Effect of wood modification and weathering progress on the radiation emissivity

Paolo Grossi[1], Jakub Sandak[2,3,4], Marta Petrillo[5] and Anna Sandak[6]

[1]CNR-IVALSA, via Biasi 75, 30010 San Michele all'Adige, Italy [email: grossi@ivalsa.cnr.it]
[2]InnoRenew CoE, Livade 6, 6310 Izola, Slovenia [email: Jakub.Sandak@innorenew.eu]
[3]CNR-IVALSA, via Biasi 75, 30010 San Michele all'Adige, Italy [email: sandak@ivalsa.cnr.it]
[4]University of Primorska, Faculty of Mathematics, Natural Sciences and Information Technology, Glagoljaska 8, 6000 Koper, Slovenia
[5]CNR-IVALSA, via Biasi 75, 30010 San Michele all'Adige, Italy [email: petrillo@ivalsa.cnr.it]
[6]CNR-IVALSA, via Biasi 75, 30010 San Michele all'Adige, Italy [email: anna.sandak@ivalsa.cnr.it]

Keywords: emissivity, modified wood, thermography, thermal images, weathering, heat transfer

ABSTRACT

The research reported here is a part of the BIO4ever project, which aims to develop numerical models simulating performance of the bio-based cladding materials in relation to the exposure time or so-called "weather dose". The value of emissivity is one of the thermodynamic material constants, highly affecting heat transfer calculations. The lack of reliable emissivity data for several investigated materials was discovered during model's preparation, especially in a case of modified woods and coated samples. It was especially important since the emissivity is directly affecting the surface state/condition, and might change due to the weathering process. The overall objective of this research was therefore to determine actual emissivity coefficients for diverse cladding materials (various wood species and modification processes) in different ambient conditions (temperature).

The thermographic (radiometric) measurements were conducted with the thermal camera FLIR T200, covering a spectral range from 7.5 to 13 µm. Tests were carried out on preselected samples to highlight the differences between diverse materials. The emissivity coefficient was determined at different surface temperatures by conditioning samples in climatic chambers for a period of at least six hours. The emissivity values obtained experimentally were used for improvement of finite element method models of the solar irradiation and of the surface moisture content changes for all investigated bio-materials. Subsequently, simulation of the façade appearance implemented within BIO4ever project, considering simultaneously time of service, geographic location, local microclimate and intrinsic material characteristic, become more realistic and trustworthy.

INTRODUCTION

Infrared thermography is a non-destructive and non-contact testing method that is applied in building physics to evaluate structure's energetic performance (Barreira *et al*. 2016). The technology is especially interesting nowadays when infrared measuring instruments become portable and affordable, being reasonably accurate at the same time (Sandak and Sandak 2017). The emissivity (material property), is defined as an amount of electromagnetic energy radiated from the material's surface to that radiated from a blackbody. The emissivity is usually defined in two spectral bands, including solar (short wavelength λ <2.5µm) and ambient (long wavelength λ >2.5µm) ranges. The usual procedure of emissivity estimation bases on the measurements of a single sample conditioned to the thermodynamic equilibrium (heating or cooling) with the surrounding ambient (Pitarma *et al*. 2016). The main disadvantage of this procedure is relatively long time that elapses before the thermal image readings, especially when the difference of temperature between the sample and the ambient is high.

In alternative, the emissivity can be determined according to ASTM1933 standard, using a radiometer (IR camera, spot IR thermometer) with two complementary methods, namely "contact thermometer method" or "noncontact thermometer method". The first method requires a direct measurement of the target surface temperature through a contact thermometer. This measurement became the reference value used to manually adjust the settings of the radiometer (first iterative step). The material specific value of emissivity is properly adjusted when equal temperatures are determined by both reference thermometer and radiometer. The second method bases on an emissivity value correction by comparing instrument readings with these performed on reference material. It is important to assure that both, reference and characterized materials are at the thermal equilibrium. The reference temperature is determined with reference material, considering its known emissivity and specific boundary conditions. In the second step, the radiometer settings are adjusted to correct the apparent temperature according to the value of reference surface temperature. Both methods are considered to have a good precision and reproducibility.

The research reported here is a part of the BIO4ever project, which aims to develop numerical models simulating performance of the bio-based cladding materials in relation to the exposure time or so-called "weather dose". The emissivity is one of the thermodynamic material properties (constants) used for heat transfer calculations. The lack of real emissivity data for several investigated materials was discovered during FEM (finite element method) model's preparation, especially in a case of modified woods and coated samples. The motivation for this research was therefore to experimentally determine real emissivity coefficients for diverse cladding materials (various wood species and modification processes) in different ambient conditions (temperatures).

EXPERIMENTAL

Experimental samples

Twenty different cladding materials investigated within BIO4ever project were selected as experimental samples (Table 1). The set included natural, thermally modified, chemically modified, impregnated, coated, surface treated wood and bio-based composites.

Experimental set-up

The setup of experimental determination of emissivity coefficient is presented in Figure 1. A thermal IR camera (FLIR T200) with a 240×180 pixels resolution with a shutter time of 100ms was used to acquire the thermal images. The camera was fixed on a tripod and exposed in the front of a sample holder (made of polyester box), minimizing infrared reflections from surround. The spectral range of the IR camera covered 7.5 to 13μm. The measurable temperature range was from -20 to 350°C, with a producer declared accuracy of ±2%. The thermal sensitivity (smallest temperature difference measurable) at 30°C was <0.08°C. The vision angle of used lenses was 25° with a minimum focusable distance between the object and the camera of 0.4 m.

Table 1: Materials investigated within this research

Sample#	Species	Material category (modification)						
		natural	composite	thermal	chemical	impregnated	surface	hybrid
A1	larch	●						
A2	scots pine					●		
A3	bamboo	●						
A4	frake			●				
A5	acetylated fiberboard		●					
B1	spruce			●				
B2	bamboo	●						
B3	acetylated fiberboard		●					
B4	radiate pine						●	
B5	bamboo fiberboard		●					
C1	pine				●			
C2	spruce					●		
C3	WPC		●					
C4	larch						●	
C5	larch	●						
D1	spruce							●
D2	pine							●
D3	spruce						●	
D4	radiate pine				●			
D5	beech					●		

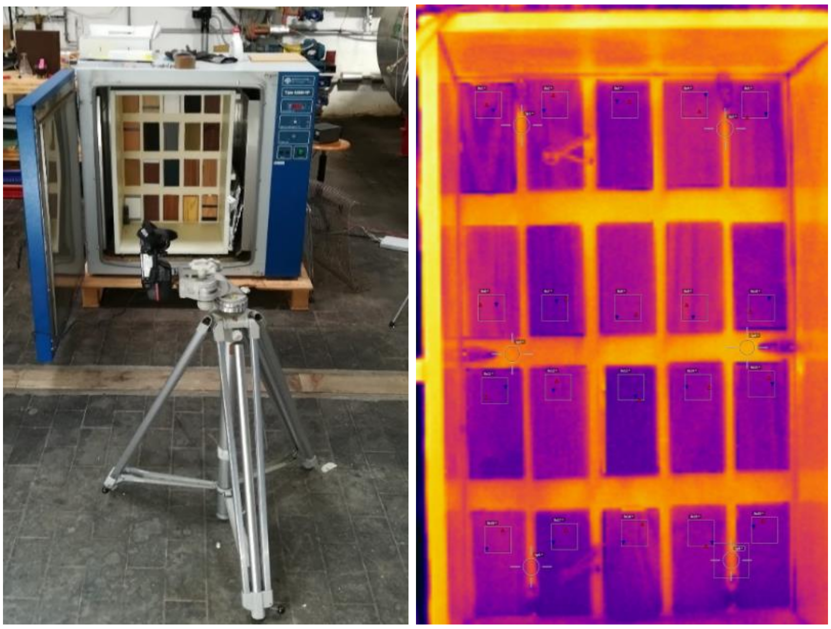

Figure 1: FLIR T200 thermal camera test setup (left), thermal image result of a test (right).

Calculations

The electrical signal recorded by the camera was transformed into a temperature value according to Equations 1, 2 and 3. The total radiation received by the camera (W_{tot}) can be expressed as the sum of the radiation emitted by the object (E_{obj}), radiation reflected by surroundings (E_{refl}) and the emission of the atmosphere (E_{at}).

$$W = E_{obj} + E_{refl} + E_{at} \qquad (1)$$

$$W_{tot} = \varepsilon_{obj} \cdot \sigma \cdot {T_{obj}}^4 \cdot \tau_{at} + \left(1 - \varepsilon_{obj}\right) \cdot \sigma \cdot {T_{refl}}^4 \cdot \tau_{at} + (1 - \tau_{at}) \cdot \sigma \cdot {T_{at}}^4 \qquad (2)$$

$$T_{obj} = \sqrt[4]{\frac{W_{tot} - \left(1 - \varepsilon_{obj}\right) \cdot \tau_{at} \cdot \sigma \cdot \left(T_{refl}\right)^4 - (1 - \tau_{at}) \cdot \sigma \cdot (T_{amb})^4}{\varepsilon_{obj} \cdot \tau_{atm} \cdot \sigma}} \qquad (3)$$

where; ε_{obj} is the target emissivity, T_{refl} is the reflected temperature, T_{amb} is the ambient temperature, T_{at} is the transmittance of the atmosphere, σ is the Stefan Boltzman constant.

The energy emission from the object and the reflected radiation detected by the sensor is reduced because the atmospheric air absorbs a part of the radiation. The effect of the atmosphere on the signal is compensated when setting of temperature (T_{amb}), considering also relative humidity of the air and distance between target and camera.

Testing procedure

The set of 20 samples was conditioned at different temperatures in two environments; low temperature (-2.5°C) in a refrigerator and the high temperature (35.0°C) in a laboratory oven. The reference temperatures in both climatic chambers were assessed with different thermometers. Six DHT22 sensors measuring temperature and relative humidity and two MLX9014 infrared thermometers were placed in diverse positions over the sample holder box. It was possible therefore to determine detailed temperature gradient (reference sample temperature) within the camber after sample conditioning. Signals from sensors were acquired with Arduino controller and post-processed on the PC. The software used for thermal images analysis was FLIR Reporter.
The raw thermometric image was acquired using value of emissivity $\varepsilon = 1.00$. The real value of ε was determined according to Equation 4 on the base of information collected by the thermal camera and temperature sensors.

$$\varepsilon_{obj} = \frac{{T_{obj,r}}^4 - {T_{amb}}^4}{{T_{obj}}^4 - {T_{amb}}^4} \qquad (4)$$

where. $T_{obj,r}$ - the sample surface temperature from the thermal image at $\varepsilon = 1.00$, T_{obj} - the reals surface temperature of conditioned samples measured by the nearest thermometer, T_{amb} - the temperature of the ambient measured close to the thermal camera.

RESULTS AND DISCUSSION

The summary of experimentally determined values of emissivity ε is presented in Table 2. Five independent tests were conducted at each ambient condition in order to improve statistical reliability of ε values computed. The variations within measurements were related to the limited accuracy of IR thermal camera as well as to the uncertainty of the

reference temperatures of the evaluated samples surface. The latest temperature was measured as close as possible, but anyway not directly on the sample surface.
It is evident from the results obtained that the emissivity ε values are different for all cladding materials characterized. In the extreme cases the value of ε ranged from 0.84 (material A4 – thermally modified frake) to 0.96 (material C3 – wood-plastic composite).

Table 2: Emissivity ε of bio-based materials conditioned in diverse climatic conditions

Material	**temperature T_{amb} = -2.5°C**						**temperature T_{amb} = 35.0°C**					
	Test #1	**Test #2**	**Test #3**	**Test #4**	**Test #5**	**Mean**	**Test #1**	**Test #2**	**Test #3**	**Test #4**	**Test #5**	**Mean**
A1	0.90	0.92	0.93	0.94	0.91	**0.92**	0.92	0.91	0.95	0.92	0.89	**0.92**
A2	0.93	0.90	0.92	0.90	0.89	**0.91**	0.88	0.88	0.91	0.89	0.87	**0.89**
A3	0.93	0.92	0.93	0.91	0.91	**0.92**	0.90	0.90	0.93	0.93	0.89	**0.91**
A4	0.88	0.88	0.88	0.87	0.86	**0.87**	0.86	0.88	0.9	0.88	0.87	**0.88**
A5	0.89	0.91	0.91	0.89	0.88	**0.90**	0.88	0.93	0.92	0.89	0.89	**0.90**
B1	0.91	0.89	0.90	0.88	0.89	**0.89**	0.88	0.89	0.91	0.89	0.88	**0.89**
B2	0.96	0.95	0.95	0.94	0.93	**0.94**	0.92	0.93	0.95	0.93	0.91	**0.93**
B3	0.90	0.92	0.91	0.90	0.91	**0.91**	0.90	0.92	0.91	0.9	0.88	**0.90**
B4	0.89	0.90	0.91	0.89	0.90	**0.90**	0.90	0.92	0.89	0.88	0.89	**0.90**
B5	0.92	0.94	0.94	0.93	0.94	**0.94**	0.91	0.93	0.94	0.93	0.9	**0.92**
C1	0.95	0.93	0.94	0.92	0.93	**0.94**	0.92	0.92	0.94	0.93	0.89	**0.92**
C2	0.93	0.92	0.93	0.91	0.90	**0.92**	0.91	0.93	0.92	0.89	0.88	**0.91**
C3	0.97	0.97	0.95	0.96	0.96	**0.96**	0.94	0.92	0.95	0.95	0.92	**0.94**
C4	0.93	0.94	0.95	0.93	0.94	**0.94**	0.93	0.94	0.93	0.9	0.91	**0.92**
C5	-	0.94	0.94	0.93	0.94	**0.94**	0.91	0.93	0.91	0.91	0.9	**0.91**
D1	0.91	0.90	0.91	0.90	0.89	**0.90**	0.90	0.92	0.92	0.9	0.89	**0.91**
D2	0.97	0.95	0.93	0.94	0.93	**0.94**	0.92	0.92	0.94	0.93	0.91	**0.92**
D3	0.93	0.92	0.91	0.90	0.91	**0.91**	0.89	0.89	0.9	0.9	0.88	**0.89**
D4	0.89	0.90	0.90	0.90	0.88	**0.89**	0.89	0.89	0.9	0.89	0.88	**0.89**
D5	0.91	0.91	0.91	0.91	0.89	**0.91**	0.90	0.90	0.9	0.9	0.89	**0.90**

It has to be mentioned that IR camera detects infrared radiation emitted not only by the target object but also related to other sources of heat, such as neighbor objects in the measurement field and/or ambient (FLIR T200 user manual (2009). The infrared radiation can be easily reflected from the sample surface into direction of the camera falsifying measurements (Olson and Talghader 2012). The measured temperature may be highly inaccurate when the operator cannot eliminate (or at least minimize) the influence of such external IR radiation sources. The same is related to the proper setting the emissivity ε (López *et al*. 2013). It is even more essential when physical modeling of heat and mass transfer within biomaterials is simulated. The availability of experimentally determined ε allowed improvement of the FEM models and better representation of the temperature distribution over the building façade as studied within BIO4ever project.
Nevertheless, in several practical applications, such as monitoring of electric connectors/fuses or detecting thermal bridges (moisture spots) in building, the exact value of temperature gradients is not critical. In that case, even tabular values of emissivity may be sufficient for successful qualitative assessments.

CONCLUSIONS

The value of emissivity measured and calculated experimentally for different cladding materials are within the ε range reported in the scientific literature (emissivity of natural wood usually varies from 0.85 to 0.95 according to different authors). Nevertheless, the experimental results revealed noticeable differences in samples of the same wood species but modified with different processes. The emissivity parameters obtained experimentally are essential for precise numerical modelling of the solar radiation and of the moisture content changes in all investigated bio-materials. Consequently, more realistic simulation of the façade appearance and its aesthetical changes become possible (the overall goal of the BIO4ever project).

ACKNOWLEDGEMENTS

The BIO4ever (RBSI14Y7Y4) is ongoing project funded within a call SIR (Scientific Independence of young Researchers) by MIUR. The authors gratefully acknowledge the European Commission for funding the InnoRenew CoE project (Grant Agreement #739574) under the Horizon2020 Widespread-Teaming program.
Special acknowledgments to COST FP1303, COST FP1407 and COST TU1403 for networking opportunity and funding STSMs that contributed to the project and to all BIO4ever project partners.

REFERENCES

American society for testing materials (2005). Standard test methods for measuring and compensating for emissivity using infrared imaging radiometers (E1993-99a)

Barreira, E., Almeida, R.M.S.F. and Delgado, J.M.P.Q. (2016). Infrared thermography for assessing moisture related phenomena in building components, Construction and Building Materials, **110**, 251-269.

FLIR T200 user manual (2009) Publ. No. 1558792 Rev. a379 – English (EN)

Olson, K.D. and Talghader, J.J. (2012). Absorption to reflection transition in selective solar coatings, *Opt. Express* **20**, A554-A559

López, G., Basterra, L.A., Acuña, L. et al. J *(2013)*. Determination of the Emissivity of Wood for Inspection by Infrared Thermography. *J. Nondestruct Eval*. **32**(2), 172-176.

Pitarma, R., Crisóstomo, J. and Jorge L. (2016). Analysis of Materials Emissivity Based on Image Software *New Advances in Information Systems and Technologies. Advances in Intelligent Systems and Computing,* **444**, 749-757.

Sandak, J. and Sandak, A. (2017). Using various infrared techniques for assessing timber structures. *International journal of computational methods and experimental measurements*, **5**(6), 858–871.