CUBI – a Test Body for thermal Object Model Validation

Alain Malaplate, Peter Grossmann, Frédéric Schwenger
Research Institute for Optronics & Pattern Recognition (FGAN-FOM)
Gutleuthausstr.1, 76275 Ettlingen, Germany
malaplate@fom.fgan.de

ABSTRACT

CUBI is a rather simple geometrical object used in outdoor experiments with the objective of gathering data which can be utilized in testing and validating object models in the thermal infrared. Since its introduction several years ago, CUBI is gaining interest by an increasing number of research laboratories which are engaged in thermal infrared modelling. Being a member of the worldwide CUBI Forum, the FGAN-FOM has installed a CUBI about 1 year ago. Since then, CUBI surface temperatures are being recorded continuously, together with a set of associated environmental data. The data collected are utilized to explore the capabilities of the FOM Thermal Object code F-TOM. For this purpose, the model was modified to represent CUBI in model space. Likewise, the well-known IR signature prediction model RadTherm/IR was applied to the CUBI problem. In this paper we will present CUBI and the philosophy behind it, the comprehensive CUBI data collection effort at our place, and the development of the two different thermal models. Experimental data and model predictions will be shown and compared. Strengths and weaknesses of the models will be discussed.

Keywords: infrared, signatures, camouflage, test body, temperature measurements, thermal modeling, model validation, temperature prediction, signature prediction, F-TOM, RadThermIR, CUBI Forum

1 INTRODUCTION

Reliable modelling of thermal infrared (IR) signatures of man-made and natural objects in real-world scenarios is required for many applications such as sensor performance studies, IR scene simulator operations, development, assessment and optimization of CC&D materials and signature management of military platforms. Physics based IR modelling must consider object characteristics such as geometry, surface structure, heat-source distribution and operational conditions. In addition, the algorithms have to take into account the effect of environmental conditions and the physical properties of target materials, and they should be capable of predicting the surface temperature over a long time.

Validation is an important step in model development. In the thermal IR, validation is rather difficult to achieve, mainly for two reasons: (i) the physical phenomena to be modelled are numerous and are not independent from each other (it is, thus, not possible to study one effect in detail while the other effects are kept “frozen” or “switched off”), and (ii) most objects available for validation are quite complex and many of their specific material parameters are not precisely known (it is, thus, often not easy to attribute discrepancies between model predictions and measured data to either, model weaknesses or insufficient knowledge of object material parameters). The first problem is basic to the physical nature of the topic and hardly be overcome. The second problem, however, can be mitigated to a large extent by introducing a test object which is not overly complex in geometry and is build of components whose material parameters are precisely known. This is the idea which led to the definition of the test body CUBI [1], [2], as it is shown in Fig. 1.

As quoted in [3] “It [is] suggested to build CUBI from 3 equal-size cubes, arranged in an L-structure, where only the external facets of the structure exist (hollow object). Each of the facets [are] isolated on its internal side and there [is] no heat generating source inside. This, it [is] believed, would be the simplest geometrical object beyond a simple cube that will have enough general form and will enable to conduct model validation on a ‘simple test-object’ ”. Detailed specifications for building CUBI can be found in [2] and [3].

CUBI is not only instrumental in the validation of an individual model, but enables also to do e.g., comparisons of different models under the same set of environmental input conditions and/or comparison of model responses under different climatological input conditions. With this claim, the CUBI Forum [4] was established, as part of the International
Workshop an Target and Background Modelling and Simulation (ITBM&S) Workshop [5] held annually at the FGAN-FOM or, alternatively now, at the French ONERA.

The FGAN-FOM is using the FOM Thermal Object Model (F-TOM) since many years [6] to establish a comprehensive library of computer codes describing the surface temperatures of natural and man-made real-world objects. Applications of this rather simple, 1-dimensional object model are mostly related to thermal infrared sensor performance modelling and to the design and optimization of signature management materials and measures. F-TOM is a semi-empirical model in that the parameters describing a given modelled object are not taken from tables or textbooks but are derived from data measured with the object under study. It was decided recently to make use of CUBI in order to study the validity of F-TOM for predicting signatures in different climates and to compare it with other, more elaborate models.

The project started in 2006. A copy of CUBI was placed on a flat meadow which is part of the FGAN-FOM institute premises. Ettlingen is located in the Central Upper Rhine Region (mittleres Oberrheintal) which is a small district of southwest Germany stretching along the Rhine river between Karlsruhe and places as far as the Swiss frontier. In spring and summer it is the warmest part of the country. It is a sunny region in summer with up to eight hours sunshine per day. Winters are however quite cold because of the distance from the ocean.

A long-term (several months) data collection was initiated with CUBI surface temperatures being measured continuously (at 5-min intervals) together with the necessary environmental parameters, including meteorological data. Based upon the data which was initially collected, a CUBI module of F-TOM was generated [7]. Once established, the model was applied to environmental data collected during later periods, and predictions were compared to measured data.

Compared to F-TOM, the IR signature prediction code RadTherm/IR [8] is a much more detailed approach, allowing to solve the heat transfer equation (HTE) for fully 3-dimensional objects. The code is used by quite many participants in the CUBI Forum [4] and also by the FGAN-FOM.

In the following Chapter 2, CUBI will be introduced briefly and the CUBI experiment conducted currently at the FGAN-FOM will be described. Chapter 3 addresses the FOM Thermal Object Model F-TOM. After introducing the 1-dimensional HTE as the basis of the model, the development and validation of F-TOM will be outlined and comparisons of model predictions with experimental data will be shown and discussed. As a more sophisticated alternative to the simplistic and rather straightforward F-TOM model, the RadTherm/IR code will be addressed in Chapter 4. Again, after giving an outline of the CUBI code development, model predictions will be presented and compared with experimental data. Having available results from two independent models for the same physical problem, it is quite interesting to do a comparison between the model results. This comparison of results will be discussed in Chapter 5, together with a comparison of the two individual models themselves, their pros and cons. Conclusions and recommendations will be summarized in Chapter 6.
2 CUBI - EXPERIMENT AND RESULTS

2.1 CUBI - Definition

CUBI is a physical test object standardized with respect to shape, size and material properties [1], [2], [3]. As shown in Fig. 1 and Fig. 2, the shape of CUBI is that of 3 cubes put together to form a step\textsuperscript{1}, or an “L”. With a cube size of 0.5 m in each dimension, the total height of CUBI is 1 m. The body is made of 4-mm thick plates of mild-carbon steel. On their back, the steel plates are thermally insulated by 10-mm thick plates of polystyrene. Following a proposal by Bushlin and Lessin [9], our CUBI has a non-transparent closure (steel plate) at the bottom end. Exact values of the material parameters are given in [2].

2.2 Experiment

At the FGAN-FOM, CUBI is placed on a flat meadow, see Fig. 2 left. The side containing the step is oriented towards the South\textsuperscript{2}. To make sure that CUBI, when illuminated by the sun or when viewed by a remote camera, is not obscured by high rising grass blades or tuft, it is not put directly on the ground rather than rested on a pallet made of plastics, see left hand side of Fig. 2.

At our place, CUBI wall temperatures are measured by 10 Pt 1000 thermistors (instead of the 20 Alumel-Chromel K-type thermocouples used by IARD [9]). In accordance with the general standard, thermistor locations are chosen such that the temperature run of each facet can be measured individually. Locations are shown as red dots in Fig. 2. Thermistor heads are placed between the back of the steel plates and the thermal insulation layer. They are wired to a data logger which stores the various temperatures, each data point averaged over 5-min intervals. The sampling rate is 12 samples/h.

Environmental data relevant to thermal signature modelling, including general meteorological data, are measured and logged - parallel to the facet temperature data - by a mobile environmental measurement station AME [10], see right hand side of Fig. 2. The AME station is placed close to CUBI but far enough not to interfere with it (e. g. through casting shadows on it). The station works fully automatically at a sampling rate – here - of 12 samples/h. Measured data include

- meteorological data,
- down-welling irradiance in the “short wave” (solar) spectral region,
- down-welling atmospheric temperature radiation (“long wave” region),
- visual range, $V_N$,
- top soil temperature and soil temperatures at some depths beneath the surface.

\textsuperscript{1} It should be noted that this description makes reference to the outer shape of CUBI only; there are no internal walls which would separate the individual cubes.

\textsuperscript{2} Analysis showed that it was much more interesting to study the shadow effects occurring when the step is oriented towards the North. Thus, in July 2006, CUBI was turned around by 180° to reflect this situation.
As a further tool, 2 thermal IR cameras are used to acquire the distribution of radiation temperatures across (some of the) CUBI facets. A FLIR Systems Indigo Merlin® Mid InSb radiometric camera and a FLIR System SC3000 provide thermal IR images of CUBI and its immediate background in 2 thermal IR spectral bands, i.e. the mid wave IR (3 µm – 5 µm, MWIR) and long wave IR (8 µm – 9 µm, LWIR), respectively. Cameras are mounted in a tower on top of the institute building at a distance of 55 m to the CUBI location. The camera field-of-view (FOV) is 5° for each camera. Both cameras acquire single images at a sampling rate of 12 frames/h. Unlike the thermistors which are measuring routinely over the entire duration of the experiment, the cameras are operated only during certain, most interesting measurement periods.

CUBI data collection at FGAN-FOM was started in May 2006 and is running since then on a routine basis.

2.3 Results

As AME data examples, some of the environmental data measured during the first days of the experiment are shown in Fig. 3. This is air temperature, \( T_{\text{air}} \), solar and long-wave (sky) irradiance, \( E_{\text{sun}} \) and \( E_{\text{sky}} \), wind velocity, \( v_{\text{air}} \), and relative humidity, \( r_h \). Apparently, weather was quite nice in this period, with warm and sunny days, but had a noticeably drop during the 2nd half of the period.

Fig. 4 shows some CUBI surface temperature data acquired by thermistors. Five different orientations are considered, i.e. South, North, East, West, and Top. The 2 days shown (May 11 and 12, 2006) were chosen from the sunny period in Fig. 3 where almost no clouds were present. Thus, the temperature run of the top plate (thermistor 8) exhibits a rather symmetrical behaviour, reflecting the course of the sun. The non-symmetric run of the temperature curves of the other surfaces can easily be associated with their different orientations towards the sun.

Fig. 3: Environmental data acquired between May 04 and 14, 2006; from top left to bottom right: air temperature, \( T_{\text{air}} \); solar and long-wave irradiances, \( E_{\text{sun}} \) and \( E_{\text{sky}} \); wind speed, \( v_{\text{air}} \); and relative humidity, \( r_h \).
Fig. 4: Temperature data collected on May 11 and 12, 2006, by thermistors 1 (south facet, black), 6 (north facet, blue), 7 (east facet, yellow), 8 (top facet, red) and 10 (west facet, green).

Fig. 5 shows two thermal IR images of CUBI as seen from a distance of 55 m. The images, on the left and right hand side, were captured in the MWIR (Merlin®Mid InSb camera) and the LWIR (SC3000), respectively.

3 F-TOM – FOM THERMAL OBJCT MODEL

3.1 1-Dimensional Heat Transfer Equation

Object surface temperatures are the result of a number of heat exchange mechanisms which take place within the object itself and between the object and its exterior. As shown in Fig. 6 there are 4 classes of effects which drive the temperature, with three of them acting externally, i.e. radiation exchange, convection heat exchange, latent heat exchange (evaporation, condensation), and one acting inside the object, i.e. heat conduction. Mathematically, the problem depicted in Fig. 6 is described by the Heat Transfer Equation (HTE).
The (differential form of the) HTE considers an object volume element and relates the rate of change of its internal energy to the net energy flux across its total surface due to the above mentioned effects. In the first part of this paper we are considering CUBI as a set of metal plates which do not interact with each other. For any flat layered, homogeneous object, the 3-dimensional HTE can be simplified to its 1-dimensional formulation. For a volume element located on the surface of such an object, the 1-dimensional HTE amounts to [6]:

\[
\frac{dT}{dt} \cdot \rho \cdot d \cdot C_p = \alpha \cdot E_{\text{sun}} + \varepsilon \cdot E_{\text{sky}} - \varepsilon \cdot \sigma \cdot (T^4 - T_i) + (h_i + h_{\text{air}}) \cdot (T_{\text{air}} - T_i) + r \cdot (h_i + h_{\text{air}}) \cdot (e(T_{\text{air}}, rh) - e(T_i, 100\%)) + \frac{k}{d_n} \cdot (T_n - T_{n-1})
\]

Here, \(T_S, T_{\text{air}}, T_n\) = object surface temperature, air temperature, temperature of the n-th layer (if the object is layered),
\(t\) = time,
\(n\) = layer number, with \(1 \leq n \leq n_{\text{max}}\),
\(\rho, d, C_p, k\) = specific density, thickness (of the n-th layer), specific heat (at constant pressure) and thermal conductivity of the n-th layer,
\(E_{\text{sun}}, E_{\text{sky}}\) = solar irradiance, irradiance due to atmospheric temperature radiation (both measured at the object surface perpendicular to the surface normal),
\(\alpha, \varepsilon, \sigma\) = (solar) absorptivity, (long wave) emissivity of the object surface; Stefan-Boltzmann’s constant,
\(h_i, h_{\text{air}}, r\) = heat exchange coefficients for free and forced convection, respectively; efficacy ratio of convective and latent heat exchange,
\(v_{\text{air}}, e, rh\) = wind speed, atmospheric water vapour pressure, relative humidity.

The term on the left hand side of Equation (1) denotes the rate of change of internal energy of the volume element, while each term on the right hand side denotes a specific contribution to the total energy flux entering or leaving the volume element across its surface. This is, from left to right, absorbed solar flux, absorbed flux of atmospheric temperature radiation, flux of thermal radiation emitted from the object surface, fluxes due to convective heat exchange (both, free and forced) and latent heat exchange (both, free and forced) and finally heat flux due to thermal conduction between the (n-1)th and the nth layer of the object. Equation (1), as it stands, is valid in this form for the uppermost, first layer, where \(n = 1\). In this case, we have \(T_{n-1} = T_0 = T_s\). For any layer with \(n > 1\), the right hand side of Equation (1) is comprised of the conduction term only. The temperature of the deepest layer (\(n = n_{\text{max}}\)) is supposed to be fixed and is called core tem-
perature. The choice of the core temperature appears somewhat arbitrary but in many cases it can be linked to some temperature level, known to be constant.

### 3.2 F-TOM Model Development

Equation (1) is the basis of the FOM Thermal Object Model (F-TOM). It calculates the energy fluxes within an object and across the object surface along the direction of the surface normal (z direction); any variations of the independent variables (object material properties and environmental input parameters) in the directions of the surface plane (x-y directions) are assumed to be zero. The (set of) differential equations (1) can be solved by known numerical algorithms as e. g., by time discretisation.

The only objects which can be modelled straightforwardly by Equation (1) are flat, layered, homogeneous slabs. When Equation (1) is used to model objects having other geometries, such as CUBI, one should keep in mind that these objects, through this particular approach, will be “replaced” by a set of “equivalent” slabs.

Since the geometry of objects modelled by Equation (1) is fixed, the only “free” parameters for modelling an individual object are its material properties. We define a “thermal model for a given object” as the entity consisting of (i) Equation (1), (ii) the numerical solver and (iii) the set of material parameters specific to this object.

A straightforward way to include into Equation (1) the material parameters specific to a given object is to look up tables in the literature and to pick the values given there. It was found, however, that the temperatures predicted this way were often not in agreement with temperatures measured for the same object. The main reason for this discrepancy, in our view, is the fact that in many cases the object material parameters are not well known – at least in the form required by thermal object models. This is why we have chosen a semi-empirical approach for determining appropriate model parameters.

The semi-empirical approach consists of 4 phases:

- **Data Collection.** A real object which is representative of the object type considered is selected as test body for experimentally collecting surface temperatures as function of environmental conditions; these conditions are also measured simultaneously. The data collection phase results in a comprehensive data base containing time histories of object surface temperatures together with associated environmental data over extended periods of time.

- **Model Development.** Time histories of surface temperatures measured in the data collection phase are used, in conjunction with the associated environmental data, in a least-square fitting process (regression) to determine a set of derived material parameters. The model development phase results in the establishment of an optimum set of material parameters.

- **Model Validation.** Validation is done by critically comparing model predictions with corresponding time histories of surface temperatures measured in the data collection phase. Care must be taken that the time periods considered in this process are “independent” from those used for regression.

- **Model Exploitation.** The model production phase makes use of the model developed, i. e. of Equation (1) in conjunction with the optimum set of material parameters derived in the model development phase; it results in the prediction of the (time history of the) object surface temperatures for any given time history of environmental data are inputs.

The solution of Equation (1) is the temperature distribution within a slab which is homogeneous in x-y-direction. The only variation of temperature occurs in the direction of the surface normal. This means, in particular, that the slab surface temperature is characterized by one and only one temperature value and that there is no temperature distribution across the x-y plane. Using F-TOM, this value is interpreted as the (surface) area averaged mean temperature of the object being modelled. In reality, most surfaces have a temperature distribution across the x-y plane with non-vanishing variance. This cannot be predicted by F-TOM. To overcome this weakness of the model, an empirical relation was added. From long-standing experimental experience it is known that the standard deviation, $\sigma_T$, of temperature $T_s$ of a surface

---

3 It should be noted that for objects with more than one layer ($n_{\text{max}} > 1$), Equation (1) is a set of $n_{\text{max}}$ equations, see Chapter 2.
exposed to the open environment is most dominantly influenced by solar irradiance, $E_{\text{sun}}$. The dependence of $\sigma_T$ on $E_{\text{sun}}$ can roughly be approximated by a linear function [11]. Thus, a linear relationship is assumed

$$\sigma_T \approx a + b \cdot E_{\text{sun}}$$

(2)

where $a$ represents the (minimum) width of the temperature distribution at night. In many measurements under moderate climatic conditions, an upper bound for the relationship was found to be given by $a = 2K$ and $b = 0.01 \text{ K m}^2 \text{ W}^{-1}$. For an extremely sunny day (with $E_{\text{sun}} \approx 1000 \text{ W m}^{-2}$), this amounts to $\sigma_T \approx 12K$. Using this relation, one can write the temperature band predicted by the F-TOM model as

$$T_S - \sigma_T \leq T \leq T_S + \sigma_T.$$  

(3)

For setting up the F-TOM model, i.e. for determining the model parameters by regression as described in Chapter 3.2, the week from May 04 to 08, 2006, was chosen. The data points used for this purpose are indicated in Fig. 7 by red colour. The reason for selecting this period is that there was considerable variation in all environmental parameters driving the thermal signatures of CUBI. The grey band around the red-coloured points is the temperature band, see Equation (3), showing the “best fit” of the experimental data points.

### 3.3 F-TOM Model Validation

Model validation is done by critically comparing model results with measured data for a time periods different from the that period used in the model development. All blue points shown in Fig. 7 are indicating the validation period. The grey band going along with these points is the temperature band predicted according to Equation (3).

![F-TOM Results](image)

Fig. 7: F-TOM Results for the top facet (thermistor 8); red and blue dots indicate measured data; the grey band is the computed temperature band. Red-coloured data were used in the model development (regression) process; blue data points indicate time periods where the F-TOM was used for predictions.

Fig. 7 shows generally a good agreement between predicted and experimental data. The predicted temperature band covers, on the one hand, quite well the diurnal temperature patterns even under different conditions, such as sunny and overcast. On the other hand, within the range given by the temperature band, predicted temperatures tend to be systematically higher than the experimental data.

The same set of model parameters as found for predicting the top facet temperatures were used to compute the surface temperatures of the other CUBI facets, too. The reason to utilize the same set of parameters for all facets is that all CUBI parts are made of the same material(s). The only difference in the calculations is caused by the different orientations of the surfaces. This has basically the following implications:
The value of direct solar irradiance on each facet changes due to the different angles under which each facets “sees” the sun.

A vertical facet “sees” only half of the diffuse solar irradiance seen by the measurement device.

A vertical facet “sees” only half of the sky hemisphere and experiences, thus, only half of the atmospheric temperature radiation.

A vertical facet receives long-wave radiation from the terrestrial background in front of it.

While the first effect is amenable to accurate numerical treatment, the other three effects are subject to some kind of simplification (there is no instrument installed in the experimental set-up measuring the parameters in question directly) and, thus, can be expressed only in an approximate way.

Fig. 8 to Fig. 11 show the F-TOM predictions for the various vertical CUBI facets. For ease of legibility, only the first few days of the data collection are considered in these diagrams. Closer inspection shows that for the vertical facets there is slightly less correlation between experimental data and predicted results than is in case of the top facet. One reason could be that some of the input data, such as the amount of short-wave and long-wave irradiance, are not measured directly rather than derived from other data, see the discussion above. There is some remaining ambiguity as to the directional structure of this data within the experimental setting given at the institute premises where CUBI is placed.

The F-TOM south facet model predictions (grey band) follow quite nicely the diurnal run of the measured temperatures.

In case of the north facet, model predictions agree with measured data quite well at night hours, while showing some systematic deviations during day.

F-TOM does not predict the temperature peaks which frequently occur in the east facet measured temperature data.
F-TOM predictions for west facet temperatures appear to be extreme: at night they are higher and during day they are lower than the measured data.

To get a more detailed view of the situation, Fig. 12 shows the same data as were shown already in Fig. 4 – i.e. surface temperatures for all five CUBI facets as measured on May 11 and 12, 2006 – but now together with corresponding results of F-TOM. Apparently, there is good agreement between measured and modelled values for all facets during night hours, while some predicted temperatures deviate from experiment in the presence of strong solar irradiation. The cause of this discrepancy is under investigation.

To get a more concise expression for the match between the modelled and measured surface temperatures, the diurnal root-mean-square (RMS) of the deviations is calculated. It is defined as the RMS taken over a period of 1 day. Diurnal RMS values provide a good insight into the quality of temperature predictions for different weather situations and also as function of seasonal variations. In the present case they were found to fluctuate quite strongly from day to day. This is hard to view as a whole. For this reason we did not plot in Fig. 13 the diurnal RMS values themselves (for the time period shown) rather than their moving mean. By doing so, one may get a good impression on the magnitude of excursions of individual diurnal RMS values - towards the beginning of the period shown - and the overall “mean of the mean” – at the end of the period.
As can be seen in Fig. 13, F-TOM is able to predict the CUBI top facet surface temperature with an overall RMS of slightly more than 1 K. But Fig. 13 also shows that predictions become worse when F-TOM is applied to facets other than the top one. While the overall RMS for the north and south facet is about 2 K, the west and, particularly, the east facet temperatures deviate by an overall mean of around to 3 K. Such large deviations have not been found in previous studies utilizing F-TOM. The reason for these rather large discrepancies in the case of CUBI is under investigations.

4 CUBI MODELING BY RADTHERM/IR

Parallel to modelling CUBI by the F-TOM model, work was undertaken to do this with RadTherm/IR [8] also. This model is much more detailed than F-TOM. While F-TOM predicts area weighted average temperatures of a flat surface and - to some extend – the standard deviations of its temperature distribution, RadTherm/IR is a fully 3-dimensional model predicting the surface temperature distribution across all outer surfaces of a 3D object.

All environmental parameters required by RadTherm/IR as input parameters are provided by the AME environmental station, see Chapter 2, except cloud cover. This parameter which is not measured by AME can be derived, under some simplifying assumption, from AME data by linearly interpolating the measured values of atmospheric temperature radiation between MODTRAN radiance values, computed for clear sky conditions, and black-body radiance values, estimated as representative of cloud base radiation at total overcast conditions [11].

4.1 RadTherm/IR CUBI Model

Being member of the CUBI Forum [4], the FGAN-FOM has access to a 3D mesh model for CUBI as it was developed and tested by Bushlin, Lessin et al. [9]. The choice of one given mesh enables direct comparison of results derived within the CUBI community for different regions and climates.

The mesh consists of 12 square parts with equal size of 0.5 x 0.5 m² representing the “visible” outer CUBI surface. Each of these squares is divided into 25 x 25 quadrilateral elements. A ground mesh of 20 x 20 elements, each of which having the same size as the CUBI squares, represents the soil background on which the CUBI set-up is located. The bottom end of CUBI is modelled as a radiative closure – in accordance with the experimental set up, see Chapter 2. Like in the experiment, the CUBI model does not “stand” directly on the soil background but is rested on a pallet consisting of black polyethylene. Material parameters are: density $\rho = 940 \text{ kg/m}^3$, specific heat $C_p = 2100 \text{ J/kg} \cdot \text{K}^{-1}$, thermal conductivity $k = 0.35 \text{ W/m} \cdot \text{K}^{-1}$, solar absorptivity $\alpha = 0.94$ and long-wave emissivity $\varepsilon = 0.92$ [12]. As in the experiment, the model allows for air to circulate almost freely between the palette and CUBI. The CUBI bottom plate is bare steel showing high reflectivity.
Both, the outside walls of CUBI and the thermally insulating lining material on the inner side had to be modelled. Usually, RadTherm/IR defaults to a 3-layered description of the mesh elements. In this sense, two of these layers are assumed to be mild steel with a total thickness of 4 mm. Material properties are: density $\rho = 7768.98 \text{ kg m}^{-3}$, specific heat $\rho C_p = 460.967 \text{ J kg}^{-1} \text{K}^{-1}$, solar absorptivity $\alpha = 0.47$ and long-wave emissivity $\varepsilon = 0.9$. The third inside layer is a 10 mm thick foamed polystyrene slab with density $\rho = 20 \text{ kg m}^{-3}$, specific heat $\rho C_p = 1350 \text{ J kg}^{-1} \text{K}^{-1}$, thermal conductivity $k = 0.035 \text{ W m}^{-1} \text{K}^{-1}$. The model soil background is completely covered by short grass (growth factor: “dormant”, surface and bulk moisture left as default values in RadTherm/IR). Solar absorptivity and long-wave emissivity are chosen as 0.7 and 0.9, respectively. The CUBI model described corresponds to the advanced thermal model described in [9] except for the pallet on which CUBI is rested, the vegetative soil background and the paint optical parameters.

4.2 Results

Fig. 14 shows a diurnal cycle (day 24/10/06) of the temperature measured by thermistor 8 (blue curve). From midnight (0 AM) to 3 AM rain fell, and cloud-covered sky was registered until 10 AM. Around noon, increased solar irradiance was recorded causing stronger heating of surfaces. Drifting clouds led to the notched characteristics of the temperature curve. From 3 PM until 6 PM, the sky became more cloud-covered. During the day, wind speed varied between 2 and 5 m/s.

Also shown in Fig. 14 is the temperature predicted by RadTherm/IR (red curve). Apparently, there is good correlation between prediction and experiment. Minor discrepancies appear during periods of lower solar radiation and of stronger cloud-cover with the latter problem arising probably from inaccuracies in the derivation of cloud-cover. The diurnal root mean square (RMS) of the differences between measured and modelled temperatures for the top facet (thermistor 8) was found to be 0.59 which is a rather small value.

Comparison between the thermally modelled CUBI with LWIR sensor images taken in the experiment can be made by inspecting Fig. 15 and Fig. 16. Pictures shown there correspond to local times 10 AM and 3 PM (MET). In both, modelled and recorded images, the east facets show considerable solar heating during morning hours (the west facets heated up in the afternoon cannot be seen in this perspective). Model results illustrate nicely the influence of the solar heating of the pallet on the bottom part of CUBI.

While RadTherm/IR calculates the temperature distribution of the CUBI facets and the background, it does not provide simulation results for sensor view. Thus, comparison with LWIR images may serve for visualization purposes only or at most - for explanation of tendencies in object temperature responses. In the present case, major differences between RadTherm/IR results and corresponding sensor images become apparent by inspecting the CUBI horizontal facets. Dark areas, as seen across these facets in the camera images, see Fig. 16, do not indicate low body-temperatures within the facets rather than specular “reflections” of the cold sky. Nonetheless, temperature “maps” predicted by RadTherm/IR could further be used as input for sensor view simulation programs.

5 COMPARISON BETWEEN F-TOM and RADTHEM/IR RESULTS

With the results given in Chapters 3 and 4, we are now ready to do a comparison between the two thermal object models considered in this paper, i.e. between F-TOM, see Chapters 3.2 and 3.3, and RadTherm/IR, see Chapter 4. In Fig. 17, the temperature predictions of both models for the top facet (thermistor 8) are plotted along with the measured temperatures. The day chosen for this comparison is May 11, 2006, which was a sunny day with almost no clouds in the sky. Both, modelled F-TOM (red) and RadTherm/IR (green) predictions follow well the measured temperature values (blue). The root mean square (RMS) difference between measured and modelled temperatures on this day for thermistor 8 was determined to be 0.82 for the F-TOM model and 1.1 for the RadTherm/IR model. This is a unique situation since normally F-TOM yields diurnal RMS values around and larger than 1 K, see for instance Fig. 13, while RadTherm/IR was found to come up with values as low as 0.6 K to 1 K in general.
Though it is an important issue, model accuracy is only one aspect to be considered in model comparisons, and there are others worth to be studied as well. A few of these are summarized Tab. 1.

While RadTherm/IR is much better suited to reproduce the temperature distributions across the various CUBI facets, the 1-d model F-TOM provides area weighted average temperatures and an estimated standard deviation, $\sigma_T$, for each of the
facets only⁴. On the other hand, F-TOM is a model which requires much less computing than RadTherm/IR. The typical run time of the RadTherm/IR CUBI model with 42970 thermal nodes for a diurnal temperature cycle was about 27 hours on a SGI PC (2x800 MHz). Compared to this, F-TOM calculations took only 10 s for an entire day.

Thus, the strengths of RadTherm/IR are seen in predicting the detailed temperature distributions of surfaces which may be useful in the design and optimization of the thermal construction of objects as well as in signature studies. The strength of F-TOM rests in its ability of predicting surface temperatures in an extremely fast, efficient manner, at the expense of some increased inaccuracy; this feature makes it well suited for studies, say, of the statistical behaviour of object-to-background temperature differences. For this reason, F-TOM is presently utilized quite heavily in the forecast of IR visibility for helicopter pilotage.

---

Tab. 1: Model comparison - summary

<table>
<thead>
<tr>
<th>Feature</th>
<th>F-TOM</th>
<th>RadTherm/IR</th>
</tr>
</thead>
<tbody>
<tr>
<td>object complexity</td>
<td>1-dimensional (slab)</td>
<td>3-dimensional</td>
</tr>
<tr>
<td>object material parameters</td>
<td>through experimentation</td>
<td>from literature</td>
</tr>
<tr>
<td>environmental inputs</td>
<td>met data + measured radiation fluxes</td>
<td>met data + radiation fluxes, some of them to be derived</td>
</tr>
<tr>
<td>output</td>
<td>surface mean temperature + standard deviation (estimated)</td>
<td>temperature distributions across all object surfaces</td>
</tr>
<tr>
<td>accuracy (diurnal rms) found so far</td>
<td>mostly between 1.5 K and 3 K</td>
<td>usually better than 1 K</td>
</tr>
<tr>
<td>computation time</td>
<td>10 s /diurnal cycle (5 min res) on regular laptop</td>
<td>27 h /diurnal cycle (5 min res) on SGI PC (2x800 MHz)</td>
</tr>
<tr>
<td>potential applications</td>
<td>statistical assessment of signatures and CC&amp;D; temperature inputs to scene simulation, IR visibility forecast</td>
<td>platform design and optimization; fast prototyping; Signature studies; signature inputs to scene simulation</td>
</tr>
</tbody>
</table>

---

⁴ Moreover, facets must be assumed to be totally decoupled in the thermal sense.
6 SUMMARY AND CONCLUSIONS

The study has shown clearly the usefulness of the CUBI concept for both, the development and validation of thermal object models and a critical comparison between different models. In the present case, it was possible to show the strengths and weaknesses of two completely different models – the FOM thermal object model F-TOM and the widespread code RadTherm/IR.

The CUBI concept provides extensive data sets generated by measuring a physical object of standardized and well-documented properties and dimensions, using measurement techniques which are also standardized and represent a high level of measurement skills and commonality.

ACKNOWLEDGEMENT

The authors acknowledge gratefully the scientific and technical support provided by their colleagues at FGAN-FOM. Dieter Clement, Alexander Schwarz and Michael Kremer. Many thanks are expressed to the CUBI Forum Manager, Alex Lessin, IARD, who provided the information concerning CUBI in general and the RadTherm/IR CUBI data in particular. Last, not least the authors thank the German Ministry of Defence and the WTD 52 who have, with their grants, supported the work to a large extent.

7 REFERENCES

[10] AME Environmental Station, company HOFFMANN MESSTECHNIK, Rauenberg, Germany