ON THE USE OF INFRARED THERMOGRAPHY TO ASSESS AIR INFILTRATION IN BUILDING ENVELOPES

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ABSTRACT

Infrared thermography is an interesting technique that is often used for qualitative assessment of the building envelope. The method allows to detect construction deficiencies e.g. thermal bridges, moisture problems, incomplete blown-in retrofit insulation of cavity walls, wind washing in insulation layers etc. in a very fast way. Another application is the use of infrared thermography in combination with pressurization tests in order to detect air leakages through the building envelope. As the airtightness plays a major role in reducing heat losses in well-insulated buildings, this is an interesting method as it allows for a quick qualitative evaluation of possible air infiltration/exfiltration locations. This paper offers a first attempt to analyse the important parameters (e.g. pressure difference, temperature difference between inside and outside) for a thermographic airtightness survey by means of simulations and in situ measurements. Furthermore an overview of the currently existing literature on thermographic surveys of the building envelope is given. Simulations show that the pressure difference does not play a significant role for the execution of a thermographic survey, while the indoor-outdoor temperature difference changes the outcome of the survey significantly. Without taking into account the environmental conditions, the survey can be either executed from the inside or along the outside. Solar radiation, wind and rain can although have a negative influence on the measurement results taken from the outside.

KEYWORDS

Quantitative/qualitative infrared thermography, Air infiltration, Pressurization test

1 INTRODUCTION

Europe has high ambitions concerning energy efficiency and the reduction of greenhouse gas emissions. By 2050, one of the goals is to reduce the CO_2-emissions by more than 80 % (BPIE, 2011). Therefore one of the key factors to satisfy the need for energy efficiency is a high performing building envelope. This can be achieved by a high insulation level and en excellent airtightness. For this application, thermography offers an alternative solution on top of the traditional techniques e.g. smoke detection, pressurization test, tracer gas measurements . It can not only be used for the detection of insulation defects but also for the detection of air leakages.

In combination with a pressurization fan, air leakage spots can easily and instantaneously be visualised by using a thermographic camera. On top of that, ongoing research reveals the possibilities of thermography to quantify and asses the severity of an individual air leakage spot. Together with the fact that thermography is fast and non-destructive, makes it a promising tool for building energy audits.

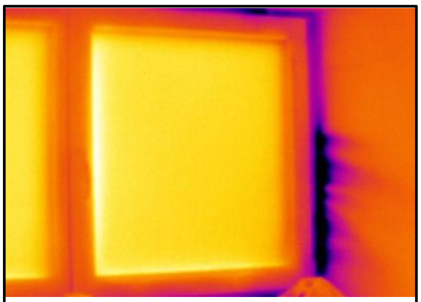


Figure 1: Example of an airtightness survey using a thermographic camera (blue spots are coldest and white spots are warmest)

Figure 1 illustrates the use of thermography in combination with a pressurization fan (imposing a pressure difference of 50Pa) to detect air infiltration spots. In this case, cold outside air was infiltrating through the window-wall interface. In general air leakage spots can be easily recognized by the temperature pattern as shown on the right hand side of Figure 1.

In the following section an overview of the currently existing literature concerning thermography for air leakage detection and the influential parameters are discussed. In section 3 an overview of the basic concepts of thermographic airtightness surveys is given. In section 4 a simulation model of a window-wall interface is developed to investigate the possibility of quantitative research. Sections 5 and 6 offer an overview of the first results, the conclusion and possibilities for further research.

2 LITERATURE OVERVIEW

The existing standards concerning infrared thermography in buildings give a set of recommendations and guidelines for thermographic surveys. These stay rather superficial and impractical, while it is in profit for every thermographer to obtain delineated guidelines in order to make the measurements reproducible. For air leakage surveys for example, it can be expected that the inside-outside temperature difference and the pressure difference imposed by the pressurization fan will play an important role. However, rarely a distinction between air leakage measurements or insulation defect measurements is made.

2.1 Normative literature

In general, guidelines concerning the required skills of the thermographer and the minimum requirements of a thermographic report are found. As in the NBN EN 13187 (CEN, 1999), these regulations mainly concern the formal aspect of a thermographic measurement. Almost no attention is paid to the influential parameters during a thermographic survey. While, environmental factors for example, are perhaps the most important aspect of a thermographic measurement, they are rarely mentioned in the normative literature. And when they are listed however, the different standards contain different values (CEN, 1999), (RESNET, 2012), (TheCH, 2010), (ASTM, 2011). For the wind velocity for example, a maximum wind velocity of 6,7m/s is recommended by ASTM (ASTM,2011) while 3,6m/s is proposed by RESNET (RESNET, 2012). An overview of the different influential environmental factors and their limit value given in normative literature is shown in Table 1.

Table 1: Review of the influencing environmental parameters and their limitations given in standards

Influential parameters	**Construction type**	**Light**	**Medium**	**Heavy**
	Solar radiation	Not allowed during 3h prior to IR (ASTM, 2011)	Not allowed during 8h prior to IR (ASTM, 2011)	/
		Not allowed 12h prior to IR (CEN, 1999)		
	Wind velocity	Maximum 6,7 m/s for evaluation of insulation defects (ASTM, 2011) Maximum 3,6 m/s (RESNET, 2012)		
	Precipitation	No influence if IR from small distance (TheCH, 2010) Measurement on wet surface or with snow covered surface not allowed (TheCH, 2010)		
	Temperature difference	$\Delta_{Ti-e} > 10°C$ during 4h prior to IR for evaluation of insulation defects (RESNET, 2012) $\Delta T_{i-e} > 1.7°C$ during 4h prior to IR for evaluation of airtightness (RESNET, 2012) $\Delta T_{i-e} > 5°C$ during 24h prior to IR (CEN, 1999)		
	Temperature gradient	$\Delta T_e < 10°C$ 24h prior to IR, $< 5°C$ during IR (CEN, 1999) $\Delta T_i < 2°C$ during IR (CEN, 1999)		
	Night sky radiation	Ideally IR when fully overcast sky (TheCH, 2010)		

For the specific case of infrared thermography in combination with a pressurization fan little normative information can be found. Among the few, RESNET provides separate guidelines for the execution, the report and the influential parameters during an airtightness survey, for instance a minimum temperature difference between inside and outside of 1,7°C is recommended (RESNET, 2012).

2.2 Scientific literature

Yet there are some authors describing the potential of thermography in combination with a pressurization fan. For example, in (Kalamees, 2007) measurements of the airtightness of a number of Estonian houses are presented and analysed. First the airtightness of each building was measured using a standardized pressurization fan. Then the typical air leakage spots were determined using a thermographic camera in combination with a pressurization fan, providing a negative pressure difference of 50 Pa. It appeared that the typical air leakage places were ceiling/floor-wall interfaces, the window-wall interfaces and the junctions of separating walls with the external walls or roof. In Figure 2 an air leakage spot at the wall-ceiling interface can be clearly spotted. As mentioned before the specific shape of the temperature pattern reveals the presence of an air leakage. A thermal bridge would be much more delineated and geometrical in shape. The penetrations of ventilation ducts and electrical sockets through the air barrier were also typical leakage spots.

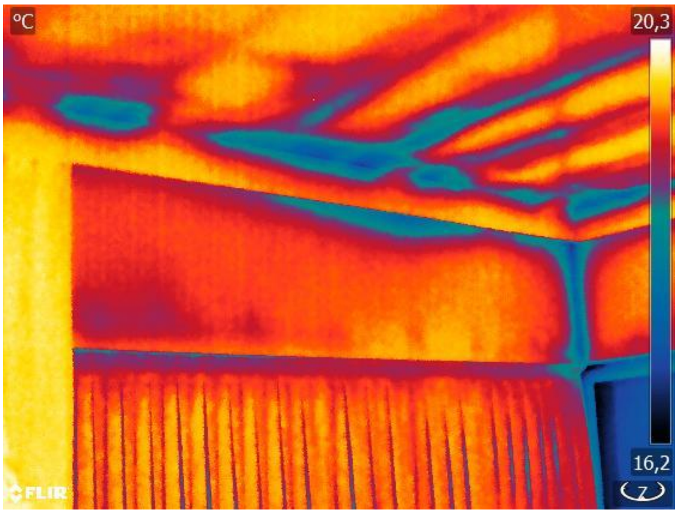


Figure 2: Air leakage spot at wall – ceiling intersection

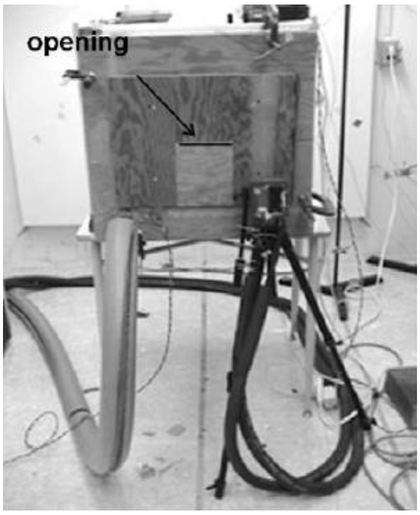


Figure 3: Experimental set-up to determine shape and dimensions of cracks (Bérubé Dufour, 2009)

In a second study a first step towards quantitative airtightness measurements using thermography is taken (Bérubé Dufour, 2009). Here, two image-processing methodologies to determine the dimensions of air leakage spots (cracks) are developed based on laboratory measurements. The experimental set up is depicted in Figure 3 and consists of a pressurized box holding the specimen panel with a crack of known dimensions in the middle of it and an air handling system. Using the thermographic pictures the authors try to make a reconstruction of the geometry of the crack. Though it can be argued that this sort of experiment is representative for the air leakage spots that are commonly found in building envelopes. In reality, air leakage spots will often be found at junctions or penetrations of the building envelope (Kalamees, 2007).

3 THERMOGRAPHIC AIRTIGHTNESS SURVEY

A thermographic airtightness survey can be performed with or without the use of a pressurization fan. When the outside wind pressure is rather high and a sufficient temperature difference between inside and outside (table 1) is reached, the most important air leakage spots can be visualised with a thermographic camera without the use of a pressurization fan. In most cases this will be sufficient to perform a qualitative thermographic research. When one is interested to visualise also the smaller air leakage spots or to use the thermographic information for quantitative purposes, a pressurization fan is recommended nonetheless a pressurization fan can also be used for qualitative measurements. Up till now in situ thermographic surveys are rarely executed for quantitative purposes. During a qualitative thermographic survey variations in the wall surface temperature are being observed without the need of an exact knowledge of that temperature. If it is the intention to obtain quantitative measurements a statement concerning the severity of the deficiency has to be made and therefore wall surface temperatures needs to be known as accurate as possible. Therefore a couple of parameters have to be determined using one of the standardized methods (ASTM, 2002 & 2005). When looking at the general formulation for infrared radiation at opaque material surfaces three terms can be distinguished (Barreira, 2013), (Dall'O', 2013) :

$$W_{tot} = \varepsilon\tau W_{obj} + (1-\varepsilon)\tau\, W_{amb} + (1-\tau) W_{atm} \tag{1}$$

Where W_{tot} is the total radiation captured by the thermographic camera [W/m²], W_{obj} the object radiation (with object temperature) [W/m²], W_{amb} the ambient radiation (with temperature of environment) [W/m²], W_{atm} the atmospheric radiation (with atmospheric temperature) [W/m²], τ the transmission trough the atmosphere [-] and ε the emissivity of the material [-]. The methods to determine these parameters (e.g. emissivity, reflectivity, transmission of the atmosphere, transmissivity) are included in standards and scientific literature (ASTM, 2005), (Albatici, 2013), (Marinetti, 2012), (Ciocia, 2012), (ASTM, 2002).Once these parameters are determined, the thermographer is ready to perform a thermographic quantitative survey. Due to the dynamic behaviour of the environment (e.g. solar radiation, wind, precipitation, orientation,…), the thermographer is obliged to determine these parameters for each room and each material.

In the Figures below thermographic images of an air leakage spot at the same window-wall interface with the use of a pressurization fan after 5 (Figure 4) and 10 (Figure 5) minutes are depicted.

Figure 4 shows a thermographic image of a window-wall interface at a pressure difference of 50 Pa after 5 minutes. The air leakage spots can already clearly be seen in the picture with their typical shape. Both pictures were taken in the morning of a sunny day, with direct solar radiation on the window examined. That is why the window seems warmer than the walls (50cm Cellular concrete block – 4cm Air cavity – 9cm bricks). With an outdoor temperature of 4,4°C and an indoor temperature of 20.5°C, the temperature difference between the inside and outside was greater than 15°C. In Figure 5, that is taken after 10 minutes, the cold outside air has clearly cooled down the window frame and the wall niche. In the graphs the temperature profile along the line L0, starting at the window frame, is given. An obvious change in temperature can be noticed, and the complete width of the window frame has cooled down. At the location of the air leakage spot (crack) the temperature reaches its minimum.

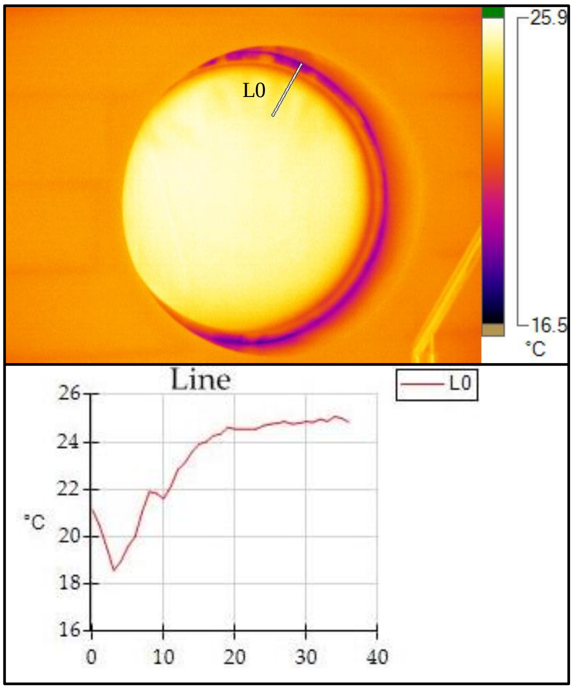


Figure 4: Window-wall interface at a pressure difference of 50 Pa after 5 minutes

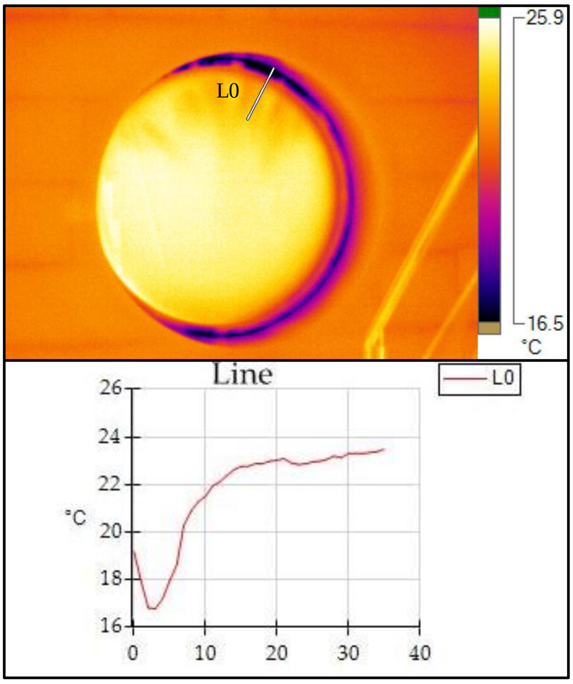


Figure 5: Window-wall interface at a pressure difference of 50 Pa after 10 minutes

While a standardized pressurization test has to be performed with a varying pressure difference between 0 and 100Pa (minimum top value is 60Pa), a constant pressure difference is recommended while executing a thermographic survey in combination with a pressurization fan. (CEN, 2001) A possible examination method consists in bringing the building to a constant over- or underpressure (infiltration of cold outside air/exfiltration of warm inside air), and then monitoring the temperature profile of the wall surface temperature after 5, 10, 15, 20, 25 and 30 minutes. As shown in Figures 4 and 5 a change of the shape of the temperature pattern caused by an air leakage will be seen. This way it can be identified whether a temperature variation is an air leakage spot or a thermal bridge, because the temperature pattern on the wall surface will not change when the deficiency that causes it is a thermal bridge. It is therefore best to start with a general thermographic examination of the whole building before using a pressurization fan to distinguish air leakages from thermal bridges (where necessary).

4 PRELIMINARY DYNAMIC SIMULATIONS

In this section the influence of the pressure difference imposed by the pressurization fan and the temperature difference between outside and inside on the course of the temperature profile is being analysed using a simulation model in Voltra. Voltra allows to study 3D dynamic heat transfer using a finite element method. Also air flows through predefined paths can be included in the model (Physibel, 2008). Both possible methods - overpressure and underpressure- are being examined with changing pressure differences from 20Pa up to 100Pa and changing temperature differences from 10°C up to 30°C. The simulation results will be compared with in situ measurements to evaluate whether similar trends are being observed.

4.1 Assumptions and simulation model preparation

A simplified simulation model of a window-wall intersection of 1m height is modelled (Figure 6). An air leakage ("crack") with dimensions 1000mm x 10mm was modelled. Several assumptions were made:

- Environmental factors like the sun, wind or rain are neglected
- The indoor temperature is kept constant at 20°C
- The outside temperature during one simulation is also kept constant -> stationary simulations!
- The window glazing (e) is replaced by an opaque material with an equivalent U-value (1 W/m²K)
- The wall structure is composed of (from inside to outside) 15mm gypsum (a) - 190mm reinforced concrete (b) - 100mm insulation (with λ=0.025 W/mK) (c) - 90mm (light) masonry wall (d).
- For the calculation of the convective heat transfer coefficient prior to the simulation the temperature inside the crack was taken as the mean value of the inside and outside temperature. Furthermore the convective heat transfer coefficient was constant over the length of the crack and did not change during the simulations.
- The specific heat and the air density were also derived from the mean indoor-outdoor air temperature.
- It was assumed that the radiative heat transfer over the length of the crack can be neglected compared to the convective heat transfer because the internal crack surfaces have a similar temperature

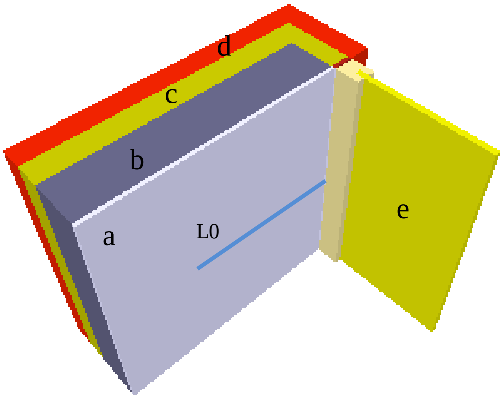


Figure 6: Simulation model used for the analysis

For an estimation of the air flow rate entering the building through the crack, the power law formulation was used (Van Den Bossche, 2005), (Hall, 2004), (AIVC, 1994):

$$V = C\,\Delta P^{n} \qquad [\text{m}^3/\text{h}] \qquad (2)$$

Where V is the air flow rate [m³/h], C the air flow coefficient [m³/(h Pa^n)], ΔP the pressure difference [Pa] and n the air flow exponent [-]. The values of the air flow coefficient and the air flow exponent are derived for specific air leakage places using in situ and laboratory measurements (Van Den Bossche, 2005), (AIVC, 1994). For the flow exponent a standard value between 0,6 and 0,7 is suggested (Van Den Bossche, 2005), (AIVC, 1994), (Jokisalo, 2009). In the current simulations a value of 0,66 is chosen for the flow exponent. For the flow coefficient values are proposed in (AIVC, 1994) depending on the type of connection. In (Van Den Bossche, 2012) the airtightness levels of 13 different typical North Western European installation methods of a wall-window interface are investigated. This study shows that the airtightness level of the investigated installation methods covers a wide range from 0m³/hm up to 31m³/hm at 50Pa. Considering a regular average Flemish building, with a mean length of window-wall interface of 105m and an average volume of 516,1m³ (Van Den Engel, 2001) this study recommends the air loss of the window-wall interface to be limited below 10% of the overall building leakage. For a newly built detached residential building in Flanders the average building airtightness n50 is 6h^{-1}. Thus the maximal acceptable air loss at the window-wall interface is equal to 3.3m³/hm at 50Pa (Van Den Bossche, 2012). This value was used for the calculation of the air flow coefficient adjusting Eq. (2):

$$C = \frac{V_{50}}{\Delta P^{n}} * x \qquad [\text{m}^3/\text{h. Pa}^n] \qquad (3)$$

Where V_{50} is the air flow rate per meter window-wall interface length at 50 Pa[m³/h m] and x the length of the window-wall interface. For a simulation model with a window-wall interface length of 1m, this gives a C-value equal to 0,25m³/hPa^n. Using these values for the air flow coefficient and exponent an expected air flow rate can be calculated for different pressure differences using Eq. (2). From the resulting air flow rate and the dimensions of the crack the air velocity inside the crack and the convective heat transfer coefficient can be calculated using the formulas for noncircular ducts (Lienhard, 2003), (Shah, 1975).

4.2 Simulations

12 Different situations are examined using the simulations, each returning a temperature profile along the line L0 starting at the window-wall interface (Table 2, Figure 6). During each simulation the indoor and outdoor temperature remain constant. The only dynamic parameter is the pressure difference that rises from 1Pa (starting situation) to the desired pressure difference (Table 2). The time step used for the simulations is 5 minutes with a start-up duration of 1 day.

Table 2: Different simulation situations

No.	**ΔP (Pa)** T_i = 20°C T_e = 0°C		No.	**T_e (°C)** T_i = 20°C ΔP
1	20		6	-10
2	40		7	-5
3	60		8	0
4	80		9	5
5	100		10	10
			11	15

5 FIRST RESULTS

Some of the preliminary simulation results are shown below. In Figure 7 a comparison is made between the temperature profiles obtained by in situ measurements and by simulation. The temperature profiles obtained from in situ measurements are the same of Figure 4, on the left after 5 minutes and on the right after 10 minutes of depressurization. For the simulation model a similar indoor-outdoor temperature difference and pressure difference is chosen than those during the in situ measurements (e.g. pressure difference of 50Pa and temperature difference of 15°C). It have to be noticed that the trends of the temperature profiles are similar of those obtained from in situ measurements.

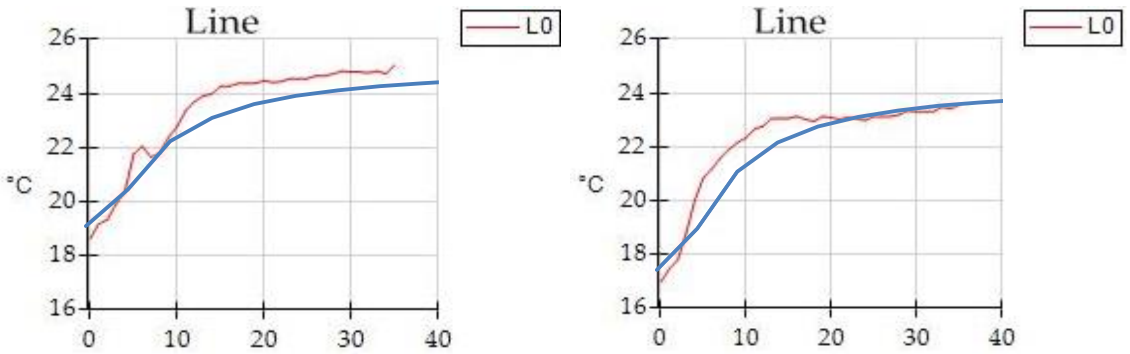


Figure 7: Comparison between the trend of the temperature profiles obtained by simulation (blue line) and in situ measurement (red line)

In Figure 8 a comparison is made between the temperature profiles obtained by depressurizing (left) and pressurizing (right) the building with a pressure difference of +/- 50Pa, an indoor temperature of 20°C and an outdoor temperature of 0°C (temperature difference of 20°C). These curves were obtained by inversing the direction of the ventilation flow inside the crack. A similar (but inverse) trend can be noticed, but taking into account the additional external environmental factors (wind, solar radiation, rain) an indoor measurement with depressurization will be recommended in most cases. In the case of an air cavity wall one may expect that an outdoor survey will be nearly impossible. Further research on that subject needs to be done.

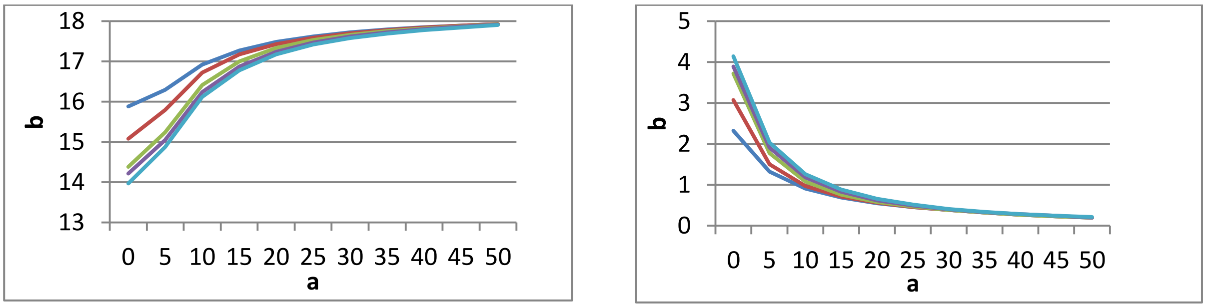
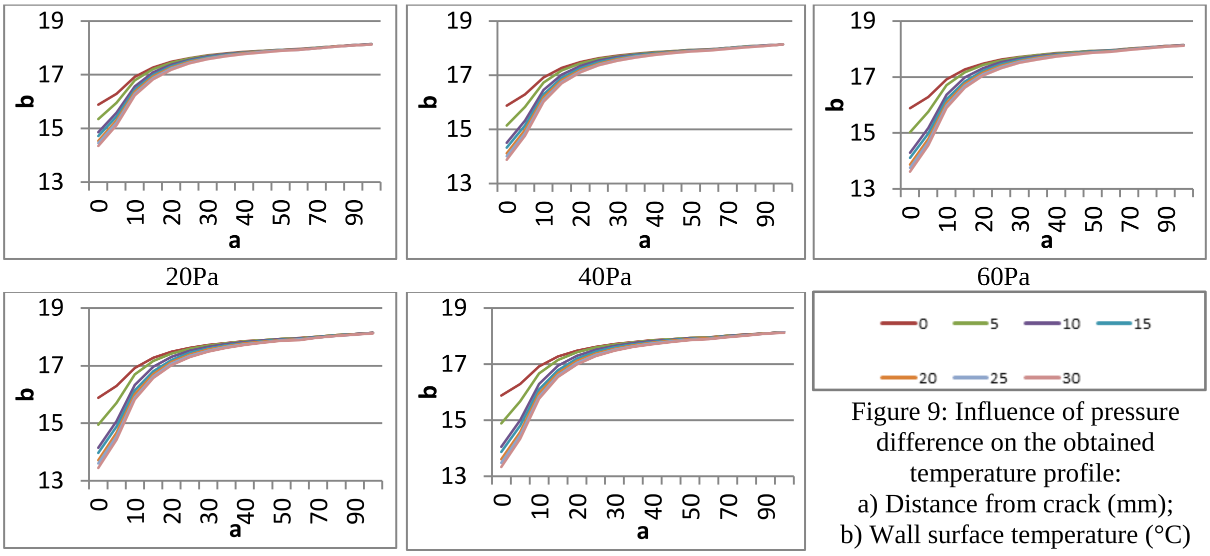


Figure 8: Comparison between the trend of the temperature profiles obtained by depressurization (left) and pressurization (right): a) Distance from leakage spot (mm) ; b) Wall surface temperature (°C)

In Figure 9 the influence of the pressure difference on the course of the temperature profile is depicted. The pressure difference varies from 20 up to 100Pa with a constant indoor air temperature of 20°C and outdoor air temperature of 0°C (ΔP = 20°C). It can be noticed that the pressure difference does not play a significant role, although the temperature difference per time step is slightly increasing with rising pressure difference. For all the examined pressure differences the cooling down of the wall surfaces is insignificant after 30 minutes of pressurization/depressurization, therefore only six time steps are considered.



20Pa 40Pa 60Pa

80Pa 100Pa

Figure 9: Influence of pressure difference on the obtained temperature profile:
a) Distance from crack (mm);
b) Wall surface temperature (°C)

Finally Figure 10 depicts the influence of the indoor-outdoor temperature difference on the obtained temperature profile. The indoor temperature and the pressure difference is kept constant at respectively 20°C and 50Pa, while the outdoor temperature varies from -10°C up to 15°C (Figure 10) (5°C < ΔT < 30°C) with a step of 5°C. This has a much greater influence than the imposed pressure difference, since the maximum temperature difference of the temperature profiles at start and after 25 minutes ranges from 0,5°C (ΔT = 5°C) to 3°C (ΔT = 30°C). A duration of 25 minutes was chosen following the results derived from Figure 9. When proposing a minimum temperature variation between the 2 time steps of 1°C a thermographic survey can be executed starting from an indoor-outdoor temperature difference of 10°C.

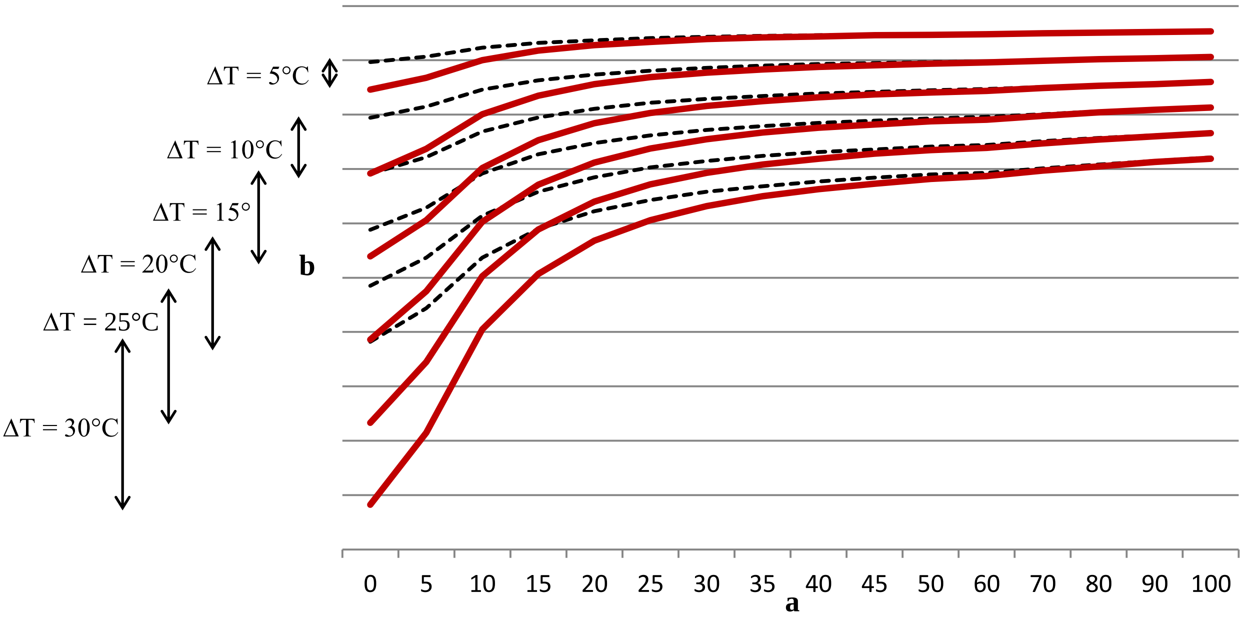


Figure 10: Influence of indoor-outdoor temperature difference on the obtained temperature profile at start (black dotted line) and after 25 minutes (red line): a) Distance from crack (mm); b) Wall surface temperature (°C)

6 CONCLUSIONS & FUTURE WORK

The airtightness of the building envelope plays a major role in the overall energy efficiency of buildings. A thermographic survey in combination with a pressurization fan seems a recommended method to identify the exact place of the air leakage spot. Currently, this method is mainly used to determine where renovation of the building envelope is needed most. Although this method has the potential for quantitative analysis of the buildings airtightness, it is rarely used for this purpose nowadays. These simulations constitute a first step towards a method for quantitative determination of air leakage cracks. Future research has to determine if it is possible to say something about the size/magnitude of the crack using the temperature profiles obtained by thermographic measurements. However, the implemented simulation model has to be finetuned and validated by laboratory tests. Another possibility is extending the current simulation model with other models representing other types of leakage spots.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

AIVC (1994). *Technical Note 44 – An Analysis and Data Summary of the AIVC's Numerical Database.* Air Infiltration and Ventilation Centre.

ALBATICI R., PASSERINI F., TONELLI A. M., GIALANELLA S. (2013). *Assessment of the thermal emissivity value of building materials using an infrared thermovision technique emissometer.* Energy and Buildings 66, pp. 33-40.

ASTM (2002). *ASTM International E 1862 – 97: Standard test methods for measuring and compensating for reflected temperature using infrared imaging radiometers.* American society for testing and materials.

ASTM (2002). *ASTM International E 1897 – 97: Standard test methods for measuring and compensating for transmittance of an attenuating medium using infrared imaging radiometers. American society for testing and materials.*

ASTM (2005). *ASTM International E 1933 – 99a: Standard test methods for measuring and compensating for emissivity using infrared imaging radiometers.* American society for testing and materials.

ASTM (2011). *ASTM International C1060 – 11a: Standard practice for thermographic inspection of insulation installations in envelope cavities of frame buildings.* American society for testing and materials.

BARREIRA E., DE FREITAS S., DE FREITAS V. P., DELGADO J. M. P. Q. (2013). *Infrared thermography application in building diagnosis.* Advanced Structured Materials 36.

BERUBE DUFOUR M., DEROME D., ZMEUREANU R. (2009). *Analysis of thermograms for the estimation of dimensions of cracks in building envelope.* Infrared Physics & Technology 52, pp. 70-78.

BPIE (2011). *Europe's buildings under the microscope. A country-by-country review of the energy performance of buildings*. Buildings performance institute Europe (BPIE), Brussels

CEN (1999). *NBN EN 13187*: *Thermal Performance of Buildings – Qualitative detection of thermal irregularities in building envelopes – Infrared method.* European Committee for Standardization, Brussels

CEN (2001). *NBN EN 13829: Thermal Performance of Buildings – Determination of Air Permeability of Buildings – Fan Pressurization Method.* European Committee for Standardization, Brussels

CIOCIA C., MARINETTI S. (2012). In situ e*missivity measurement of construction materials.* 11th QIRT Conference.

DALL'O G. (2013). *Infrared Audit.* Green energy audit of buildings, pp. 111 – 125.

HALL M. (2004). *Quantifizierung von Luftdichtheits-Leckagen*, bauen mit holz, nummer 8

JOKISALO J., KURNITSKI J., KORPI M., KALAMEES T., VINHA J. (2009). *Building leakage, infiltration, and energy performance analyses for Finnish detached houses.* Building and Environment 44, pp. 377 - 387

KALAMEES T. (2007). *Air tightness and air leakages of new lightweight single-family detached houses in Estonia.* Building and Environment 42, pp. 2369-2377.

LIENHARD J. H. IV, LIENHARD J. H. V (2003). *A heat transfer textbook: third edition.*

MARINETTI S., CESARATTO P. G. (2012). *Emissivity estimation for accurate quantitative thermography.* NDT&E International 51, pp. 127 – 134

PHYSIBEL, VOLTRA (2008). *3-dimensional dynamic simulation tool using the finite element method.* Version 7.0, Physibel Software, Maldegem, Belgium.

RESNET (2012). *Interim guidelines for thermographic inspections of buildings.* Residential energy services network.

SHAH R. K. (1975). *Laminar flow friction and forced convection heat transfer in ducts of arbitrary geometry.* Int. J. Heat Mass Transfer Vol. 18, pp. 849-862.

TheCH (2010). *Standard de qualité bâtiment.* Association Suisse de thermographie (theCH), Switzerland.

VAN DEN BOSSCHE N. (2005). *Luchtdichtheid: Experimenteel onderzoek naar schattingsmethodes bij woningen.* Thesis.

VAN DEN BOSSCHE N., HUYGHE W., MOENS J., JANSSENS A., DEPAEPE M. (2012). *Airtightness of the window-wall interface in cavity brick walls.* Energy and Buildings 45, pp. 32-42.

VAN DEN ENGEL J. J., OP'T VELD P.J.M. (2001). *Luchtdicht Bouwen – Ontwerpaanbevelingen.* Stichting BouwResearch, Rotterdam, The Netherlands.