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The thermal resistance of retrofitted building components based on in-situ measurements

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ABSTRACT

Buildings are responsible for a large share of the worldwide energy use. For new buildings very strict objectives for the energy performance of buildings are set. The main energy use however occurs in existing buildings emphasizing the need for renovation of the older building stock. In order to detect deviations from the theoretical performance, in-situ measurements of the envelope performance after renovation can give insight in the workmanship and issues with different renovation techniques. Therefore, the focus of this paper is to determine the thermal resistance of building components from in-situ measurements, before and after renovation.

Different methods were applied to examine the thermal resistance of the building components: the average method, linear regression, Anderlinds' method, ARX modelling (Auto-Regressive models with eXogenous inputs) and Grey Box Modelling. All of these methods seem to lead to similar results with only a small variation in confidence intervals, except for linear regression, which couldn't capture dynamic heat flows due to solar radiation.

For the assessed exterior walls, different phenomena influencing the thermal resistance were noted. The measured thermal resistance answers the estimated theoretical value of the building components quite well before renovation, but after renovation the difference is varying due to cavity air flows.

KEYWORDS

Thermal resistance – In-situ measurement – Renovation – Building components – Characterization techniques

INTRODUCTION

Being responsible for ca. 25 % of the total energy consumption (Eurostat 2017), the residential sector holds a large opportunity to increase energy savings. However, for each renovated dwelling, the resulting energy savings can deviate from the theoretically designed energy savings, amongst others because of poor workmanship for instance causing short circuiting of the insulation layers (Hens 2007 & Baker 2011). Several phenomena can be distinguished: wind-washing (air cavity flows due to wind pressure), rotational air flows (air flow loop around the cavity insulation), inside air washing (caused by air leaks in the interior cavity leaf), etc.

Therefore, the focus of this paper is to assess discrepancies between the actual and the designed renovated building envelope, by thermal resistance characterization based on in-situ measurements. Besides the most commonly used average method (EN ISO 9869-1:2014), four other characterization methods are compared. In the methodology section, first the case study and the performed measurement campaign are explained, followed by an overview of the used characterization methods. Subsequently, the estimated thermal resistances and the discrepancies with the theoretical values will be discussed both before and after renovation of the dwelling.

METHODOLOGY

Case study

The analysed case is part of the ‘Ecoren’ project, one of the Flemish VLAIO renovation pilot projects. It concerns a terraced house that is chosen from a block of four single-family dwellings, originally constructed in 1975 and renovated in 2017.

Table 1 shows the theoretical thermal resistances of the exterior walls, calculated following the national standard (NBN B 62-002 2008). The wall before renovation is an uninsulated wall that consists of an outer leaf made out of bricks, an air cavity of which it is unknown whether it has a (partly) ventilated air cavity or not and an inner brick leaf finished with a gypsum layer. During renovation, the outer brick layer was replaced by an insulated prefabricated element, constructed of a timber frame construction. For both dwelling states, the thermal resistance is shown for non-ventilated and ventilated walls: The thermal resistance of the original ventilated cavity wall is calculated as the thermal resistance of only the inner cavity leaf and its finishing (NBN EN ISO 6946:2007), while the thermal resistance of the renovated structure is decreased by 50 %, based on findings of Maroy (2017) and Deconinck (2016).

Table 1. Range of theoretical thermal resistance of the exterior wall of the case study before and after renovation

	Before renovation			After renovation		
	λ (W/mK)	d (m)	R (m ² K/W)	λ (W/mK)	d (m)	R (m ² K/W)
Outer cavity leaf	0.61 - 1.24	0.09	0.07 - 0.15	0.053	0.21	3.87
Non-ventilated air cavity		0.05	0.18		0.03	0.18
Inner cavity leaf	0.30 - 0.64	0.14	0.22 - 0.47	0.30 - 0.64	0.14	0.22 - 0.47
Gypsum layer	0.52	0.01	0.02	0.52	0.01	0.02
$R_{\text{non-ventilated}}$ (m ² K/W)			0.49 - 0.81			4.29 - 4.54
$R_{\text{ventilated}}$ (m ² K/W)			0.24 - 0.49			2.15 - 2.27

Measurement campaign

Several in-situ measurements are carried out on the dwelling. First, the air permeability of the dwelling in both states was measured using a blower door test (NBN EN 13829:2000), and an infrared scan was performed. Second, the heat flow meter method was carried out, for which the surface temperatures at both sides of the building component and the heat flux through the component must be measured (EN ISO 9869-1:2014). The surface temperatures are measured with thermocouples, having an accuracy of ± 0.50 °C, which corresponds with ± 7 % for a mean temperature difference of 15 °C. The Hukseflux HFP01 sensors, used to measure the heat flux, have an accuracy of ± 3 %, and are attached with silicone as recommended by the manufacturer (Hukseflux Thermal Sensors 2018). Hence, the overall measurement accuracy is ± 10 %.

The heat flow meter method was performed before and after renovation of the dwelling. As this method is a local assessment, multiple locations of the exterior wall were carefully chosen, aiming to minimize the influence of thermal bridges. Before renovation, two exterior façade locations were monitored, namely the back and the front façade of the dwelling. Subsequently, after renovation, four locations were monitored: the back façade at the ground floor and first floor, and the front façade at the first floor at two locations. Since the dwelling was uninhabited, a constant indoor temperature could be maintained, which is preferable since the research of Deconinck (2016) showed that a free-floating indoor temperature complicates the thermal resistance estimation. The measurement campaigns are summarized in Table 2, with T_{int} the interior set temperature, T_{ext} the outdoor temperature and I_{sol} the global horizontal irradiation,

of which first the variation during daytime is given in W/m² and second the hours in % for which I_{sol} exceeds 100 W/m².

Table 2. Measurement campaign boundary conditions

Campaign	Period	Duration	T _{int} °C	T _{ext} °C	I _{sol} W/m ²	I _{sol} % hours
Before renovation	05/Jan/2016 - 09/Feb/2016	35 days	20	Min. -7.67	Min. 0.42	11.2 %
				Mean 5.84	Mean 85.84	
				Max. 16.22	Max. 405.4	
After renovation	07/Feb/2018 - 22/Feb/2018	15 days	22	Min. -6.62	Min. 0.45	26.3 %
				Mean 1.85	Mean 164.5	
				Max. 10.4	Max. 486.5	

Data assessment models

Consecutively, five data processing models are applied to estimate the thermal resistance: two semi-stationary models, i.e. the average method and linear regression, and three dynamic models, i.e. Anderlind's regression, ARX modelling (Auto-Regressive models with eXogenous inputs) and Grey Box Modelling (GB modelling). Semi-stationary models are quite easy to use, but they rely on steady state boundary conditions, which are never encountered on site. The dynamic models, on the other hand, capture dynamic building behavior more accurately, although they are more complex in usage. (Madsen et al 2015 & Deconinck 2016)

First, the average method assumes that the thermal resistance R can be calculated by dividing the mean temperature difference by the mean heat flux q over a period of time n. This method results in a single value (equation (1)), without further knowledge of the reliability of the estimated value. The second semi-stationary model is simple linear regression, for which the estimated slope is the inverse of the thermal resistance (equation (2)).

$$R = \frac{\sum_{j=1}^n (T_{si,j} - T_{se,j})}{\sum_{j=1}^n q_j} \quad (1)$$

$$q_j = \frac{1}{R} (T_{si,j} - T_{se,j}) + \epsilon_j \quad (2)$$

The first dynamic model is the Anderlind's regression method, which assumes that the heat flux q at given time j is a function of the temperature difference over the building component, but also of the interior and exterior surface temperature changes in the past. A 24-hour time lag is applied here, following the recommendations of Deconinck (2016), leading to equation (3):

$$q_j = \frac{1}{R} (T_{si,j} - T_{se,j}) + \sum_{l=j-p}^{j-1} A_l (T_{si,l+1} - T_{si,l}) + \sum_{l=j-p}^{j-1} B_l (T_{se,l+1} - T_{se,l}) \quad (3)$$

For the ARX model, a backshift operator B is applied to the input and output, using the polynomials of which the order (n_q, n_i and n_e) indicates how many data points from the past are taken into account (equation (4.1)). For this model type, the thermal resistance is calculated using minimum variance weighting of the first-order polynomials (equation (4.2)).

$$\begin{cases} Q(B)q_j = \omega_{si}(B)T_{si,j} + \omega_{se}(B)T_{se,j} + \epsilon_j & (4.1) \\ \frac{1}{R} = \lambda \frac{\omega_{si}(1)}{Q(1)} - (1 - \lambda) \frac{\omega_{se}(1)}{Q(1)} & (4.2) \end{cases}$$

The used Grey Box model belongs to the class of stochastic state space models, existing of a system equation (5.1) and a measurement equation (5.2), with C the thermal capacitance. Since

in this paper a one order model is used, there is only one system equation. For this model, the total thermal resistance of the component is the sum of R_1 and R_2 .

$$\begin{cases} dT_1 = \frac{1}{c_1 R_1} (T_{si} - T_1) dt + \frac{1}{c_1 R_2} (T_{se} - T_1) dt + \sigma_i d\omega_i & (5.1) \\ Q_{hfm,j} = \frac{1}{R_1} (T_{si} - T_1) + \epsilon & (5.2) \end{cases}$$

All five characterization methods are applied to the collected data, which was averaged to hourly data sets. The models were validated by two major checks, following the guidelines of Annex 58 (Madsen et al 2015): (1) the parameters and related model orders were selected on their significance (p-value) and (2) the residuals were tested to be white noise by plotting the AutoCorrelation Function (ACF), the QQ plot and the time series plot of the residuals.

RESULTS

Air tightness of the renovated dwelling

As a result of the blower door test of the dwelling, air permeability at 50 Pa was identified to be $18.11 \text{ m}^3/(\text{hm}^2)$ before renovation, and $24.49 \text{ m}^3/(\text{hm}^2)$ after renovation. Hence, the air tightness is decreased, indicating the presence of air leaks. In addition, the infrared scan also visualized air leaks after renovation. Figure 1.a) shows low interior temperatures at the bottom of the back façade, caused by cold air infiltrating the cavity from the outside at the bottom of the prefabricated element. Figure 1.b) shows high temperatures at the top of the back façade, indicating rising warm air that infiltrated the cavity from the inside.

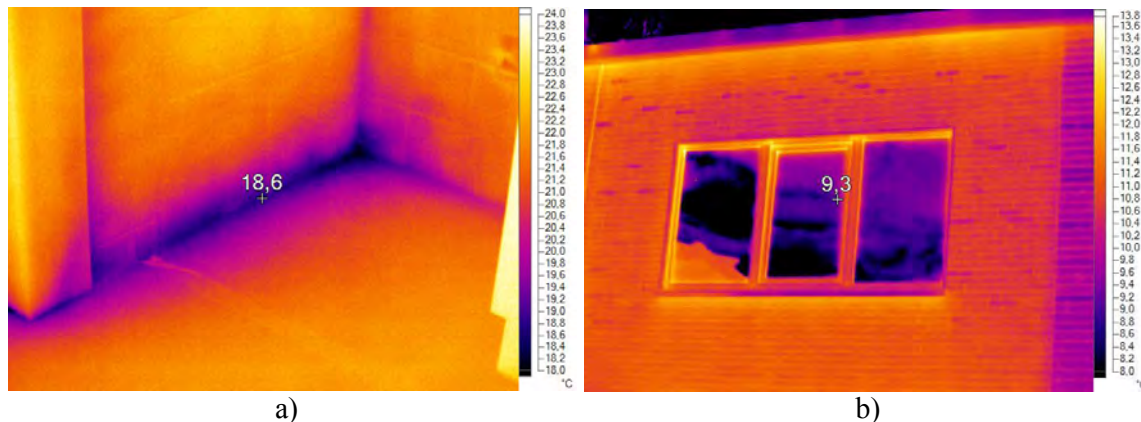


Figure 1. Infrared scan of the renovated dwelling. a) Inside view: Cold air infiltration at the bottom of the back façade b) Outside view: Warm air exfiltration at the top of the back façade

Thermal resistance estimation

The thermal resistances estimated by the five prediction models with usage of the complete dataset are shown in Figure 2; Note the different vertical scales for Figure 2.a and 2.b. First, Figure 2.a) shows that the calculated thermal resistances correspond to the unventilated reference value for the original façades. For both façades, the results of the five different models differ by maximum 5 % which is within each other's confidence interval. Comparing front and back, it is observed that the thermal resistance of the front façade is about 10 % higher than for the back façade. This may be caused by solar radiation, as the front façade is southeast oriented and thus influenced by solar radiation. However, linear regression of both night-time and daily-averaged values resulted in similar results, so different air cavity behavior is more plausible. Still, it can also be a measurement error, since the accuracy is about 10 %.

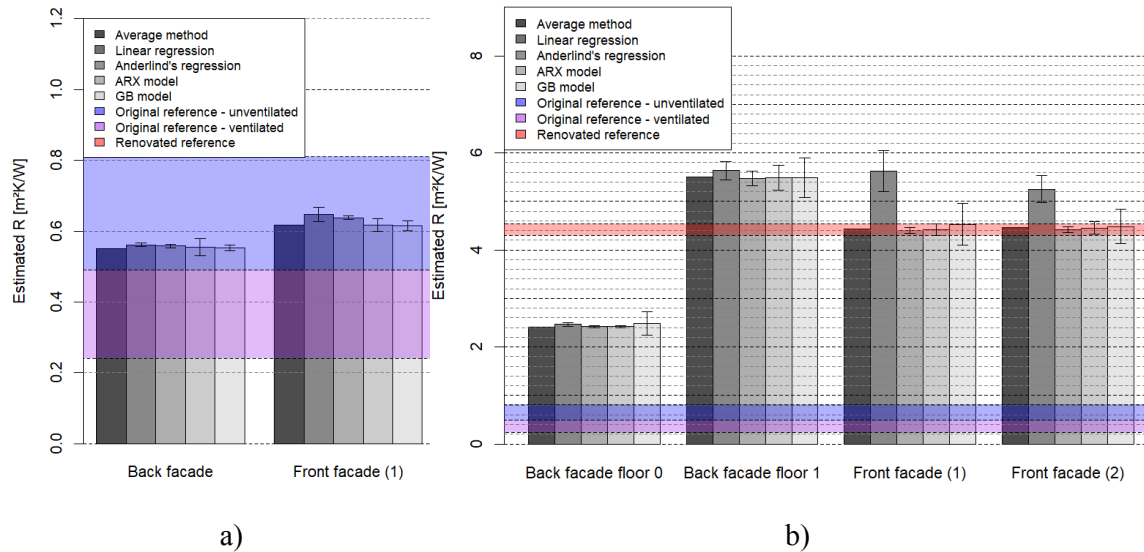


Figure 2. Estimated thermal resistances using the five analysis methods of (a) the original terraced dwelling (b) the renovated terraced dwelling. Note the different vertical scale.

Subsequently, Figure 2.b) shows the results for the renovated dwelling. Firstly, it can be noted that both measured resistances of the back façade do not correspond to the reference value. The measured thermal resistance on the ground floor is only 50 % of the reference value here, while on the first floor the result is about 20 % higher than the reference value. These findings can be explained by the influence of the air leaks shown in Figure 1, causing natural convection. As Lecompte (1989) and Maroy (2017) assessed in their numerical analysis of cavity walls, the measured thermal resistance of a building component will be lower if air infiltration from the outside decreases the temperature in the cavity. Hence, the temperature difference increases and the thermal resistance will decrease (see equation (2)). Inversely, at the top, air cavity temperature will increase due to interior air leaks, resulting in a higher thermal resistance.

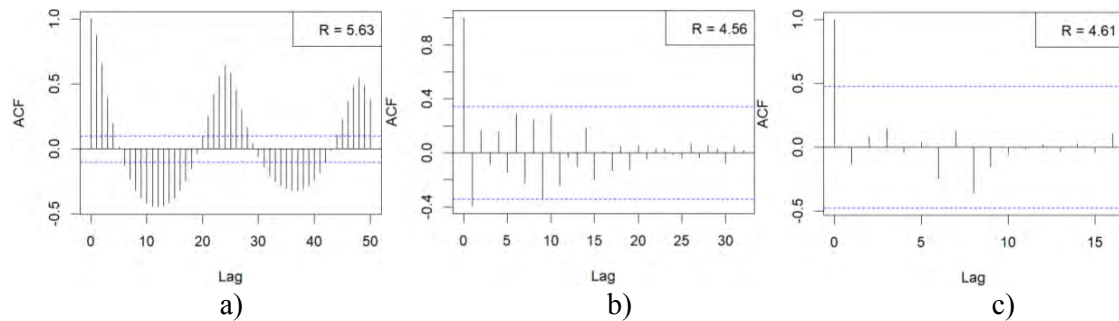


Figure 3. AutoCorrelation Function (ACF) of the linear regression for the renovated state of the front façade (1) with a) 1 hour sample time b) 12 hour sample time and c) 24 hour sample time

A second observation from Figure 2.b) is that the five models result in similar values for the back façade, while linear regression is an outlier for the front façade. Since linear regression is a semi-stationary model, here applied to a one hour data set, the model fails to capture the dynamic heat flows through the wall due to solar radiation. (Deconinck 2016) However, linear regression with an increased sample time estimates a thermal resistance similar to the results of

the other models. Hence, if the sample time of the data set is increased, the linear regression model is more reliable, as can be observed in the ACF-plots of the residuals in Figure 3, because now the dynamics are averaged out. This also explains why the average method estimates a similar thermal resistance as the dynamic methods, as the dynamic effects are also averaged out for this model. Still, this method does not give any information on the reliability of the estimate.

CONCLUSIONS

First of all, quite similar thermal resistances of the exterior façades were estimated by five characterization methods, besides a varying confidence interval size. Only the linear regression model failed to capture dynamic building behaviour for a 1 hour data set. Hence, longer sample times should be used here. Secondly, only one of the two exterior facades of the renovated dwelling corresponded to the reference value, despite the fact that the same renovation measure was performed. Discrepancies were caused by different cavity behaviour and the air leaks.

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