THERMAL MANAGEMENT EVALUATION OF THE COMPLEX ELECTRO-OPTICAL SYSTEM

by

Srećko NIJEMČEVIĆ[a1], Milan M. TASIĆ[b],
Branko G. LIVADA[a], Dragana PERIĆ[a], Marko M. TASIĆ[b]

[a]VLATACOM Institute, Belgrade, Serbia
[b]University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia

Original Scientific Paper
DOI:

Abstract: *The thermal management of a complex electro-optical system aimed for outdoor application is challenging task due to the requirement of having an air-sealed enclosure, harsh working environment and an additional thermal load generated by sunlight. It is essential to consider the effect of heating loads in the system components, as well as the internal temperature distribution, that can have influence on the system life expectancy, operational readiness and parameters, and possibility for catastrophic failure. The main objective of this paper is to analyze internal temperature distribution and evaluate its influence on system component operation capability. The electro-optical system simplified model was defined and related thermal balance simulation model based on Solid Works thermal analysis module was set and applied for temperature distribution calculation. Various outdoor environment scenarios were compared to evaluate system temperature distribution and evaluate its influence on system operation, reliability, and life time in application environment. This work was done during the design process as a part of the electro-optical system optimization. The results show that temperature distribution will not be cause for catastrophic failure and malfunction operation during operation in the expected environment.*

Key Words: *Thermal analysis, Thermal management, Electronics cooling, Outdoor enclosure cooling, Solar load*

1. Introduction

Electro-optical (E-O) systems have significant role in various applications (military, homeland security, border control, etc.). They have a complex design and a number of engineering disciplines (mechanical, structural, thermal, optics, electronics and software) are needed to design and build them. In addition, they are often used in the outdoor environment. Design and analysis are performed according to functional and environment requirements. Design reviews are necessary to refine and improve design according to analysis results.

Thermal management validation is an important part of the system performance analysis, in order to confirm suitability and conformance of the system design. System thermal modelling is one of the most important validation techniques, on one hand, while on the other hand, it is complicated due to complex design. Reasonable simulation model simplifications can help to achieve accurate analysis results faster. Systematic approach and scientifically based methodology ensure that E-O system

[1] Corresponding author: srecko@vlatacom.com

simplification would be accurate enough for validation purposes.

Review of the thermal management of electronic equipment is presented in [1,2]. Thermal design of the electronic equipment and packaging is analyzed in [3,4]. General thermal engineering methodology is presented in [5]. Thermal management evaluation of electronic equipment is considered in [6-8].

In this paper well known methodology is applied for equipment having specific structure (E-O system) using a simplified model for subsystems thermal behaviour. In addition, real environment parameters and thermal management evaluation criteria are used to analyze system design suitability for aimed application.

The core research content is based on determination of the temperature distribution inside hermetically sealed E-O system housing in the diversified environmental conditions. A forced air stream inside housing is realized using the internally built fans, without air exchange with the outside environment.

The key research goals are to explore the possibility to decrease the temperature value at surfaces on sensitive E-O components using forced air circulation inside housing, and evaluate the improvement of the device thermal management in the environmental conditions.

Environmental conditions define thermal scenario (solar thermal load, ambient temperature and wind conditions). Electro-optical system structure is described and system components thermal behaviour (thermal activity and vulnerability) are identified. Applied system thermal model simplification for thermal calculation is described. Simulation results are presented and discussed. System thermal evaluation criteria are defined and system thermal behaviour is evaluated according to environmental conditions.

2. Influence of the environmental conditions

Electro-Optical system is aimed for outdoor application where solar thermal load, ambient temperature and wind conditions have influence on system thermal balance (heating and cooling) and should be considered during evaluation process.

2.1. Solar thermal load

The Sun is a G class star with a mean surface temperature of approximately **5900 K** according to the best fit black-body curve or about **5770 K** for temperature of a black-body source that is the size and distance of the sun and would produce an exo-atmospheric total irradiance of 1390 W/m^2. [9, 16]

Mean solar irradiation out of atmosphere, zero air mass – **AM0** (adopted values with 1% uncertainty):

$$\mathbf{1367}\ \mathrm{Wm^{-2}} = \mathbf{1960}\ [\mathrm{calcm^{-2}min^{-1}}] = \mathbf{432}\ [\mathrm{Btuft^{-2}h^{-1}}] = \mathbf{4{,}921}\ [\mathrm{MJm^{-2}h^{-1}}]$$

Mean solar irradiation at the sea level, air mass 1 – **AM1** (adopted by IEEE for solar load modelling):

$$\mathbf{747}\ [\mathrm{Wm^{-2}}] = \mathbf{1071}\ [\mathrm{calcm^{-2}min^{-1}}] = \mathbf{236}\ [\mathrm{Btuft^{-2}h^{-1}}] = \mathbf{2{,}689}\ [\mathrm{MJm^{-2}h^{-1}}]$$

Total solar radiation energy is distributed in different spectral regions as shown in Tab. 1, and Fig.1.

Thermo-optical properties of a surface (ε_s - emissivity, and α_s - absorption) depend on the material used (as illustrated in Fig.2) and determine the heat balance due to solar thermal load heating and radiation cooling.

Electro-optical system design has solar load thermal shield incorporated in the design. Shield thermal load is equal:

$$Q_{sl} = \alpha_s \cdot A_s \cdot M_{AM1}$$

where: Q_{sl}– shield solar thermal load, α_s – absorption, A_s – solar shield area and M_{AM1} – solar constant at sea level. In the worst case the solar thermal load at radiation shield is about 30 W, but a small part is transferred towards the system enclosure due to an insulation air gap.

Table 1: Spectral distribution of solar radiation

Spectral region (type of radiation)	Wavelength band [μm]	Relative contribution to total radiation [%]	
		AM0	**AM1**
Ultraviolet (invisible) - **UV**	0.29 to 0.38	**6**	**1.5**
Visible (**VIS**)	0.38 to 0.78	**45**	**54**
Near Infrared (N**IR**)	0.78 to 2.5	**43**	**43**
Far Infrared (**FIR**)	> 2.5	**6**	**1.5**

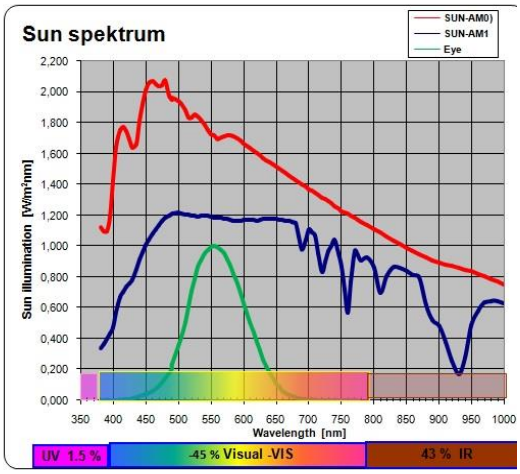

Figure 1: Sun radiation spectrum (adapted from [9])

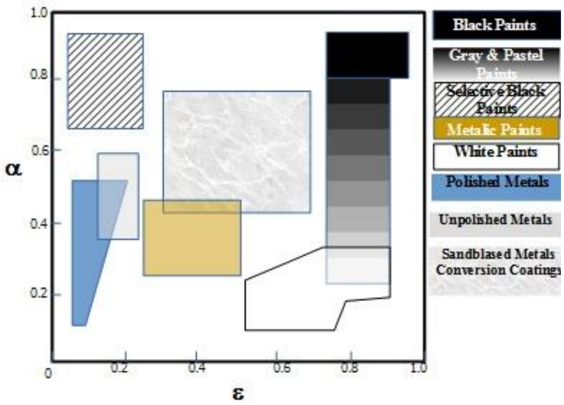

Figure 2: Emissivity and absorption ranges for common materials applied at surface [8]

2.2. Ambient temperature

Ambient conditions are defined for the anticipated environmental conditions (tropical climate), and characterized by air temperature and wind speed. Air temperature measurement results at the mission site during the hottest period are presented in Figure 3. Ambient temperature values recorded during the period of 19 days (24 hours a day) are in the range 24ºC to 25ºC. The higher value (25ºC) is selected to be used in the simulation.

2.3. Wind

Related wind measurement results are presented on Figure 4. Recorded wind speed values are in the range between 5 m/s to 8 m/s. Sensor head housing is partially exposed to the wind so we adopted value of the 4 m/s as parameter to be used in simulation. Heat transfer coefficient related to the selected wind speed is $\alpha = 25\ Wm^{-2}K^{-1}$. [10, 13]

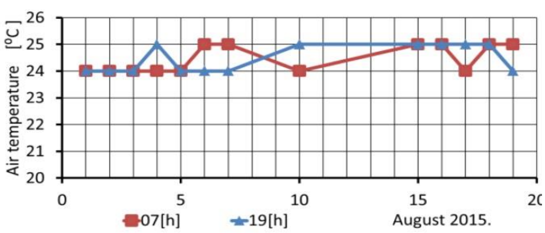

Figure 3: Ambient temperature profile at mission site

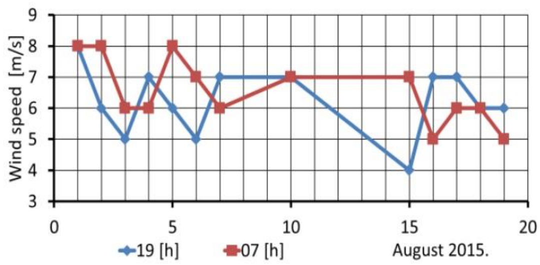

Figure 4: Wind speed measured at mission site during 19 days

3. Electro-optical unit structure and thermal properties of components

Design of the modern Electro-optical (E-O) unit is a multidisciplinary task. Specific design models are developed by specialized engineers. Design and analysis are conducted in parallel aiming to fulfill requirements. Therefore, the potential sensor-level design issues tends to occur relatively late in the design process, sometimes after the hardware has already been built. In addition, expensive and sensitive components are used and the design should be compact. The thermal influence analysis is very important due to application in harsh environment.

The most important E-O system part is the sensor head whose structure is presented in Figure 5. Heat sources are distributed in components as illustrated in Figure 5. At the same time these components are heat sensitive devices. Using built-in fans, generated heat is redistributed through housing and exchanged with environment through the heat convection process at the housing wall.

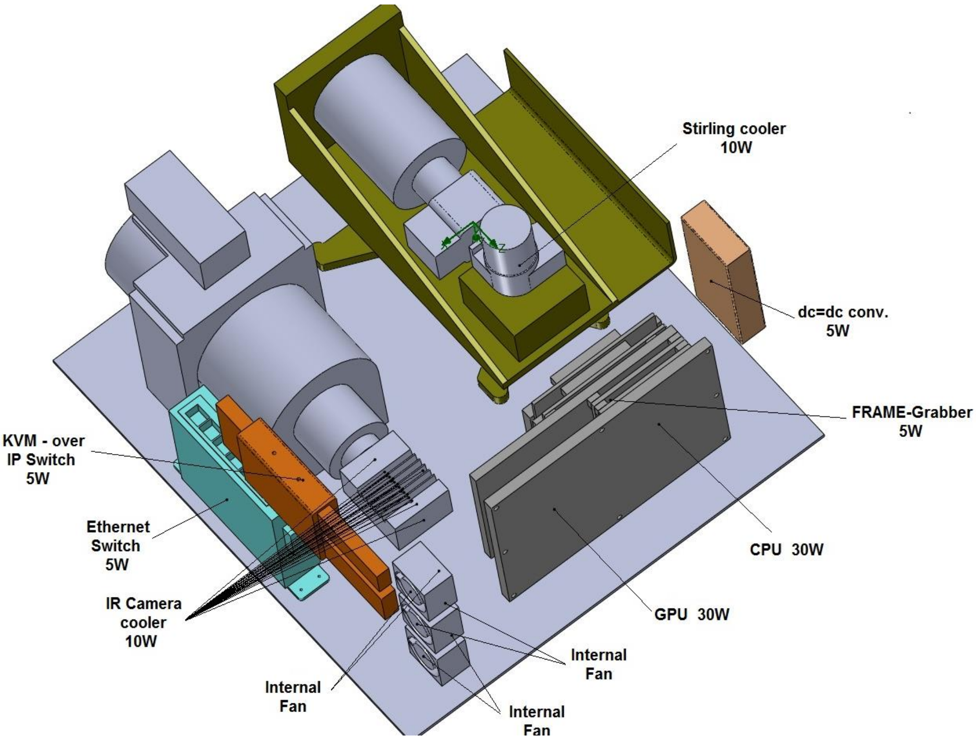

Figure 5: E-O sensor head structure and heat sources

The E-O sensor head key components, thermal load and boundary operation temperature values used in the modelling and evaluation process are summarized in Table 2.

Table 2: Thermal load and limiting operating temperature values of E-O sensor head key components

E-O sensor Head key components	Heat Load [W]	Limiting Temperature [ºC]
Stirling cooler compressor electromotor	10	50
Computer Central Processing Unit - CPU	30	50
Graphical Processing Unit - GPU	30	50
FRAME Grabber - Image processing Unit	5	50
IR Camera cooler	10	70
Video camera zoom motor	10	50
Other components	15	50

4. Thermal model description

Thermal process simulation is realized using numerical tools (finite elements and finite volume) incorporated in commercial software packages. Heat exchange inside housing through forced airstream have uneven velocity and temperature distribution, and accordingly uneven heat transfer coefficient. Heat exchange with environment is done through housing outer wall. The heat exchange coefficient is defined in accordance with the ambient temperature and wind conditions.

4.1 Heat exchange coefficients

Heat exchange coefficients between housing and environment are defined using data from [1, 10, 15, 17, 18], and experimental data (Figure 6.) from French and German Railway institute reports [13,14].We adopted extrapolated values as presented in Table 3.

Table 3: Heat exchange coefficient values versus ambient conditions

Ambient conditions	Heat exchange coefficient α [W/m^{2}K]
No wind	6
Wind speed 4 m/s	25

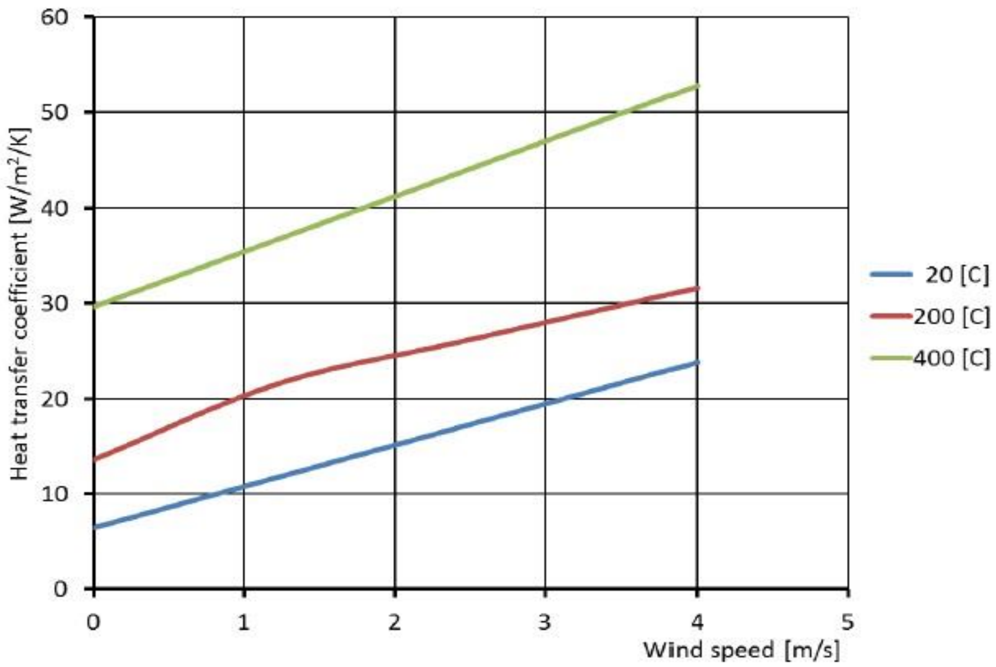

Figure 6: Heat exchange coefficient experimental values [13, 14]

4.2 Numerical simulation model

Using 3D CAD software, the detail E-O system model is defined. This model is simplified to be applicable for numerical analysis. The views of the detailed and simplified model are presented in Figure 7.

The space inside E-O sensor head housing is divided into 160764 finite volume elements. The finite volume mesh is illustrated in Figure 8. Simplified 3D model and finite volume mesh define analysis geometry.

Material thermal properties are outlined in Table 4. All metallic parts are treated as aluminum alloy 5052, and all other non-metallic parts (PCB, electronic parts and plastic housing parts) are treated the same way.

Table 4. Material thermal properties

Thermal property	Unit	Metallic parts	Non-metallic parts
Density	$[Kgm^{-3}]$	2680	1026
Specific Heat	$[Jkg^{-1} K^{-1}]$	921	1386
Thermal Conductivity at 20ºC	$[Wm^{-1} K^{-1}]$	140	10

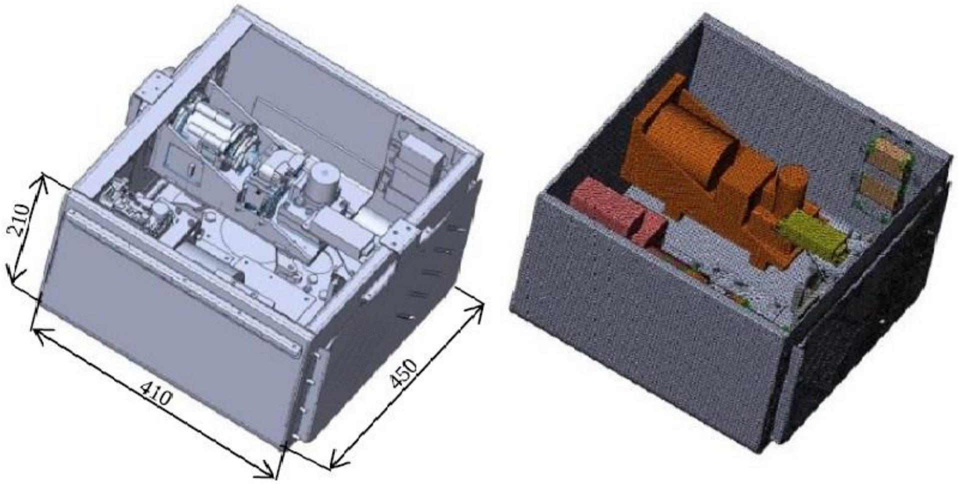

Figure 7: 3D model views: detailed (left) and simplified (right)

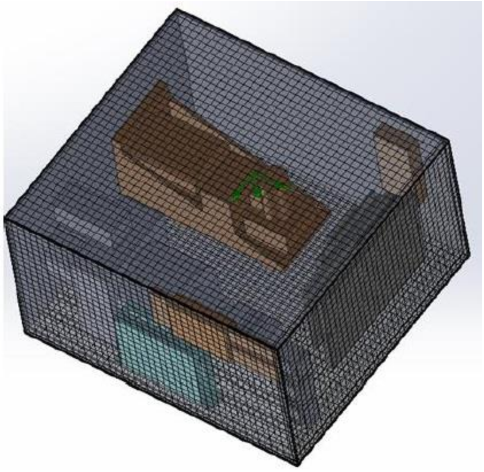

Figure 8: 3D finite volume mesh

5. Evaluation methodology and criteria

Evaluation of the electro-optical thermal system design is a part of the overall system design review process and has a very important role because the excess internal temperature distribution can lead to:

- ***System reliability*** (MTBF- Mean Time Between Failures) shortening some of critical components lifetime.
- ***Limited system functional performances*** due to lower performances of critical subsystem at elevated temperatures
- ***System damage*** or shutdown due to damage of some components at high temperatures.

Verification of the system thermal design could be done using several techniques [1] such as:

- ***Modelling***– defining system's thermal simulation model and temperature distribution and level over critical subsystem comparison with related and known threshold values. This approach is applied in this article.
- ***Measurement and testing*** – Measurements of the temperature at the selected critical components during system operation in simulated environmental environment.
- ***Real data analysis*** – Analysis of the data collected for temperature, environmental parameters and system operation during system field operation. This method is applicable in the case that the system is manufactured and deployed. The data collection should be well planned and carefully executed using predefined procedures. On one hand, this method provides the most accurate reliability data, but on the other hand, it is complex and costly. It is applicable for mature system aimed for long term application and can provide reliability data significant for system maintenance activities planning.
- ***Applied technology analysis*** – based on good knowledge (know-how) and similarity analysis based on knowledge about used thermal management technological solutions and/or similarity analysis with other systems using the same or similar solution.

The simplified system thermal modelling technique is selected as input for thermal evaluation. System damage and limited functional performances are not allowed, but some minor influences on system reliability parameter MTBF (Mean Time Between Failures) could be allowed. The analysis of the MTBF degradation could not be done in details, because E-O system uses components from other manufacturers that do not have sufficiently defined breakdown of the MTBF dependence on temperature. For completely accurate MTBF analysis we need to use detailed data at component level failure rate using defined methodology [11,12]. This analysis is out of the scope of this paper.

6. Thermal simulation results

A thermal shield is used to protect the sensor head from excess solar thermal load. Heat absorbed due to solar load, $Q_s=30\ W$, could be transferred to housing by radiative transfer, conduction through connection bars and air gap. The solar shield design provides that conduction through air gap (good insulation) and connection bars (small cross section) could be neglected. In the worst case, radiative transfer is $Q_r=Q_s\cdot\alpha\cdot\varepsilon \simeq 3$ W, that is lower than any other heat source, so we neglect solar load in further simulations.

Heat exchange inside housing is modelled using two interactive processes: determination of the velocity and temperature field distribution.

The example of the velocity and temperature field distribution for selected ambient conditions (temperature 25 ºC and wind speed 4 m/s) is presented in Figure 9.

Maximal temperature difference in the housing is about 10 ºC (computer region about 10ºC, thermal imager about 5 ºC, and about 7 ºC on the housing top area), meaning all component temperatures are under critical temperature limit.

Additional simulations were done for extreme ambient conditions. Results are presented in Fig. 10.

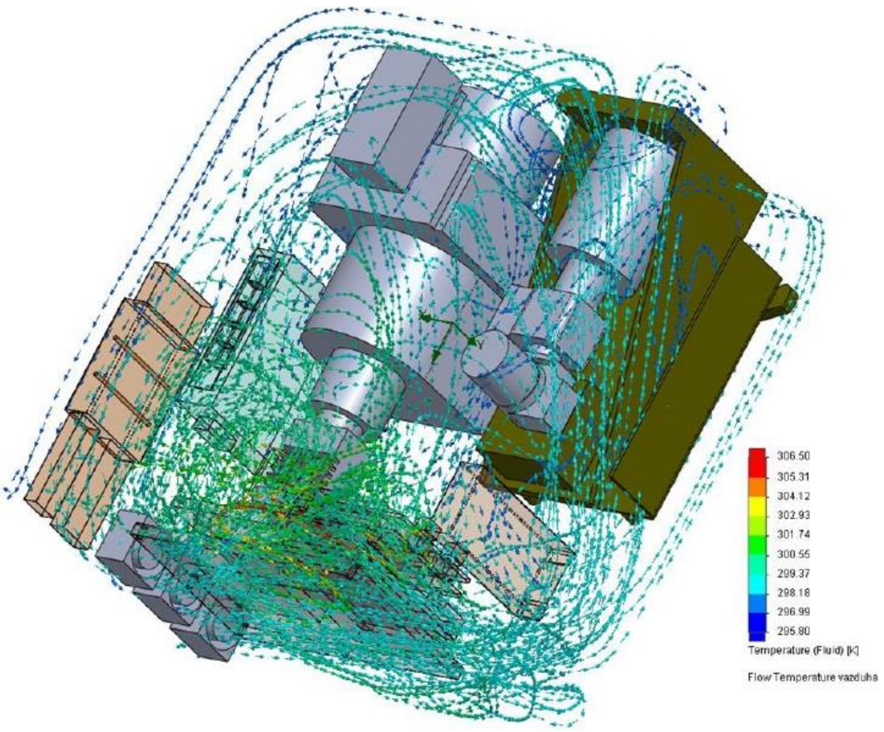

Figure 9: Simulation results: Temperature and velocity field for selected ambient conditions (25 ºC and 4 m/s)

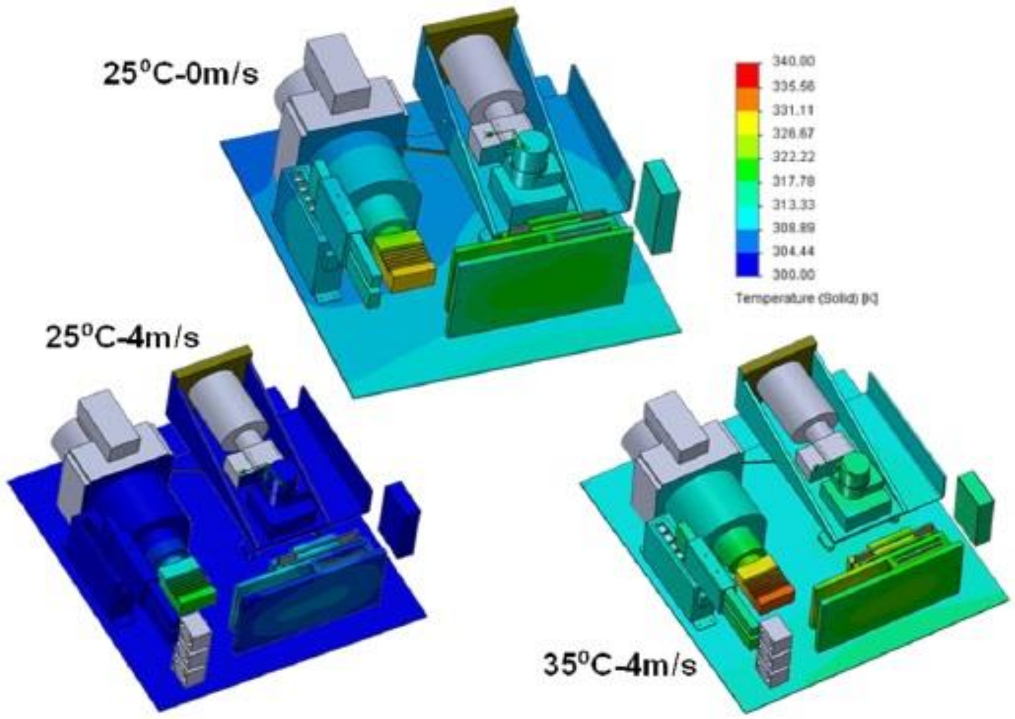

Figure 10: Additional simulation results: Temperature distribution for selected ambient conditions

The summarized review of the component average temperatures versus ambient temperature with 4 m/s wind speed is presented in Fig.11.

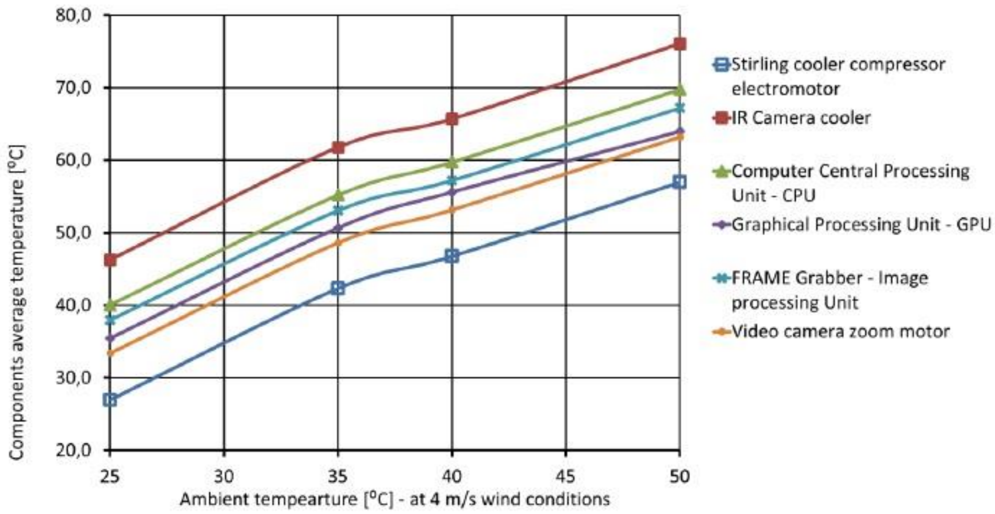

Figure 11: E-O sensor components average temperature versus ambient temperature at 4 m/s wind speed

7. Validation of thermal simulation results using field measurements data

During the field trials, ambient mean temperaure of 26 ^{0}C and wind speed of 3 m/s were registered. In the same time, temperature sensor built in housing had a readings of mean temperature of 36.5 ^{0}C.

Using these results we re-run model with corrected value of the heat transfer coeficient 19.5 $Wm^{-2}K^{-1}$ and different number of elements in the mesh. The resuilts are summarized in Table 5.

Table 5. The review of the calculation time and calculation error for selected calculation mesh elements

Number of elements	Calculation time	Average sensor temperature	Estimated error field vs. CFD
	[min]	[^{0}C]	[%]
74734	50	33.98	7,4
83321	60	34.33	6.3
160764	150	34.48	5,8
320838	420	34.50	5.6

8. Discussion

After analysis of the simulation data, representative data are presented. The E-O sensor head components have different temperatures, as expected. The highest temperatures are at the camera heat sink, central processing unit, graphical processor, image processor, and part of housing in vicinity of the computer unit. The lowest temperature is at thermal imager compressor. The common fact is that all components temperatures have nearly linear dependence on ambient temperature.

At normal operational conditions (25ºC, and 4 m/s), none of the components are having temperature higher than defined critical operational temperature. This yields to a conclusion that at normal operational conditions no deterioration of the system operation is expected. This could be stated even for ambient temperatures up to 32ºC.

The mesh density, which is used in calculation, has influence on calculation error. Higher the number of elements results in higher calculation accuracy (lower error). Acceptable calculation error of 5,6 % is achieved using 160764 elements with reasonable calculation time.

Since the components' manufactures did not specify threshold for damage caused by temperature, so we are not able to determine values of the ambient temperature that cause component and/or system damage.

According to mission site meteorological data collected for the worst heat load conditions, it is clear that all components in E-O sensor head / observation unit will work properly without damage or deterioration in reliability.

9. Conclusions

Using thermal analysis tools incorporated into 3D design and simulation package, accompanied by design model simplification and application of the finite elements and volumes approach, thermal processes inside E-O sensor head were analyzed. Under predefined environmental conditions on the mission site, E-O sensor thermal management is analyzed.

In the normal operation conditions no damage or performance deterioration is expected. It is expected that system will behave on the same way at ambient temperatures up to 32ºC.

It is shown that modern 3D simulation software and built in analysis tools could be successfully applied to thermal management analysis of complex opto-electronic systems using reasonable 3D model simplifications. In addition, more data regarding components thermal behaviour, will allow more detail thermal management analysis. As one of our future challenging tasks we will consider analysis of ambient thermal conditions influence on the system reliability parameter – MTBF.

Acknowledgement: VLATACOM support during this work is appreciated. We are thankful to prof. Branislav M. Todorović for continuous help in preparing this paper.

References

[1] Anandan S. S., Ramalingam, V., Thermal Management of Electronics: A Review of literature, *Thermal Science*: *12* (2008), 2, pp. 5-26

[2] Shende D. M., Mahalle A., Cooling Of Electronic Equipment with Heat Sink: A Review of Literature, *IOSR Journal of Mechanical and Civil Engineering(IOSR-JMCE), 5*, (2013), 2, pp. 56-61

[3] Remsburg R., *Thermal design of electronic equipment*, CRC Press LLC, Boca Raton, Florida 33431, USA, 2001

[4] Jamnia A., *Practical Guide to the Packaging of Electronics: Thermal and Mechanical Design and Analysis*, Marcel Dekker Inc., New York, USA, 2003

[5] Kreith F. (Editor), *The CRC handbook of thermal engineering*, CRC Press LLC, Boca Raton, Florida 33431, USA, 2000

[6] Wankhede M., Khaire V., Manhandar A., Mahajan S.D., Evaluation of Cooling Solutions for Outdoor Electronics, *Proceedings of 13th International Workshop on Thermal Investigation of ICs and Systems (THERMINIC),* Budapest, Hungary, 2007, pp. 162-167

[7] Heindenen R., Karjalaihen M., Lankinen R., *Verification of the thermal design of electronic equipment*, VTT publication 320, VTT Technical Research Centre of Finland, 1997

[8] ASHRAE – American Society of Heating, Refrigerating and Air-Conditioning Engineers, *IT Equipment Thermal Management and Controls*, ASHRAE technical report, TC 9.9, USA, 2012

[9] (Ed. Zissis G.), *The Infrared and Electro-Optical Systems Handbook, Vol 1. "Sources of Radiation"*, SPIE Optical Engineering Press, Bellingham, Washington, 1993

[10] Hsu, C.-N., et al., Heat Transfer and Structure Stress Analysis of Micro Packaging of micro packaging component of high power light emitting diode, *Thermal Science*, *17*(2013), 5, pp. 1277-1283

[11] MIL-HDBK-338B – *Electronic Reliability Design Handbook*, US Department of Defence, USA, 1998

[12] MIL-HDBK-217F – *Reliability Prediction of Electronic Equipment*, US Department of Defence, USA, 1991

[13] ORE B 106/RP 12, *Standardisation of coaches, Standardisation of a block-bracked solid wheel (tread diameter 920mm) for coaches with a top speed of 160 km/h*, Basic calculations, Utrecht, 1989

[14] ERRI B 169/RP 8, *Standardisation des essieux Determination de la tenacite des rouesmonoblocen R7, Definition d` unemethoded`essai et d` un critered`acceptation*, (engl. Determination of toughness of mono block wheel R7, Definition a method of calculation and acceptation criteria),Utrecht, 1995

[15] Wang T., Ma S., TEG heat performance study about improved fin structures, *Thermal Science,* published online: 2016-04-09, DOI:10.2298/tsci150801064w

[16] Fok S.C., Tan F.L., Sua C.C., Experimental investigations on the cooling of a motorcycle helmet with phase change material, *Thermal Science*, 15(2011), 3, pp. 807-816

[17] Hsu C.-N., Chang Y.-H., Liu, C.-Y., Fang S.-H., Huang C.-C., Heat transfer and structure stress analysis of micro packaging component of high power light emitting diode, *Thermal Science*, 17(2013), 5, pp. 1277-1283

[18] Sivasankaran H., Asirvatham G., Bose J., Albert B., Experimental analysis of parallel plate and crosscut pin fin heat sinks for electronics cooling applications, *Thermal Science*, 14(2010), 1, pp. 147-156