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HYGROTHERMAL BEHAVIOUR OF ENVELOPE ELEMENTS AN OVERVIEW OF ITS DETERMINATION *IN-SITU*

BY

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Abstract. In the current context – where climate change has become not only a certitude but also, according to several studies, even irreversible – the mitigation of the negative impact of human niche on the environment has become an absolute value in the underlying systems of value within human society. The accelerating rhythm of climate transformations suggests that the global scientific society has been taken by surprise.

In the field of civil constructions, responsible for a significant amount of gas with greenhouse effects – caused by both the energy input for their exploitation and the energy embodied in their execution – substantial efforts have been made lately in order to implement the principles of sustainable development. To this end, complex material and compositions were designed, to obtain higher energetic efficiency levels.

Whereas the building materials are assessed before the execution, their behaviour in situ has not been analysed most of the times. Furthermore, the analysis methods are limited and they involve long-term monitoring processes.

The paper proposes a synthesis of the analysis methods of the hygrothermal behaviour of the systems of envelope *in-situ*.

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Keywords: energetic efficiency; envelope elements; hygrothermal behaviour; experimental determinations *in-situ*; numerical modelling.

1. Introduction

In the year 2019, the day humanity exceeded the available resources for the current year was July 29 (https://www.footprintnetwork.org/), which means that in the last five months of the year, people are using resources meant for the years to come. The negative impact of the human niche upon the planet has becomes a fact. Although at the highest political levels, there are still denials of the anthropic causes for climate change and although even some scientists deny the role of people in climate change, the evidence showing that the industrial development of human species led to the sometimes-disastrous situation of the present has been multiplying.

In the last five decades, consistent efforts have been made to mitigate the negative impact on the environment, while sustainable development with its three elements – social, economic and environmental – has accumulated enough information for it to be considered a science. Hence, sustainable development governs most levels of human society management, thus the field of civil engineering, too. The application of sustainable development principles in this field has pushed human society towards a third industrial revolution, to a reality where alternative energies are the ones setting society in motion (Rifkin, 2011).

In what regards the current concept of a civil building, it has changed significantly from the 70s. Currently, the required energetic efficiency levels are very high, accompanied by dramatically reduced levels of embodied energy. Increased energetic efficiency of buildings was possible by using performing materials in terms of thermal conductivity, which has generated a highly dynamic thermal insulation market, currently in full bloom. Thus, new materials have emerged, as well as complex systems of envelopes. Though in most economic systems of the planet, the materials used for execution are tested beforehand, their behaviour during the exploitation has been little analysed; in-situ measurements are actually scarce. Furthermore, the combined mass and heat transfer, as well as other environmental factors affect the properties of materials within the layers of envelope elements. There may be significant differences between the designed situation – that considers the hygrothermal properties of the materials, declared and agreed upon – and the real transfer phenomena. It may be concluded that the behaviour of the envelope elements over time must be assessed, mostly through measurements performed in-situ.

This article is the result of the research part of the published literature necessary to design the experimental stand for the research project "Researches to improve the hygrothermal behaviour of energy efficient buildings

<ECOKIT>", within the project "Eco-innovative Products and Technologies for Energy Efficiency in Construction" EFECON”, MySMIS code: 105524, ID: P_40_295.

It has been noticed that during the design phase for the experimental stand, issues may emerge when choosing the measurement method and the sensors or acquisition units used. In addition, the improvement of in-situ measurements using numerical modelling involves choosing the right software. Thus, it is necessary to know all measurement methods, temperature, relative humidity and thermal flux sensors available on the market, acquisition units and software available.

The paper proposes a comprehensive synthesis of in-situ measurements featured in the scientific literature, as well as a presentation of the offers for measurement sensors, acquisition units and numerical modelling programs.

The purpose of the current paper is to introduce young researchers to the field of in-situ measurements and to facilitate the design of the experimental stand needed, by reducing the time necessary to choose the elements comprising it.

2. Brief Description of the Research Project

Within the research project "Researches to improve the hygrothermal behavior of energy efficient buildings <ECOKIT>", private partner S.C. ECOKIT S.R.L. wanted to obtain information on the hygrothermal behavior of the envelope elements of the buildings in the company's portfolio, in order to intervene on them for obtain efficient levels of energy efficiency and to eliminate condensation risk areas.

ECOKIT S.R.L. is a company that produces buildings with wooden box structure. The infrastructure of the proposed buildings consists of continuous or isolated foundations of reinforced concrete, and the superstructure of timber framing walls, the floors being also of timber frame panels. The insulation used generally is made of mineral wool, rigid or in the form of a mattress, in the case of the walls and the upper floor, respectively extruded polystyrene for the lower floor.

The project involves four stages of development, namely the acquisition of a device for measuring the thermal conductivity in variable regime of the thermal flux ISOMET 2114; the research of the published literature in order to design the experimental stand; carrying out measurements in order to determine the hygrothermal behavior of the envelope elements; dissemination of results.

The information gathered after completing the second stage of the project, namely the research of the published literature, was organized and disseminated in the present article, the authors intention being to provide a tool to the young researchers.

3. Analysis Methods Based on *In-Situ* Acquisition Data

3.1. Determining Unidirectional Specific Thermal Resistance Using the Flux Meter Method

This method involves the use of sensors for the continual measurement of superficial, indoor and outdoor temperatures and of the thermal flux.

The method is standardised (Latif *et al*., 2011; SR EN 1934:1998) and it consists in reporting the measured intensity of the thermal flux to the measured difference in temperature:

$$R = \Phi_t/\Delta_t, \quad [\mathrm{m^2 \cdot K/W}], \tag{1}$$

where: R is the unidirectional specific thermal resistance of the element; Φ_t – intensity of the thermal flux, [W/m^2]; Δ_t – difference between the temperatures measured for the interior and the exterior surfaces of the element, [K].

It is worth noting that it is very important for the thermal flux to enter the stationary transfer regime. It has been observed that, due to the use of thermal insulations with ever-greater thicknesses, the thermal flux enters in stationary transfer regime only in case of long-term great temperature differences, of over 72 hours. Consequently, it is recommended for the measurements to be conducted during the cold season, when temperature is low both during the day and during the night. Outside this period, the thermal flux has a chaotic behaviour, as it is influenced by many factors, from alternating heating cycles to direct sun radiation, which leads to an increase in the temperature of outer surface.

3.2. Measuring Temperatures on the Outer Surface Using IR Cameras

This method is used both to identify the thermal bridges and – using devices that are more recent – to assess liquid water accumulation in the layers of envelope elements. The identification of thermal bridges, as well as their thermal insulation level is very important because it provides a clear image about how to correct unidirectional specific thermal resistance. It is mentioned that even for processing thermal bridges from the project phase to the execution phase, inconsistencies may appear, which leads to lower thermal resistances in-situ than the ones designed.

The images reprised in the IR spectrum may be processed using special software programs, thus it can be extracted temperature variation graphs along a line or weightings for each temperature separately from the image overall, Fig. 1. (https://www.fluke.com/en-us/products/fluke-software/connect, http://www.ntcexpert.ru/documents/IRSoft_IM_0970_0805_en_08.pdf).

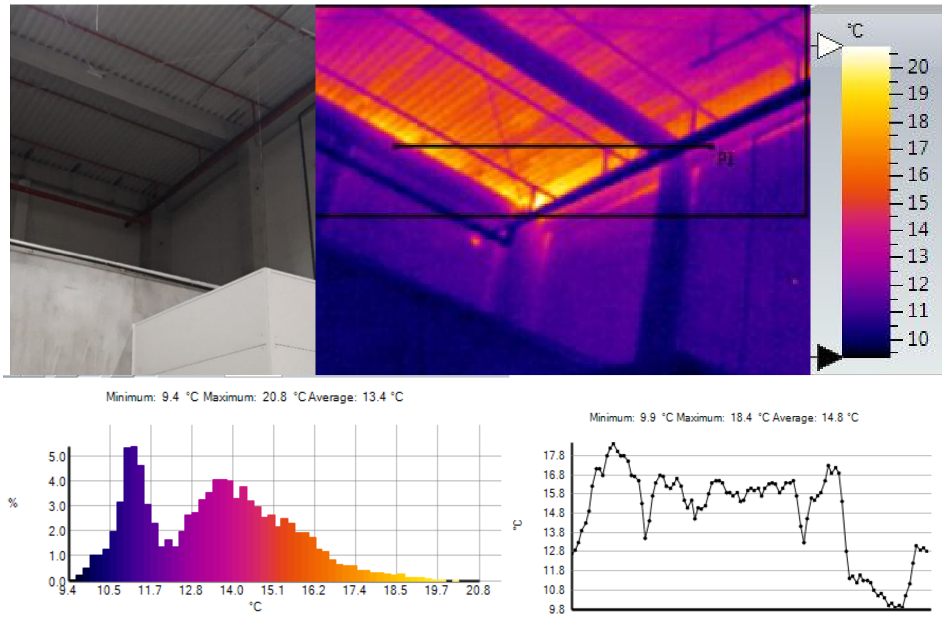

Fig. 1 **–** Image in luminous spectrum – upper left, Image in IR spectrum – upper right
Image processing – down

3.3. Measuring the Thermal Conductivity of the Materials by Extracting Samples and by Using Laboratory Devices

It involves extracting material samples and measuring their status parameters in the laboratory. In this respect, one may use thermal conductivity measurement devices in stationary regime, such as those using the method of guarded hot plate (SR EN 12664:2001, SR EN 12667:2001).

In addition, in order to determine the relative humidity of the materials, thermobalances may be used. They are designed for measuring the relative humidity in a controlled environment. To this end, the samples are sealed with foil shortly after extraction to preserve the relative humidity unaffected by the environment.

3.4. Measuring the Thermal Conductivity of the Materials *In-Situ* by Using Portable Devices

The method involves the direct measuring of the thermal conductivity by using portable devices. These measuring devices function in a transitory regime of the thermal flux. The most commonly featured device in the scientific literature is ISOMET, currently at the 2114 model (Fig. 2) (https://www.appliedp.com/download/manual/isomet2114_ug_en.pdf).

This is a portable measuring tool for direct measurements of the thermal properties for a wide array of building materials including both rigid thermal insulations and less rigid ones, plastic, glass, wood and minerals. It is endowed with various types of sensors, as follows: needle sensors for the less rigid materials and surface sensors for highly rigid materials. It is based on a method of thermal flux measurement in variable regime, which reduces the duration of measuring thermal conductivity to 10,...,16 minutes, advantageous because it does not have a significant influence on humidity.

The device may be used for measuring the thermal conductivity with values ranging between 0.015,...,6.00 W/mK and volumetric heat capacity with values ranging between 4.00 × 104 – 3.00 × 106 J/m3K, with an array of temperatures between –20 and +70ºC. The errors introduced range between 5,...,10% for measuring the thermal conductivity and 15% for determining volumetric heat capacity.

Fig. 2 – Measuring device ISOMET 2114.

4. Sensors Used for In-Situ Measurements and Data Acquisition Units

In the measurements conducted in-situ, sensors are used for measuring temperature, relative humidity and thermal flux intensity.

4.1. Thermocouples

Thermoelectricity represents the emergence of electrical power in a closed circuit, comprising two different metals, while maintaining their junction points at different temperatures. Each thermoelectric circuit is characterized by a certain thermo-electromotor tension (t.e.m.t.), on which the size of the power crossing the circuit depends. A pair of conductors bound in such a way as to produce a t.e.m.t., when their junctions are at different temperatures, was called a thermocouple. Within an illustration of this circuit (Fig. 3,) the power will circulate from metal A to B, crossing first of all the colder junction. In this case, it is stated from a thermoelectric perspective, metal A is positive, in relation with metal B (https://physics.uvt.ro/~stef/Metode/S3-Termocuplul.pdf).

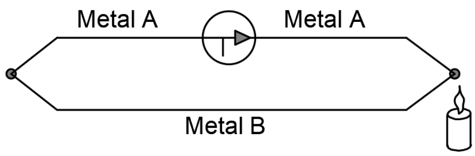

Fig. 3 – The Seebeck effect.

The most common combinations of conductors used in the manufacturing of thermocouples were ascribed three literal names; hence, the following thermocouples are worth noting: **S (**90 % Platinum (Pt) – 10 % Rodiu (Rh)**), R (**87 Pt–13 Rh/Pt**), J (**iron/constantan thermocouple**), T (**copper/constantan thermocouple**), K (**chromel/alumel thermocouple**), E (**chromel/constantan thermocouple**)**. In civil engineering, J, T, K thermocouples are used.

Type J thermocouple.

They are designed for industrial thermometry. The typical representative is the iron/constantan thermocouple. However, the iron for the thermocouples contains small amounts of other elements that affect the thermoelectric properties. Constantan is a 57 Cu–43 Ni alloy with traces of other elements. Such thermocouples are cost-efficient and they may be used in atmospheric conditions of up to 800°C. The sensitivity increases up to 26 μV/degree for –190°C to 63 μV/degree for 800°C. The accuracy of measurements cannot reach comparable values, characteristic to S and R thermocouples, because threads cannot be manufactured homogeneously, which generates temperature gradients. In addition, the thermoelectric properties of iron/constantan thermocouples are not sufficiently reproducible.

Type T thermocouple.

The main representative is the copper/constantan thermocouple whose sensitivity increases from 15 μV/degree for –200°C to 60 μV/degree for 350°C. for highly accurate measurements, these thermocouples are safer than J thermocouples, because one may use electrolytic copper (without oxygen), which is very homogeneous and which has reproducible properties.

Type K thermocouple.

The representative of this group is the chromel/alumel thermocouple that may be used between –200°C and 1370°C. Chromel is the 90 Ni–10 Cr alloy characterised by a highly positive t.e.m.t. in relation with platinum, while alumel is the 94 Ni–3 Mn–2 Al–1 Si alloy, which has a negative t.e.m.t. compared to platinum. Platine is a 3 Au–83 Pd–14 Pt/65 Au–35 Pd thermocouple, characterised by a t.e.m.t. four times higher than that of the S thermocouple. In scientific literature, the most common thermocouples are the T ones, (Douzanea *et al*., 2015; Vanpachtenbeke *et al*., 2017; McClung *at al*., 2014; Campbell *et al*., 2017).

4.2. Sensors for Relative Humidity

The sensors for relative humidity may be classified by the parameter used for measuring humidity and they are capacitive sensors (electric permittivity), resistive sensors (electric conductivity) or sensors using the thermal conductivity as a parameter (https://www.electronicshub.org/humidity-sensor-types-working-principle/, http://52ebad10ee97eea25d5e-d7d40819259e7d3022d9ad53e3694148.r84.cf3.rackcdn.com/Acal-BFi-Selecting-the-right-humidity-sensor.pdf). For economic reasons, the most common of them are the capacitive and the resistive sensors.

4.3. Combined Sensors Temperature-Relative Humidity

In order to measure temperature and relative humidity for very long periods and to store them, without having to use data acquisition units, measuring devices encompassing sensors of temperature and relative humidity were created, or even sensors meant to measure both parameters, along with microchips on which to store the information. This way, sensors may be installed inside the envelope elements for long periods, the information being downloaded cyclically every 3, 6 or even 12 months. Such sensors are rather often used for in-situ measurements, being identified in the measurements featured in the scientific literature (Rahim *et al*., 2017; Hamid & Wallenten, 2017; Hansen *et al*., 2018; Moujalled *et al*., 2018).

4.4. Sensors for Measuring the Intensity of the Thermal Flux

A heat flux sensor is a transducer generating an electric signal proportional with the total heat ratio applied to the surface of the sensor. The heat ratio measured is divided to the surface of the sensor to determine the thermal flux. Usually, the sensor will be incorporated into a substrate with high thermal capacity, to reduce to a minimum the dynamic errors associated with constant materials on a short-term basis.

The most commonly used ones are those produced by Hukseflux (https://www.hukseflux.com/products/heat-flux-sensors/heat-flux-meters?gclid

=CjwKCAjwkqPrBRA3EiwAKdtwkyYRoqpVUcoyjz8UbyMtSuXvs7hEa2NKyADBLvE6HVg4Pldh50jGwhoCSHMQAvD_BwE), Fig. 4 (Campbell *et al.*, 2017).

Fig. 4 – HFP01 flux sensor.

4.5. Thermovision Cameras

In situ measurements, in the published literature, have been made using cameras produced by Fluke, Flir and Testo.

5. Analysis Methods Based on Numerical Modelling

The numerical modelling of envelope behaviour to combined mass and heat transfer has enabled the accelerated simulation of the alternation between the hot and the cold season regarding to the environment, in order to obtain higher accurate values for heat losses through the envelope and through ventilation. In addition, the details of envelope elements may be defined in details, which leads to obtaining precise information regarding the influence of thermal bridges on unidirectional specific thermal resistances. Whereas the assessment of the composition of envelope elements is an activity specific to the design phase, it may be noted that the programs featured below could be used for analysing the existing buildings. This may be carried out by introducing both the information obtained using temperature, relative humidity or thermal flux measurements and the information related to the technical data of the buildings.

The simulation software may be designed only for the analysis of particular phenomena such as thermal transfer through thermal bridges (RDM, HEAT or THERM) and the calculation of unidirectional thermal resistance the appraisal of condensation emergence (Ubakus, Isover, DELPHIN), or programs that have been developed for global analyses, endowed with multiple tools, which may performed the aforementioned analyses and other, which may be significantly more complex (WUFI®, PHPP, EnergyPlus, TRNSYS, IES-VE, BEopt, Green Building Studio).

Below are few software programs that are most frequently used in the others research and scientific studies.

5.1. WUFI®

WUFI® represents a family of software products that allows realistic calculation of the transient coupled one- and two-dimensional heat and moisture transport in walls and other multi-layer building components exposed to natural weather. WUFI® software uses the latest findings regarding vapour diffusion and moisture transport in building materials. The software has been validated by detailed comparison with measurements obtained in the laboratory and on IBP's outdoor testing field.

The WUFI products are actually **WUFI®Pro**, performs one-dimensional hygrothermal calculations on building component cross-sections, taking into account built-in moisture, driving rain, solar radiation, long-wave radiation, capillary transport, and summer condensation. Furthermore, it is the standard tool for most simulations of building components and the easiest software to use from the WUFI® family; **WUFI® 2D** is a specialised software tool for investigating the two-dimensional hygrothermal behaviour of building components. It has been designed for advanced WUFI® Pro users and it is mainly applied in scientific investigations, such as heat and humidity bridge simulations; **WUFI®Plus** combines the evaluation of hygrothermal components with the simulation of the entire building; **WUFI® Passive** that combines the procedure of monthly energy balance for passive houses with dynamic assessment of the hygrothermal behaviour of the entire building. It allows the design and assessment of passive houses in monthly and yearly balances, by taking into account the gains and losses through envelope elements, ventilation or indoor loads.

5.2. Passive House Planning Package (PHPP)

PHPP is an easy to use planning tool for energy efficiency. PHPP provides reliable results to calculate the heating demand per year [kWh/(m²a)], maximum heating load [W/m²], cooling demand per year [kWh/(m²a)] and maximum cooling load [W/m²] (in case of active cooling). In addition, the software can calculate summer comfort in case of passive cooling: frequency of overheating [%], demand for renewable primary energy (PER) per year and primary energy demand (PE) of all energy services in the entire building [kWh/(m²a)] or the annual renewable energy gains [kWh/(m² ground a)].

5.3. EnrgyPlus™

EnergyPlus™ is a whole building energy simulation program that may be used to model both energy consumption – for heating, cooling, ventilation, lighting and plug and process loads – and water use in buildings. Energy Plus is a free, open-source software.

5.4. TRNSYS

TRNSYS is a flexible graphically based software environment used to simulate the behaviour of transient systems. Whereas the vast majority of simulations focus on assessing the performance of thermal and electrical energy systems, TRNSYS can equally well be used to model other dynamic systems such as traffic flux or biological processes.

6. Conclusions

Upon reviewing the literature in the field, it has been identified a series of measurements for the energetic performances of the buildings, performed in-situ. Most of them used sensors for measuring temperatures, relative humidity and thermal flux intensity. In general, the hygrothermal behaviour of thermal insulation systems has been analysed.

It is worth highlighting that for greater thicknesses of thermal insulation – of over 15 cm – the thermal flux enters in stationary transfer regime with great difficulty. Great temperature differences are necessary between indoor and outdoor, as well as a relatively long period where outdoor temperature remains constant. Hence, it is appropriate for the measurements used to determine the unidirectional specific thermal resistances to be carried out during the cold season, especially in January and February.

In order to assess water build-up in the layers with condensation risk, it is indicated to install relative humidity and temperature sensors in the layers and to monitor the values recorded for long periods, at least 24 months, to allow water build-up and evaporation.

The performances of IR cameras have increased constantly, and they are currently used for the energetic assessment of buildings. Besides temperature measurements, they provide the user with the possibility of identifying the areas with highly risk of condensation, which facilitates the application of punctual technical solutions to local problems, thus entailing cost reductions.

The direct determination of the thermal conductivity has become – using methods in variable regime of the thermal flux – a rather common activity for in-situ measurements. On the market of measurement devices, such devices are quite common, whereas there are no technically agreed methods to allow the certification of the materials based on such measurements.

Compared to the design phase, in the execution phase, various situations may emerge that lead to malfunctions of the envelopes. In this respect, it is recommended the implementation of procedures for permanent monitoring of thermal insulation layer to obtain direct information in what regards the level of thermal insulation that it provides. Therefore, it is possible to determine precisely when the system of thermal insulation no longer ensures its designed functions and needs to be replaced. The authors believe that in the near future, intelligent buildings should be endowed with sensors, to provide an accurate overall image of real energetic efficiency for the building in question.

In the research project, the intensity of the thermal flux and the temperature difference, as well as the thermal conductivity of the thermal insulation from the envelope elements composition will be measured. Thermal flux sensors, temperature sensors, but also combined temperature-relative humidity sensors will be used. Also, the relative humidity of the thermal insulation will be measured in the laboratory with the thermo-balance, on extracted samples. The measurements will be completed by taking IR images, for the precise identification of the thermal bridges.

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* * * SR EN 1934:1998, *Performanţa termică a clădirilor. Determinarea rezistenţei termice prin metoda cutiei calde cu fluxmetru. Zidărie* 300 SR EN 1935:2003/AC:2004**).

COMPORTAREA HIGROTERMICĂ A ELEMENTELOR DE ANVELOPĂ
O prezentare generală a determinării sale *in-situ*

(Rezumat)

În contextul actual, unul în care schimbarea climei a devenit nu numai o certitudine ci, după unele studii, chiar ireversebilă, diminuarea impactului negativ al nişei umane asupra mediului devine valoare absolută în sistemele de valori ce stau la baza organizării societăţii umane. Accelerarea schimbărilor climatice lasă impresia că societatea ştiinţifică planetară a fost surprinsă nepregătită.

În domeniul construcţiilor civile, unul care produce o cantitate însemnată de gaze cu efectă de seră, atât cauzată de energia consumată pentru exploatare acestora, cât şi de energia înglobată în execuţia lor, în ultimii ani s-au întreprins eforturi substanţiale în vederea implementării principiilor dezoltării durabile. În acest scop, au fost propuse materiale şi alcătuiri complexe pentru obţinerea de niveluri de eficienţă energetică superioare. Cu toate că materialele de construcţie sunt verificate înainte de punerea în operă, comportarea acestora *in-situ* nu a fost de cele mai multe ori analizată. De altfel, metodele de analiză sunt limitate şi implică monitorizări pe termen lung.

Lucrarea propune o sinteză a metodelor de analiză a comportării higrotemice a sistemelor de anvelopă *in-situ.*