The use of Infrared Thermography and Thermo-Aeraulic Simulation to Approach the Real Performance of Existing Buildings

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Abstract

The objective of this study is to develop a relatively simple accurate method to represent the current energy state of an existing building to ensure its optimal rehabilitation. Firstly, infrared thermography was used to estimate the envelope thermal transmission coefficient (U). Secondly, the dynamic building simulations were realized through TRNSYS 17 to determine the studied building's energy performances. Each element of the envelope receives a measured U to represent the as is building condition. Finally, in this study, we have coupled CONTAM software with TRNSYS to evaluate the thermo-aeraulic behaviour of an existing building located in the north of Morocco.

Introduction

The building sector accounts for 34.96% of the primary energy use in Morocco which is greater than the industrial sector (Energy Efficiency 2018). 26.37% and 8.32% of this energy use is consumed by residential and tertiary buildings respectively, where a vast majority is still produced using non-renewable resources. Following dynamics development of Morocco in this sector (Lahlou 2011), this energy demand will increase in the future, hence it is essential to reduce buildings energy loads in particularly by improving energy efficiency of existing buildings. A key challenge of reducing the energy use in existing building is to characterize and provide accurate representation of the as-is energy building conditions (Larsen et al. 2011). As without accurate representation of the as-is building conditions, it is difficult to choose from a range of high cost solutions and services and then achieve an optimal renovation of the studied buildings.

Over the past 30 years, literally many of building energy programs (TRNSYS, EnergyPlus, EQUEST, DOE-2, ESP-r, ECOTECT, DeST, Energy-10, PowerDomus, HEED, Ener-Win, SUNREL and Energy Express) have been developed to predict the existing building's energy performance. In this context, several studies have been carried out on the prediction of the existing building's energy performance using some of this building energy software (Ferrante, Mihalakakou, and Odolini 1997; Florides et al. 2002; Babbah et al. 2005; Al-ajmi and Hanby 2008; Saelens, Parys, and Baetens 2011; Gasparella et al. 2011; Domínguez et al. 2012; Friess et

al. 2012; Beccali et al. 2013; Gagliano et al. 2013; Romani et al. 2015; Cascio et al. 2017; Lebied et al. 2018).

Despite the effectiveness of these energy modelling, they present some limits:

- Non-determination of the performance deviations caused by construction defects or degradations;
- Non-representation of the actual energy performances, since the as-is building envelope during the modelling process is not taken into account.

To address this situation, in this paper, we propose to use infrared thermography (IRT) to integrate real building characteristic, through a case study involving a host building located in Tangier (north of Morocco). Today, the IRT is widely used to detect, to analyse thermal defects and to evaluate the buildings thermal performances. In this respect, several studies have been demonstrating the IRT potential in the estimation of the existing buildings actual thermal performance (Balaras and Argiriou 2002; Kato, Kuroki, and Hagihara 2007; Kalamees 2007; Albatici and Tonelli 2010; Fokaides and Kalogirou 2011; Asdrubali, Baldinelli, and Bianchi 2012; Dall'O', Sarto, and Panza 2013; Kylili et al. 2014; Ohlsson and Olofsson 2014; Danielski and Fröling 2015; Tejedor et al. 2017; Rocha and Santos, C F Póvoasb 2018b; 2018a).

In order to identify the building Envelope's heat lose, an experimental protocol was carried out. Thereafter, the different outside surface temperatures of the building envelope are used to estimate the in-situ thermal transmission coefficient (U-value). The obtained U-values were then used for the energy modelling of the studied building using TRNSYS 17 software, where each envelope element receives a U-value measured during the diagnosis. Finally, this building real energy needs were estimated through coupling of the TRNSYS energy simulation program with the CONTAM multizone airflow to choose the appropriate solutions for an optimum renovation of the studied building (Figure 1).

Figure 1: Schematic description of the studied approach to estimate the buildings real energy performances.

Methodology

Building description

The assessed building is one of the two host buildings located in north of Morocco. It consists of a ground floor and a first floor (Figure 2), giving a space living area of 44.39 m² with a ceiling height of 2.8 m. This building is equipped with single glazed wooden windows which are distributed on the South and North outside walls. The overall window rate is 5.87%.

Figure 2 : Plan of the studied building ground floor (a) and first floor (b).

In order to have the composition of the building's walls we have drilled a small hole (Figure 3) in the wall as shown in the figure below.

Figure 3 : The small hole on the outside wall.

The thermal conductivity of some building materials such as brick is measured using the hot box method of the Thermal, Solar Energy and Environment team from the Faculty of Sciences in Tetouan. The air gap thermal conductivity is obtained according to the thickness of this layer ("The Thermal Resistance of the Air Layers" n.d.). Table 1 summarizes the composition of building outside wall, ceiling and roof.

Table 1 : The outside walls and the floors structure.

Walls and floors	Materials (layers)	Thickness [cm]	Conductivity [W/(m.K)]	U-total value [W/m ² K]
Outside wall	Cement coating	1.5	1.15	1.88
	Hollow brick red	7	0.5	
	Air gap	10	-	
	Hollow brickred	7	0.5	1.86
	Cement coating	1.5	1.15	
	Tiles (kitchen wall)	0.7	1.4	
Roof	Cement coating	0.4	0.42	2.77
	Waterproofing membrane	0.7	0.23	
	Cement mortar	1	0.42	
	Concrete	4	2.3	
	hollow block	16	0.6	
	Cement coating	1.5	1.15	
Ceiling	Tiles	0.7	1.4	3.06
	Cement mortar	1	0.42	
	Concrete	4	2.3	
	hollow block	16	0.6	
	Cement coating	1.5	1.15	

Building thermal diagnostics

As already mentioned above, the infrared thermography was used to carry out a thermal diagnosis in order to represent with accuracy the actual thermal state of the studied building. In this thermal diagnosis, the used infrared thermal camera (Figure 4) was a model type Flir E50bx (2012) with an operating temperature range between -20°C and $+120^{\circ}\text{C}$ and a precision of $\pm 2^{\circ}\text{C}$ or $\pm 2\%$ of the displayed value. Furthermore, temperature loggers type Tinytag ULTRA2 (Figure 4) have been used to measure temperature with an accuracy of $\pm 0.4^{\circ}\text{C}$ and relative humidity between 0 and 95% with an accuracy of $\pm 3.0\%$ RH (Ultra, 2014).

Figure 4 : Schematic drawing of the experimental protocol.

Before making the measurements, the thermal camera should be calibrated for the studied element to avoid readings errors on the obtained thermal imagery. In other words, the reflected ambient temperature ($T_{reflected}$) and the emissivity (ε) of the studied building envelope are required to be measured. In this study, the reflective temperature was measured by means of a crumpled aluminium foil fixed on the surface (Figure 5) where the emissivity of the thermal camera at this measuring point was set at 1. This process is performed at each thermal image capture.

The determination of the emissivity value (ε) can be achieved by two methods, the first one is based on the reference emissivity values according to the type of material and the second one is through the direct measurement of the radiation reflected by the material by means of a heat source. In this study, the measurement of the wall's emissivity is performed according to the in situ method because it depends not only on the surface materials, but on the real surface conditions suffering from pollution, humidity, roughness and so on. We first moving a hot elements close to the wall surface as a soldering iron (Figure 6) and through applying the Energy Conservation Law (between an energy source and an opaque element) and Kirchhoff's Law, the thermal emissivity can be expressed as follows:

$$\varepsilon = 1 - \left[\frac{T_r^4 - T_{out}^4}{T_s^4 - T_{out}^4} \right] \quad (1)$$

Where T_s is the hot source temperature, T_r is the reflected image temperature and T_{out} is the outside air temperature.

Figure 5: Arrangement for determination of reflected temperature: digital image (a) and thermogram (b).

Figure 6: Thermal image of the soldering iron used to measure emissivity.

Therefore, the envelope temperature distributions can be obtained by the thermal imagery adjusted with the found emissivity value. Finally, the building envelope thermal transmission coefficient U (2) can be estimated based on the obtained envelope temperatures by assuming that the heat transfer from the envelope to the camera is mainly attributed to heat flow by convection (Φ_{cv}) and heat flow by radiation (Φ_{rad}), given by equations (3) and (4) (Fokaides and Kalogirou 2011)(Nardi et al. 2016).

$$U = \frac{\Phi_{cv} + \Phi_{rad}}{S(T_{in} - T_{out})} \quad (2)$$

$$\Phi_{cv} = h_{cv,out} \times S \times (T_{wall,out} - T_{out}) \quad (3)$$

$$\Phi_{rad} = \varepsilon \times \sigma \times S \times (T_{wall,out}^4 - T_{reflected}^4) \quad (4)$$

Here $h_{cv,out}$ is the outside convective heat transfer coefficient ($\text{W}/\text{m}^2\cdot\text{K}$), $T_{wall,out}$ is the wall temperature, $T_{reflected}$ is the reflected temperature, T_{out} is the outdoor air temperature, all expressed in Kelvin, ε is the wall emissivity and σ is the Stephan-Boltzmann constant. The convective heat transfer coefficient $h_{cv,out}$ is calculated using Liu and Harris correlations (2015) as presented in Table 2 .

Table 2 : Expressions used in the model by Liu & Harris for V_{loc} and V_R as function of V_{10} .

Surface orientation	Expression	
	V_{10} and V_{loc}	V_{10} and V_R
Windward	$V_{loc} = 0.26V_{10} + 0.06$	$V_R = 0.55V_{10} + 0.67$
Leeward	$V_{loc} = 0.19V_{10} + 0.14$	$V_R = 0.43V_{10} + 0.24$

Where V_{loc} is the wind speed measured at a certain distance d from the building facade and at a certain height (H) from the ground, V_{10} is the wind speed measured at 10m above ground level in the upstream undisturbed wind flow and V_R is the wind speed measured at height H_0 from the roof surface.

A heating system was installed within the building 15 days (360 hours) before the diagnosis to achieve steady-state regime. Figure 7 shows the evolution of the inner air temperature during the thermal diagnosis process.

Figure 7: Inside air temperature profile measured by Tinytag data loggers.

Therefore, a temperature difference of more than 10°C was ensured between the building inside and outside with an outside air velocity of about 2.05m/s. Given that the outside temperature is measured by the Ibn Battouta airport weather station in Tangier, due to the proximity of the airport to the studied building. In fact, we have performed the diagnosis several times during the winter season as February twenty-three, February twenty-eight and March twenty-three (Figure 8), before sunrise to avoid the solar radiation influence.

Figure 8: Outside air temperature profile.

The building Envelope's heat lose (Figure 9), were visualized then using the infrared camera in the facades and the roof. All the U -values measured with IRT were used subsequently in the studied building energy modelling.

Figure 9: Digital and thermal image of the studied building.

Before proceeding to the temperatures reading through the FLIR Tools software we compared the obtained

temperature values with a thermocouple measurement. the results of this comparative study showed a good agreement between the values measured by the thermography and the thermocouple values. Moreover, to calculate the U -values from the obtained thermal imagery, we have carried out a zoning on the building envelope, for both the walls (A) and the concrete framework (B) in the obtained image (Figure 10).

Figure 10: The zoning carried out in the lateral facade.

We have also performed this zoning process for all building envelope surfaces (Figure 11) to obtain the different temperature values of the studied building envelope surfaces and then calculate the in-situ thermal transmission coefficient.

Figure 11: Thermal images of the studied building envelope areas.

As an example, table 3 groups the average value U of all in situ test results for the case of image C in the figure 11.

Table 3 : U -value measured with IRT for image C .

envel ope part	wall	Left post	Right post	high beam	Low beam	Roof
U_{meas} [W/m ² K]	2.8 ±0.7 1	2.35 ±0.6	2.36 ±0.5	4.54 ±0.69	4.40 ±0.62	5.41 ±0.7
U_{th} [W/m ² K]	1.88	1.41	1.41	1.64	1.32	2.77

As it can be seen, that the building element which gives the greater deviation in all cases tested is the roof, followed by the concrete frame structure. At the facade level, according to this study the maximum values of the U -value are obtained in the areas located on the first floor

and the most possible explanation is the proximity of this area to the ground and the accumulation of hot air in the corners. It is highly possible that part of the difference between the measured results and those calculated analytically to be due to the fact that the theoretical calculation of the U-value deviates from the real condition due to the degradation of the building envelope during the construction and operation phases. All these U-values were used subsequently in the studied building energy modelling as explained below.

Building modeling

After the realization of the thermal diagnosis and the estimation of the building envelope surfaces real U-values, we have proceeded to the thermo-aeraulic modelling of this building. We have performed a comparison study of three different cases of our building: the reference building by using the theoretical U-values, the building diagnosed by using measured U-values for walls without the concrete framework (Figure 12) and the building diagnosed with the concrete framework (Figure 13) by using both measured U-values.

In this part, the building geometry, its operation and the thermo-aeraulic numerical model are developed under the TRNSYS-CONTAM environment. The building geometry was obtained by using Google Sketchup software and then saved with TRNSYS 3d plug-in (Figure 12 and 13). In fact, we have divided the building into different zones and we have considered that each room is a thermal zone.

Figure 12 : TRNSYS3d representation of studied building without the concrete framework.

Figure 13 : TRNSYS3d representation of studied building with the concrete framework.

In this modelling, it is essential to take into account the different contributions of heat gains from different sources: people, lighting and equipment. In this context, we supposed that our building is occupied by four people. Each room in the building has a gain that depends on the activity level of these people and their occupation. Concerning the person's activity level, it has been considered in accordance with the ISO 7730.

Regarding the occupation, the two bedrooms are occupied every day from 22h to 7h. The living room is used for relaxing in the evening, so it is occupied from 17h to 18h by four people. However, the dining room is used only for eating meals (breakfast, lunch and dinner). The kitchen is occupied by two people during the day from 7h to 7h30, 12h30 to 12h and from 18h to 19h.

The contributions due to the artificial lighting depend on the type of lamp used, as well as the installed power and the operating period. We have opted for our study on incandescent lamps of 100W (the same lamps used in the building studied) for an operating period from 19h to 23h. The building is equipped with different types of equipment that are shown in the table4.

Table 4: Power generated by the appliances.

Appliance	Area	Operating time	Power [W]
TV	Living room	In occupation from 17h to 18h	75
Laptop	2-bedroom	In occupation from 22h to 23h	100
Fridge	kitchen	24/24	125

Moreover, the ground three dimensional modelling is performed to account the thermal effect of the ground in the energy balance of the studied building by using the coupling between the 56 types (thermal model of the building) and 49 (slab on grade model) . In this regard, we considered a distance of 10m from the slab in each direction (x, y and z). The temperature in the horizontal plane at 10m depth is calculated by the model of Kusuda (Kasuda; and Achenboch 1965) given by equation (5) while the vertical boundaries are supposed adiabatic.

$$T_{sz}(t) = T_{su, moy} + \Delta T_{su} \cdot e^{-z \sqrt{\frac{\pi}{a_{sol} \Delta t}}} \cos \left(\frac{2\pi t}{\Delta t} - z \cdot \sqrt{\frac{\pi}{a_{sol} \Delta t}} \right) \quad (5)$$

With ΔT_{su} is the amplitude of surface temperature variation over the considered period, Δt is the considered period and a_{sol} is the thermal diffusivity of the ground.

On the other hand, we have chosen to perform a coupling between the thermal model developed under TRNSYS and an aeraulic model via CONTAM software in order to simulate thermal and energy parameters as well as the air flows between the studied zones and between the zones and the outdoors, knowing that the airtightness of this building is equal to 0.621 h^{-1} . The advantage of this coupling is that the temperatures in the building areas depend on the air flows, which in turn depend on the temperature differences. However, the TRNSYS software does not calculate the airflows between the building zones

and the airflow programs such as the CONTAM software do not model the building's thermal energy.

As for the thermal model, the studied building is divided into different zones (rooms or groups of rooms), connected by openings (doors, windows, cracks or leaks, ventilation ducts or air openings) (Barhoun 2006). The studied building model under CONTAM is a multi-zone nodal model. Although the CONTAM does not require the plans full-scale drawing for airflow calculations, the graphical interface allows a scaling value to be assigned for the drawing cells. This option was used in the studied building plan for later used with Google Sketchup and TRNSYS. Air flows through the building (Figure 14) result from pressure differences between adjacent areas or between an inside area and the outside of the building. These pressure differences are governed by the natural ventilation motors which are wind effect and thermal draught. The various flow rates are calculated by expressing the mass conservation equation at each of the network nodes. The air temperature is known by coupling with the type56 which receives as input the flow rates calculated by CONTAM (type97).

Figure 14: Airflow and pressure distributions in the ground floor (a) and the first floor (b) calculated by CONTAM.

During this modelling, the space cooling and space heating demands are determined considering the room air temperatures controlled to remain at 20°C during the winter (the statutory heating period in Tangier from 1st November to 15th April) and 26°C during summer (considering as cooling period the days in which the internal temperature exceeds 26°C). The value of external convective heat transfer coefficient for building envelope is assumed to be constant and equal to 17.8W/m² K and for the internal side, the value chosen is 3W/m² K (Klein et al. 2010).

Results and discussion

To evaluate the energy performance of the studied building, we carried out a comparative study between the

obtained results from numerical simulations for the three cases (Figure 15): the reference building (a), the building diagnosed without the concrete framework (b) and the building diagnosed with the concrete framework (c).

Figure 15: The three studied approaches.

As shown in the figure below, the building diagnosed with the concrete framework has about 75.4% higher heating needs than the building reference and 2.12% higher than the diagnostic building without the framework.

Figure 16: Building heating demand.

On the other hand, the building diagnosed with the concrete framework cooling needs are 48.05% higher than those of the building reference and 7.16% higher than those of the diagnostic building without the framework (Figure 17).

Figure 17: Building cooling demand.

This comparative study between the obtained results for the building reference and the diagnosed building with and without concrete framework shows the importance of the existing buildings energy diagnosis to increase the buildings energy efficiency and their indoor comfort. Indeed, the energy diagnosis allows us to represent the

real energy state of buildings using the estimated thermal transmittance U.

Conclusion

This research work concerns an energetic performance study of a building located in Tangier (north of Morocco) to ensure its optimal rehabilitation. Firstly, a non-destructive measurement using infrared thermography was performed to detect, analyse the thermal defects and evaluate this building thermal performances. An experimental protocol was carried out to identify the building Envelope's heat lose and then the different outside surface temperatures of the building envelope are used to estimate the in-situ thermal transmission coefficient (U-value). Those measurements were repeated several times, during the winter season, before with at least 10-15°C difference between inside and outside temperature to allow a measurable heat exchange through the envelope. The obtained U-values were then used for the Thermo-aeraulic modelling which is essential for establishing the studied building energy performance under different interior and exterior climate conditions. The building geometry it's developed under the TRNSYS17-CONTAM environment and then each envelope element receives a U-value measured during the diagnosis. Afterwards, the energy simulation is performed for three cases: the reference building, the building diagnosed without the concrete framework and the building diagnosed with the concrete framework in order to determine the accurate studied building's energy performances and heating/cooling energy needs. Finally, after having estimated the real energy needs of the studied building we will proceed to an optimization study to choose the appropriate solutions for an optimal rehabilitation of the studied building.

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