10-minute interval. The weather station was placed close to the test panel.

3.4 Signature Modelling

A number of coupled physical phenomena have to be considered in the modelling of thermal signatures. Heat transfer, atmospheric effects, and radiometry need to be modelled in order to predict the in-band radiance / apparent temperature detected by thermal cameras[14]. In this study, TAITHERM IR-thermal signature prediction software developed by M/s Thermo Analytics was used. General input parameters for thermal signature modelling are as follows: -

- Model drawing: A CAD model of an object and terrain is the main prerequisite for thermal signature modelling.
- Thermal parameters: Thermal parameters are of paramount importance for physics-based modelling and simulation of thermal signatures. The main thermal material parameters are density (kg/m3), thermal conductivity (W/m-K) and specific heat (J/Kg-K). The values for these parameters may be derived from experiments or taken from literature. In addition, some geometrical inputs like thickness of material, number of layers are also needed for the completion of thermal properties[14].
- Optical Parameters: These parameters include paint reflectance data, paint emissivity data, types of paints, absorptivity of paints etc.
- Weather data: It data includes air temperature, relative

humidity, wind speed, wind direction, solar radiation, long wave sky radiation, etc.

3.4.1 Methodology for Thermal Signature Modelling

To start with, the geometry of the test panel was created using CAD software and exported to mesh generation software (In this case, HyperMesh) for the creation of mesh over geometry. The coarse mesh (Element Size: 50 mm) was created and exported to thermal signature modelling and simulation software TAITHERM IR. A simple surface with desert sand-like spectral reflectance was also used in TAITHERM IR to simulate the background. The entire model (Test panel and sand background) was tilted and rotated to simulate the experimental setup conditions. Then boundary conditions along with all material parameters such as bulk and surface properties, including the number of layers, material thickness, etc., were set. The measured weather parameters were input to TAITHERM IR through a weather file, and geo-locations of the measurement site were also input. After this, the view factors were calculated, and thermal simulation was invoked. As soon as the thermal solution was completed, the diffuse radiosity solution was invoked, and BRDF rendering was carried out in order to generate the thermal image in the desired spectral band.

3.4.2 TAITHERM IR Calculations

TAITHERM IR first takes up the view factor calculations and saves the results in to a separate. vfs file[15]. In the next step,

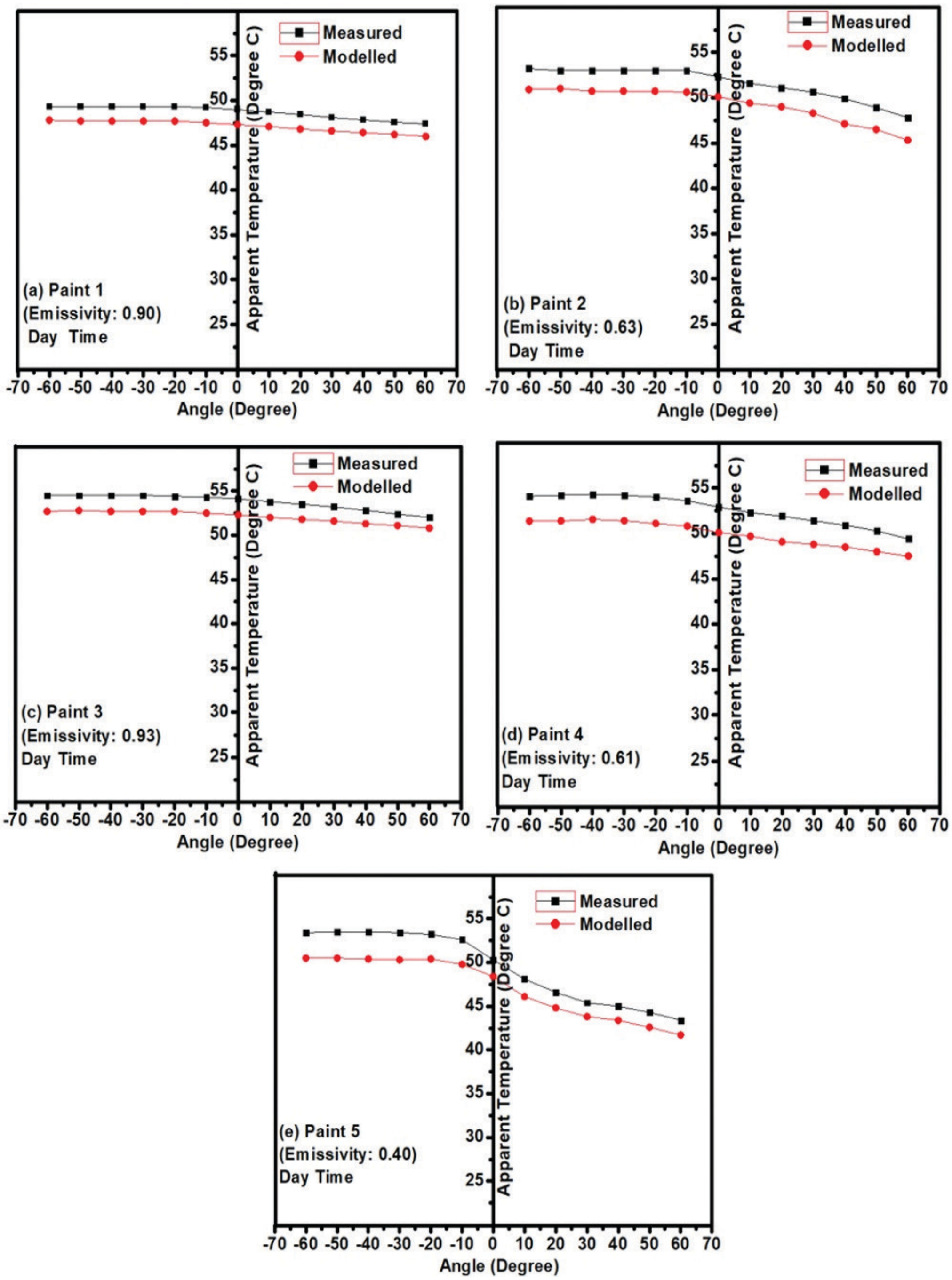

Figure 4. Angular variation of apparent temperature with angle in MWIR for day time.

a thermal solution is invoked, and the energy balance is solved simultaneously for convection, conduction and radiation. The last step is radiance calculation, which is to be taken up for each specified wavelength band separately.

4. RESULTS AND DISCUSSION

In the previous section, we briefly described the measurement setup and methodology along with input parameters and how the thermal signature simulation is performed using TAITHERM IR. In this section, we present the results of the measurement and simulation study. The results have been presented in terms of representative data of measured and modelled apparent temperature with tilt angle for day as well as night time. Though the data were measured diurnally for the sake of simplicity, the representative data for daytime and nighttime have been discussed.

Figure 4 to Fig. 7 represent the angular variation of different emissivity surfaces with tilt angles in MWIR and LWIR bands for daytime as well as for nighttime. The following observations may be drawn from these figures: -

- For high emissivity surfaces ($\varepsilon \geq 0.9$) the variation of apparent temperature with angle is quite small and found almost constant for day time
- For a negative tilt angle ($-60 \leq \theta < 0$), the apparent temperature is found to be constant in accordance with eqn (4). This observation indicates that when a surface is tilted towards the sand background, its apparent temperature is

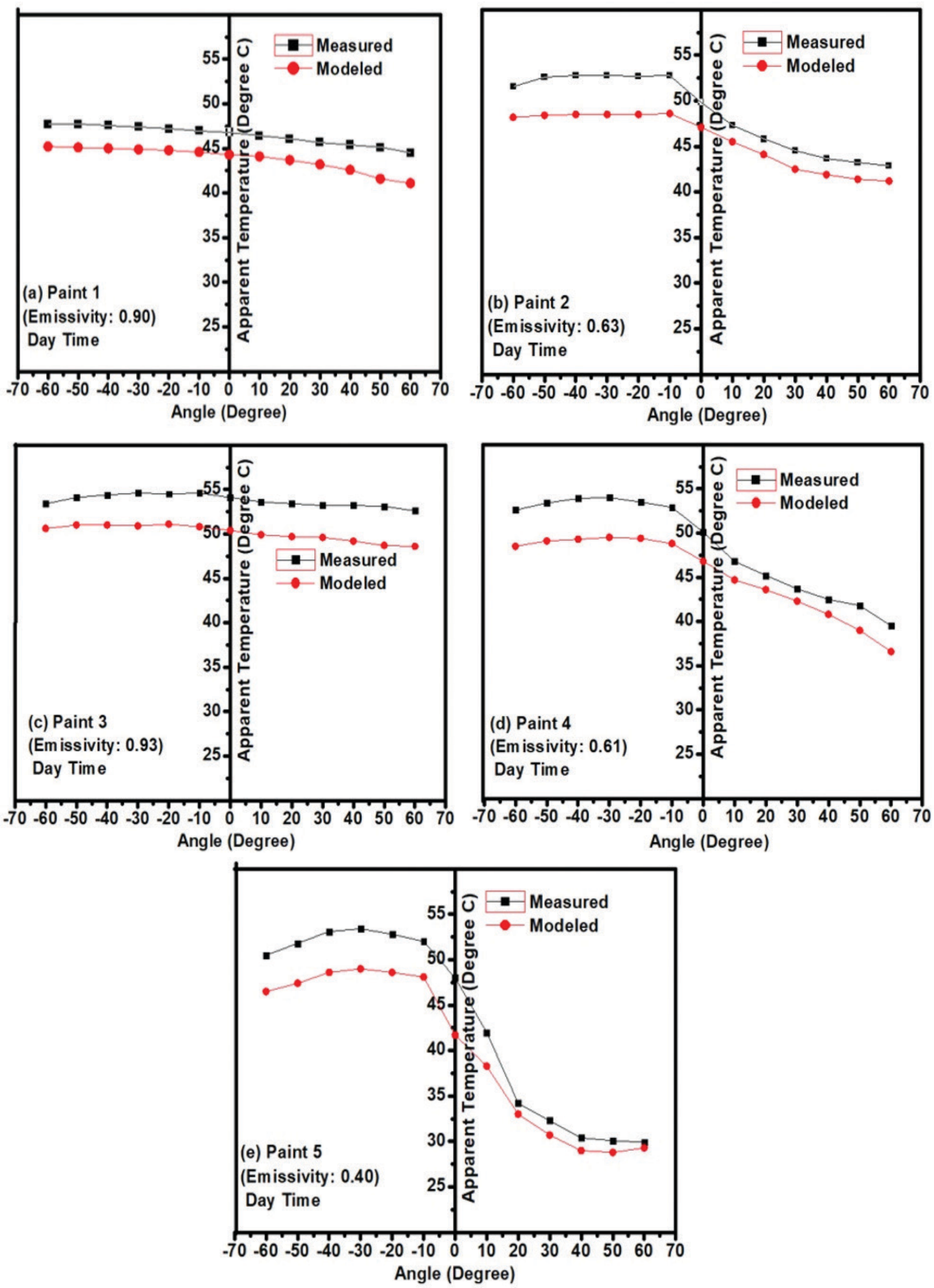

Figure 5. Angular variation of apparent temperature with angle in LWIR for day time.

almost constant irrespective of the tilt angle and emissivity values

- For positive tilt angle, the apparent temperature varies significantly with respect to tilt angle by eqn (5). The paint with much lower Emissivity shows more variation in apparent temperature than other paints, which indicates that when a low emissivity surface is tilted more towards the sky, the apparent temperature decreases. This effect is more pronounced in the LWIR band than in the MWIR band due to the major sky radiance in the LWIR, causing low emissivity surfaces to reflect a much colder sky background. Here, it is important to note that for opaque surfaces, Emissivity + Reflectivity = 1, which is why the low emissivity surfaces tend to have more reflection of major background radiation
- For a negative tilt angle ($-60 \leq \theta < 0$), the major background is the sand background, which has a temperature slightly higher than the ambient temperature. This corroborates that a negative tilt angle's apparent temperature is almost constant
- For a positive tilt angle, the major background is the sky background, which has a temperature quite lower than the ambient temperature, and this lower temperature is reflected by the surface having a positive tilt angle
- In the daytime, solar absorption compensates for the reflection of colder sky radiation by low-emissivity surfaces, resulting in a small variation in apparent temperature up to a 30° tilt angle
- Although the Emissivity of paint 1 and paint 3 are very near (0.9 and 0.93), there is a ~5°C difference in the

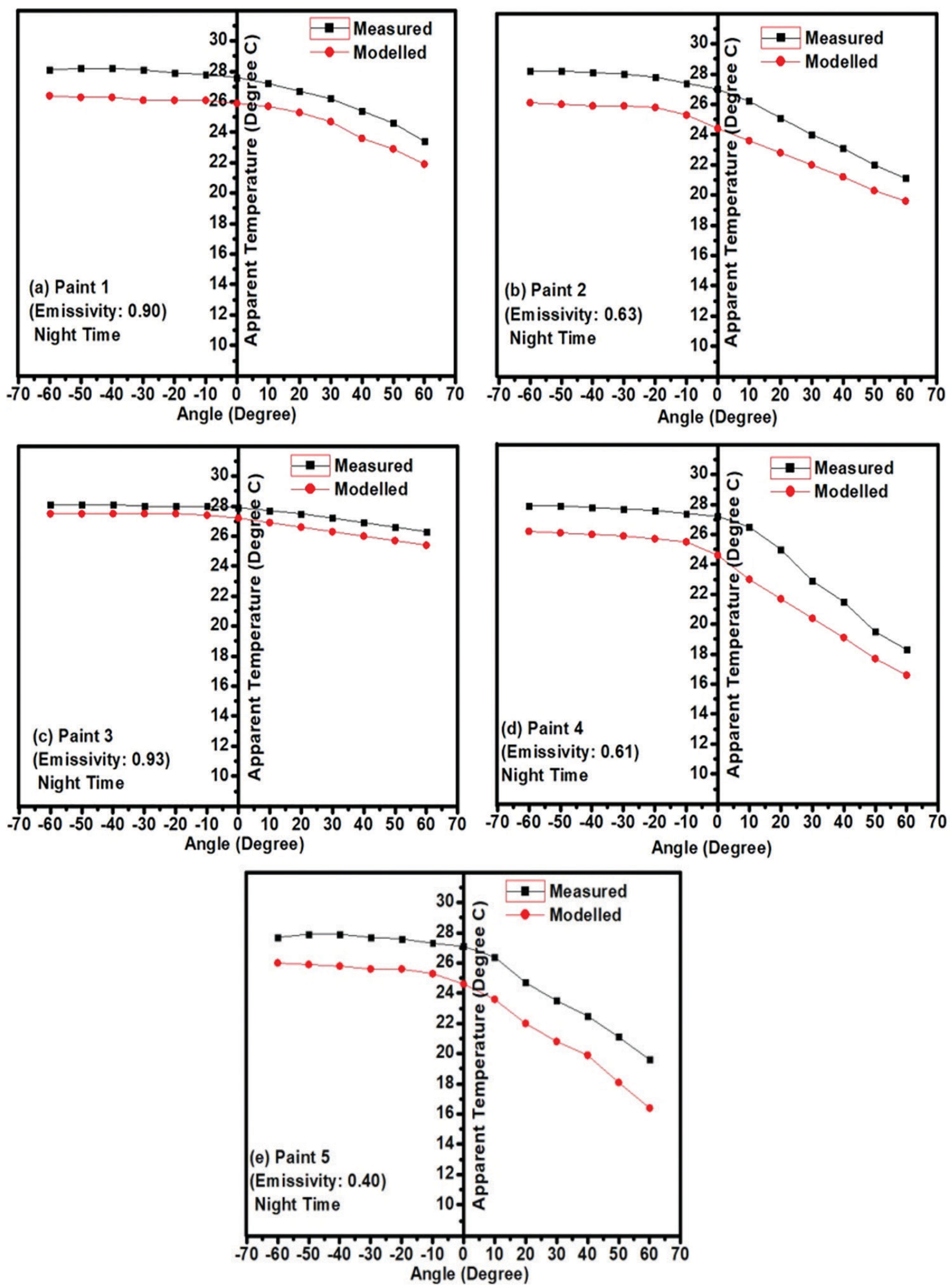

Figure 6. Angular variation of apparent temperature with angle in MWIR for night time.

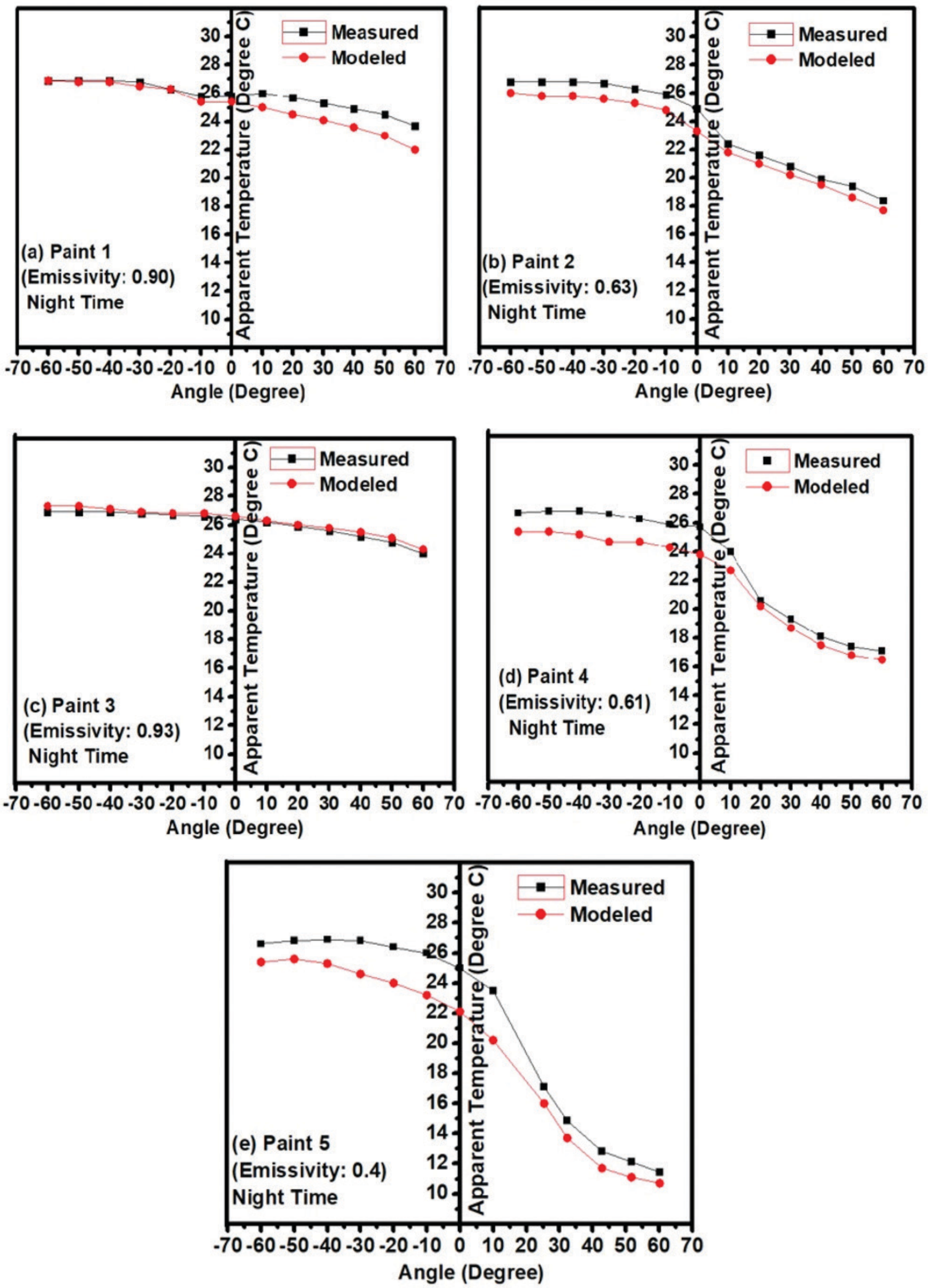

Figure 7. Angular variation of apparent temperature with angle in LWIR for night time.

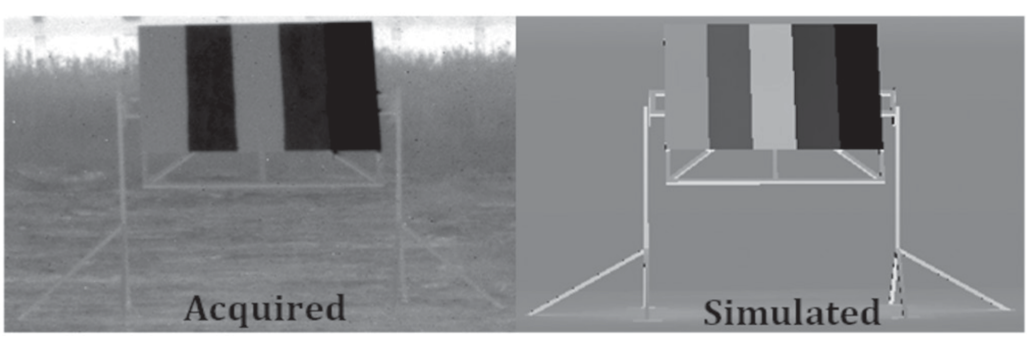

Figure 8. Comparison of acquired and simulated LWIR thermal images at 40° angle for night time.

apparent temperature of both paints due to the difference in their solar absorptivity

- The effect of sky radiance on apparent temperature is much more prominent at night time than in daytime.
- If the tilt angle is positive, the variation in apparent temperature of high emissivity surfaces ($\varepsilon \geq 0.9$) is greater at night than during the day due to the absence of solar radiation
- The measured and modelled temperatures are in agreement. However, a nearly constant difference is observed between them. This may be attributed to the use of modelled reflectivity values for the sand background and the assumption of approximate BRDF values.

The experimentally acquired and simulated thermal image of the test panel at angle 40° for night time in LWIR band is shown at Fig. 8 for illustration. It is clear from this images that the acquired thermal image of test panel is almost similar to simulated thermal image of test panel except background as the real background has vegetation and its reflectance values are different than the modelled background having sand.

5. CONCLUSIONS

In this paper, the results of the measurement study, as well as the simulation study of the effect of tilt angle on thermal signatures of different emissivity surfaces, have been presented. The effect of angular variation on apparent temperature for different emissivity surfaces was modelled using TAITHERM IR. The simulated data show good agreement with measured data, which may be considered a validation study for TAITHERM IR. This study may serve as a basic tool for designing IR stealth technology for military vehicles using paints/coatings. The present study gives more impetus for providing certain inputs that may be taken care of while designing camouflage using a low observable technique using surface treatment. Further, this study may be a framework for designing disruptive thermal pattern painting for military vehicles.

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In the current study he done conceptualisation of work & writing the manuscript.

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In the current study he contributed by measuring through MWIR thermal camera & Analysis of acquired thermal images through MWIR thermal camera.

Mr Pankaj Agrawal obtained his BTech (Electrical Engineering) from MNIT, Jaipur (Deemed University), Rajasthan and PGDBA from Symbiosis University, Pune. He is working as a Scientist at DRDO-Defence Laboratory, Jodhpur. His areas of interest include: FPGA-based instrumentation and infrared signature management.
His current contribution: Measurement through LWIR thermal camera and analysis of acquired thermal images through LWIR thermal camera.