# Retrofit cavity-wall insulation:

# performance analysis from in-situ measurements

M. Delghust, A. Janssens & J. Rummens
*Ghent University, Department of Architecture and Urban Planning, Research Group on Building Physics, Construction and Climate Control, Ghent, Belgium*

ABSTRACT: Great potential for the reduction of energy consumption in the Flemish houses can be found in retrofit cavity wall insulation. This is due to the reduced costs and the reduced complexity of the procedure in comparison to interior and exterior retrofit wall insulation and to the vast amount of non-insulated cavity-walls in Flemish houses. Nevertheless, retrofit cavity wall insulation isn't as widely applied, controlled and promoted in Belgium as it is in countries such as Great-Britain by Ciga and the Netherlands by Venin. This is mainly caused by some bad experiences from the past and a lack of local, well documented exemplary projects, performance analysis and quality control framework. As an attempt to respond to these demands, a study on this technique was launched, putting together several Belgian research institutes.

As a part of this study, 25 houses were analyzed as case-studies. This test-group was composed as a sample of the main products used for retrofitted cavity wall insulation in Belgium. Performance analysis was applied on several complementary levels and aspects such as thermal properties, air-tightness, indoor climate, thermal bridges and energy consumption. Therefore, the following measurements were used: heat flux-measurements and infrared thermography, blowerdoor-tests, measurements of indoor-climate and surface temperatures, record-keeping of heating consumption. When possible, measurements were performed before and after retrofitting the walls. These measurements were put against lab-measurements, theoretical analysis and computer-based simulations of theoretical energy-consumptions and 3D-simulations of thermal bridges. The results showed good correlations between theory and practice, except for energy consumption if individual user-related factors are not thoroughly analyzed and taken into account. U-values of the walls were reduced by a factor 2 to 3. Although the changes in air-tightness were relatively small, reductions of the air infiltration were measured in every case-study, regardless of the used insulating material. Retrofit cavity insulation was shown to have a positive, though almost negligible effect on the interior surface temperature at cold bridges.

This paper will focus on the measurements made on the case-study-houses. The main goal will be to compare the on-site-measurements with the theoretical analysis, focussing mainly on the thermal properties of the walls, thermal bridges and air-tightness.

## 1 INTRODUCTION

The European Union has set itself some clear energy-saving goals, which are translated in different measures by the member states. Great potential therefore resides in tackling heavy energy-consumptions within existing buildings. The Flemish government has made a list of priority measures, putting forward mainly roof insulation, the replacement of old glazing and of old furnaces. Until recently, insulation of exterior walls has not been put forward in the list. This is partly because of the costs and the complexity faced by interior and exterior retrofit insulation, as well as because of some urbanism regulations on façade changes. This has lead to a very poor state of wall insulation in the older houses, showing only very slow improvements over the last years.

Cavity wall insulation bypasses several problems faced by other wall insulation techniques: most important, the façade and interior finishing remain unaltered, the procedure is quick and relatively cheap (approx. 25€/m²). Of course, the achievable thermal resistance is limited by the width of the cavity. As most of the existing houses in Flanders, dating from after the second war, have cavity walls, the potential of large-scale implementation of cavity wall insulation is obvious. This large scale implementation has greatly been restrained by the lack of knowledge and trust in this technique. Contrary to other countries such as Great-Britain and the Netherlands, there is a huge lack of well documented exemplary projects, performance analysis and a quality control framework for retrofitted cavity wall insulation within the Belgian building framework. While some thorough studies on retrofit cavity wall insulation have been made, e.g. in Great Brittain by the British Research Establishement (BRE, Doran S. & Bernard C., 2008), those studies never took place in Belgium. Because of some differences in insulating materials, construction practice and framework, complementary research within the local, Belgian situation was needed. Therefore, a study was launched, putting together several Belgian research institutes.

The results presented in this paper were gathered in the framework of the Tetra-project 70127 'Injected insulation of existing cavity walls: analysis of quality and suitability of materials and installation methods'. This research was mainly financed by the Institute for the Promotion of Innovations through Science and Technology in Flanders (IWT) and was lead by the Ghent University (Ugent) together with three other research partners, the Belgian Building Research Institute (BBRI), Sint-Lucas School of Architecture-Ghent and the Belgian Insulation Board (CIR). One of the main tasks of the Ghent University, was the analysis of case-studies, comparing field-measurements with theoretical models and measurements in laboratories.

## 2 CASE-STUDIES: VARIABLES, SELECTION AND APPROACH

The goal of this field research was to check the theoretical assumptions and to extend and to compare findings from foreign experiences and studies to the Belgian field of practice. This was done by analyses on a representative sample of the Belgian practice for retrofit cavity wall insulation. To build up that sample, the main variables between retrofit insulated cavity walls had to be identified.

### 2.1 *Insulating materials*

Within the Belgian market of retrofit cavity wall insulation, three groups of material types can be distinguished, based on their macro-structure. The first group, is that of the 'fibre'-materials. These are the mineral wools: rock wool (RW) and glass wool (GW). The second group covers the 'pearl'-materials. Expanded polystyrene (EPS) and soda-lime-silica (SLS) are the base materials. The third and last one, is the group of the 'foams'. Both polyurethane (PU) and urea-formaldehyde (UF) are commonly used. Further variations of these products exist, from one manufacturer or placer to the other.

For each of these materials, samples were gathered in test-boxes. These were used for laboratory tests on heat and moisture characteristics.

### 2.2 *Evolution of the insulating materials in practice*

Most of the materials, as well as the insulating practices, have evolved through the years. Retrofit cavity wall insulation has been used in Belgium for over more than thirty years. However, not all the products existing now, have been equally used through the years. While mineral wool and UF-foam have been constantly present, older cases with PU-foam and EPS are harder to find in Belgium. SLS on the other hand, only appeared during the last decade, in which it temporarily disappeared from the Belgian market due to commercial reasons, reappearing only two years ago.

### 2.3 *Wall construction*

Besides the insulating material itself, the existing wall constructions do also vary considerably. After the second World War, cavity walls quite rapidly became standard practice in Belgium, especially in Flanders, but the variations seen from one wall to another remain considerable. Some factors such as surface finishing don't influence the thermal performance of the wall greatly. Others, such as the type of masonry-blocks used and the width of the cavity, are not to be neglected when analyzing the field practice and the field measurements.

An evolution towards better insulating, hollow core, masonry bricks can be seen through the years, for the inner bearing leaf of the wall. However, this evolution didn't take place in a structured, uniform way, nor in time, through the years, nor in practice over the large number of actors within the Belgian building sector. Still, selecting houses from different building periods and widely spread over the country helped to gain insights into those variations.

### 2.4 *Sample description and procedure*

The sample consists of 25 retrofit cases. All of these cases are freestanding or semi-attached single-family houses, in accordance to the vast majority of the target group for retrofit cavity wall insulation in Belgium. They were mainly gathered by an open call towards house-owners directly.

For each of the six insulating materials, cases were selected with varying ages, dating from 1956 to 1994. The retrofit cavity wall insulation was placed between 1967 and 2009. For cases insulated during the period of this research (2007-2010), it was possible to execute the measurements both before and after the insulation was placed. Although the sample remains too small for extended statistical analyses, relevant indications could be gathered about different performance aspects of retrofit cavity wall insulation.

### 2.5 *Data-gathering*

For each case-study, information was gathered mainly through the owners and measurements were performed in-situ.

The collected information consists of building plans, data on building materials and heating equipment, data on energy consumption, motivation of the owners for this and other energy-related interventions, their experience and appreciation of the intervention and its consequences and other experiences.

The in-situ measurements were aimed at analyzing the thermal performance of retrofit cavity wall insulation and possible side-effects in practice. To achieve this, thermal performance was analyzed through thermal infrared imaging and heat-flux measurements. Thermal bridges were analyzed both with thermal imaging and temperature measurements (air and surface). Blowerdoor-tests were executed to measure the impact of the insulation procedure on the air-tightness of the building. The indoor comfort was assessed by measuring inside and outside temperature and air humidity. For a few cases, an inspection of the cavity was made with an endoscope. The owners were briefed before the start of the measurements on the procedures and the research, to ensure that the measurements would take place in optimal conditions.

Most of the data gathered from the owners were aimed for further analysis reaching beyond the scope of this paper, such as study of real-life energy-savings, behavioural aspects etc. The paper will now further focus on the in-situ measurements related directly to cavity wall insulation. The main focus will be on the thermal performance of the wall.

## 3 THERMAL PERFORMANCE

To assess the thermal performance of the applied insulation, both thermal infrared imaging and heat-flux measurements were used. For older insulation cases, they give an indication of the total thermal resistance that can be reached and the homogeneity over the walls. Where measurements were made before and after the cavities were filled, the effect of the insulation itself in relation to the total structure of the wall could be distinguished.

### 3.1 *Thermal infrared imaging*

The goal of these measurements was to investigate the homogeneity of the thermal resistance of the building envelope, to identify the major thermal bridges and to check the homogeneity of the insulation once placed inside the cavity.

First of all, these measurements confirmed the vast amounts of well known thermal bridges, stressing the growing relative importance of those thermal bridges in the heat losses of the building after the walls are insulated. The most typical cold bridges seen for those older cavity-wall constructions are concrete lintels and floor plates that connect inner and outer masonry leafs and built-in roller shutters above windows.

Secondly, thermal imaging can assess if the location of the heat-flux measurement is representative for the whole wall. Heat-flux measurements are punctual measurements allowing to define an absolute value for the thermal resistance of the wall. Infrared imaging can give an indication of the thermal performance of a whole building envelope, but are vastly limited to a relative indication of the thermal resistance of adjacent elements. Both techniques do complement each other well.

### 3.2 *Heat-flux measurements*

#### 3.2.1 *Procedure: in-situ measurement*

For each case-study, a heat-flux measurement was made during the winter, measuring the heat-flux on the inside wall surface and the surface-temperature on both sides of the wall. Each measurement period lasted at least 6 or 7 days, with measurement intervals smaller than 1 minute for the sensors on the inside surface and smaller than 5 minutes for the temperature sensor on the outside.

#### 3.2.2 *Procedure: data-analysis*

The measurement data was analyzed with both the average method and the dynamic method in accordance to ISO 9869:1994(E).

The average method is based on the simple relationship between heat-flux, temperature difference across the wall and thermal resistance of the wall (equation (1)). Because of the dynamic boundary conditions in-situ, the measured values are averaged over a large amount of time, of at least 3 days. Taking into account the prominent daily cycles of the boundary conditions, the end-result is calculated after a round number of 24 hours. For most of the cases, the necessary convergence criteria were only met after at least 5 days.

$$R = \frac{\sum_{j=1}^{n} T_{sij} - T_{sej}}{\sum_{j=1}^{n} q_j} \qquad (1)$$

where $R$ = thermal resistance [m²·K/W]; $T_{sij}$ = inside surface temperature [K]; $T_{sej}$ = outside surface temperature [K]; $q$ = heat flux [W/m²].

As the inside surface temperature was measured next to the heat-flux sensor, the thermal resistance can be defined as

$$R = \frac{\delta T}{q} - R_{hfm} \qquad (2)$$

where $R_{hfm}$ = thermal resistance of the heat-flux sensor.

This summation over time might not always be enough to compensate for the variations in inside and outside temperature, depending on the thermal capacity of the wall. Therefore, “storage correction” factors are proposed in the norm, based on estimations of the thermal properties of the wall. With these correction factors, the required convergence might happen after a smaller measurement period. The standard states that this is only necessary if the analysis doesn’t reach the proposed validation criteria without the use of these correction factors. This might happen e.g. if the outside temperature doesn’t only fluctuate strongly in a cyclic way over a day-period, but also over the whole measurement period. In the framework of this research, the average method was always applied both with and without these correction factors, even when it was not necessary according to the norm. Estimations of the thermal properties of the wall were mainly based on building documents from the owner, information on the insulating material from the manufacturer and from the laboratory measurements and on analyses of the composition of the wall in accordance to material characteristics from ISO 10456:2008(E) and NBN B 62-002.

The other method described in the norm, the dynamic method, was also applied on all measurements. This approach is build on a set of linear equations to be solved in order to find the time-based relationship between the temperature variations on both sides of the wall and the measured heat flux. The accuracy of the defined variables is tested by comparing the measured values of the heat-flux over time to an estimate, calculated with these variables. With this more complex method, the thermal conductivity of the wall can often be determined after a smaller measurement period. For each set of data, the dynamic analysis was applied repeatedly with 1 to 8 time constants, selecting afterwards the result with the smallest confidence interval.

Using the different methods on each measurement made it possible to better assess the error margins due to the calculation procedure. It also helped to identify the best set of data inside each measurement period to determine thermal resistance with a smaller confidence interval. Further individual analysis of each measurement, mainly through visual analysis of the charts appeared to be crucial for reaching the best results.

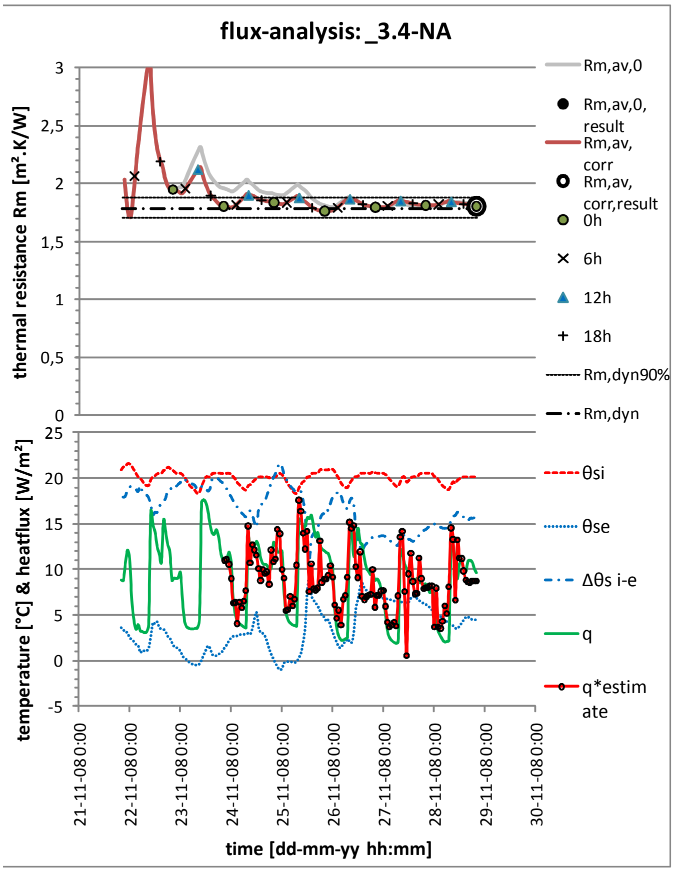

Fig. 1 heat-flux measurement, example of analysis

Fig. 1 shows as an example the analysis on one heat-flux measurement (case 3.4, after insulation of the cavity wall). Within the same chart, the results of the different calculation methods can be compared and analyzed. The abscissa is the time-axis. The lower part of the chart shows the measured inside and outside surface-temperature [°C] and heat-flux [W/m²] as well as the calculated temperature difference across the wall. Superposed to the line of measured heat-flux lays the line of the final estimated heat-flux according to the dynamic method. The upper chart shows the calculated thermal resistance [m²·K/W]. The light gray line represents the running average without storage correction according to equation (1). The dark line with indication of periods of 6, 12, 18 and 24 hours represents the running average calculated with the factors for storage correction. The three horizontal, dotted lines indicate the resulting thermal resistance from the dynamic analysis method and the lower- and upper limits of its 90% confidence interval.

### 3.2.3 *Results: U-values*

Fig. 2 shows the results from the heat-flux measurements on the different cases, expressed in U-value [W/m²·K]. For each insulating material, the cases are ordered with the most recently insulated cases on the right.

The hatched bars represent the results before insulating the walls. The plain bars show the results after insulation. For each measurement, a maximum of three bars are shown, representing the results calculated with the different analysis methods, from left to right (and from paler to dark): average method without factors for storage correction, average method with factors for storage correction and dynamic method. The error bars represent the confidence intervals in accordance to ISO 9869:1994(E) The horizontal lines on the error bars indicate the error on the calculation method itself (not taking into account operational errors, calibration errors...)

The measured U-values for not insulated walls reach between 1,1 and 2,1 W/(m²·K), indicating as predicted large variations in thermal properties of the masonry itself. After insulation, the U-values drop by 50 to 70% (Fig. 3) and reach values of 0,35 to 0,84 W/(m²·K). One case (5.3), forms an exception with a very poor result after insulation, probably mainly due to bad practice (too low density at placement).

As a comparison base and in connection to another research, two more walls were measured that hadn't been retrofitted. Case 7.1 was built in 1982 with a layer of mineral wool as cavity wall insulation. Case 7.2 was built in 1958 without cavity insulation, but with an inner leaf of very lightweight concrete. Both cases are rare examples of early 'insulated' walls. Reaching U-values of respectively 0,52 and 0,63 W/(m²·K), their performance lies in the same area as the measured values on the retrofitted walls.

For the cases where measurements were also made before the insulation was applied, the increase in thermal resistance was calculated and compared to the criteria for the two applicable government incentives (Fig. 4). For applying for federal tax reduction and regional financial aid, the theoretical added thermal resistance, calculated as the quotient of the thickness and the thermal conductivity coefficient of the wall, must be over respectably 0,75 and 1,3 m²·K/W. Corrections are applied to the measured increase in thermal resistance, to take into account the measured effect of the metal wall ties and the replaced thermal resistance of the cavity air. The air cavities were considered as moderate ventilated and, as such, having a thermal resistance of 0,09 m²·K/W. The corrections for the wall ties were calculated for each wall by iterations from the measured value before and after insulation was placed, using the formulas described in NBN B 62-002 (equation (3)) backwards. As an estimation, a standard amount of 5 steel ($\lambda_f$ =50W/(m·K)) wall ties per square metre with a diameter of 4mm were considered. Except for the same one case (5.3), all the cases reach the limit for tax reductions, but some do not reach the limit for the regional incentive.

$$\Delta U_f = \alpha \cdot \frac{\lambda_f . A_f . n_f}{d_1} \cdot \left[ \frac{R_{U,ins}}{R_{T,h}} \right]^2$$

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where $\Delta U_f$ = correction on thermal conductivity for the wall ties [W/(m²·K)]; α = 0,8 ; $\lambda_f$ = thermal conductivity coefficient of the wall tie [W/(m·K)] ; $A_f$ = section of the wall ties [m²] ; $n_f$ = number of wall ties per square metre [$m^{-2}$] ; $d_1$ = width of the cavity [m] ; $R_{U,ins}$ = calculated thermal resistance of the insulation layer without the wall ties [m²·K/W]; $R_{T,h}$ = calculated thermal resistance of the wall without taking the wall ties [m²·K/W]

### 3.2.4 *Considerations on measured thermal conductivity*

When analyzing these results, the considerable confidence intervals have to be taken into account. Using both the average and the dynamic analysis method appeared to be of great use to improve the accuracy of the analysis.

Comparing measured values with calculated values, it is common, not only for retrofit cavity wall insulation, to see considerable differences. Although the thermal resistance promised by the contractors weren't always achieved, it can be stated that the real, measured improvement of the thermal resistance can be considered as very good, especially considering the small investment cost and complexity.

## 4 THERMAL BRIDGES

The frequent presence of typical cold bridges was confirmed by the thermal infrared images. As the retrofit cavity wall insulation does not interrupt those cold bridges, they remain unsolved. Thermal computer-simulations as well as thermal imaging confirmed the growing importance of the thermal losses through those thermal bridges, once the surrounding walls are insulated. The importance of tackling those thermal bridges for reducing heat losses, speaks for itself. However, the question remains of the influence of the cavity wall insulation on the risks of condensation on the internal wall surface.

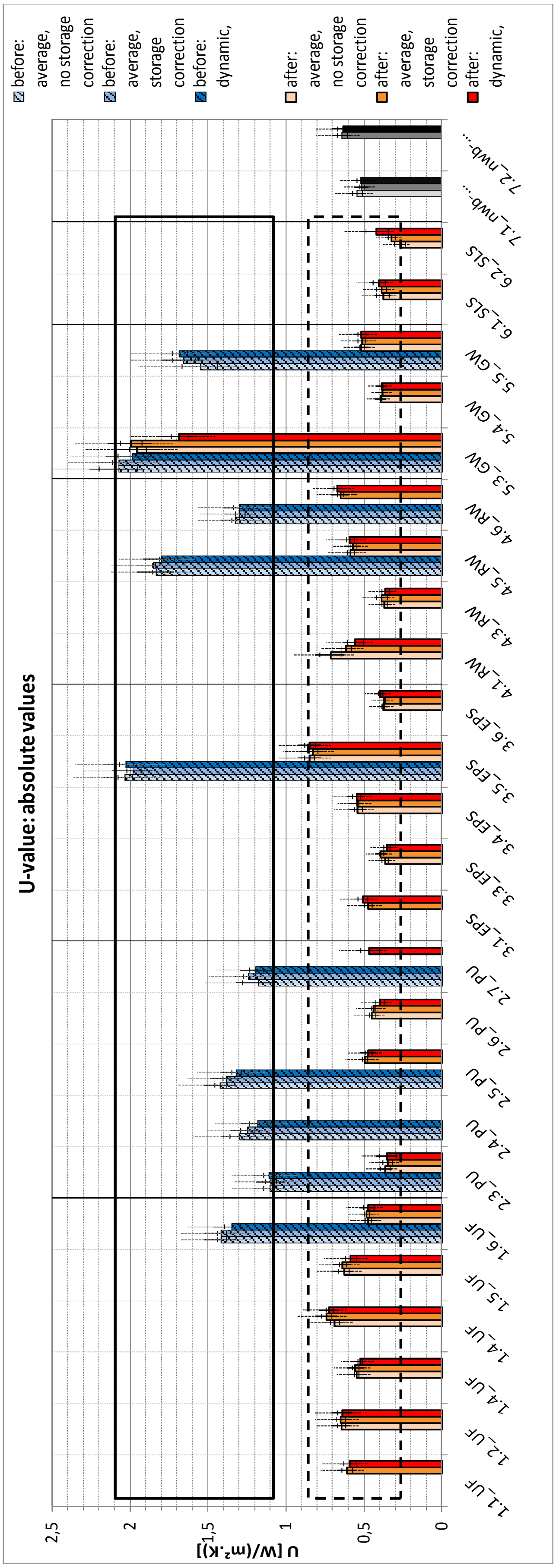

Fig. 2: heat-flux measurement, U-values

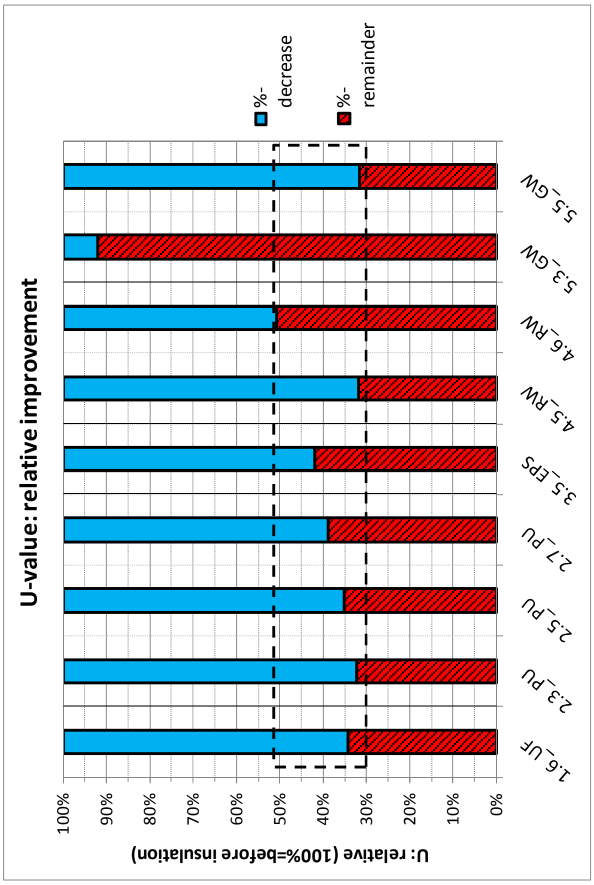

Fig. 3: heat-flux measurement:
relative decrease of the heat losses

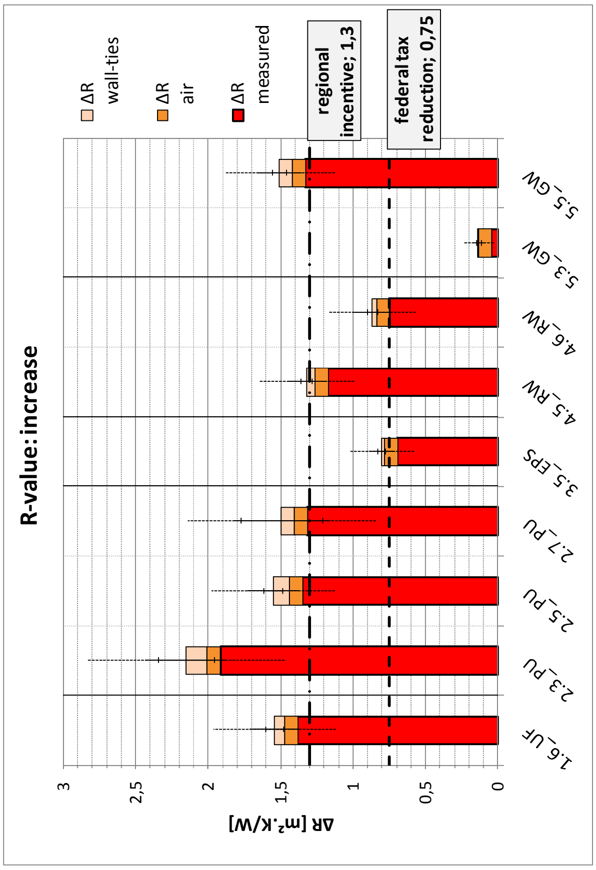

Fig. 4: heat-flux measurement:
thermal resistance increase

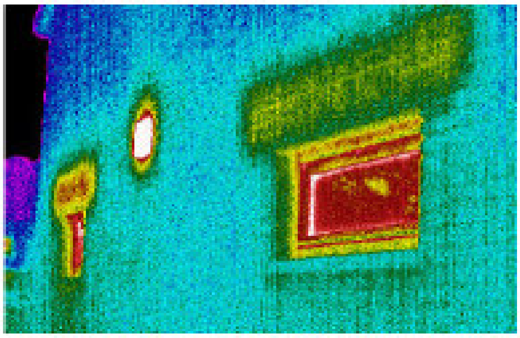

Fig. 5 thermal infrared image of lintels

## 4.1 *Temperature-factor (f-factor)*

To determine the risk of condensation on the interior surface, the temperature factor f (equation (4)) of common cold bridges were analyzed and compared before and after insulating the wall.

$$f = \frac{T_{si} - T_{ae}}{T_{ai} - T_{ae}} \qquad (4)$$

where $f$ = temperature-factor [-]; $T_{si}$ = inside surface temperature [K]; $T_{ae}$ = outside air temperature [K]; $T_{ai}$ = inside air temperature [K].

Due to the added presence of insulation inside the wall, the inside surface temperature on the plane wall will rise after the cavity wall insulation is applied. Indirectly, the now warmer inner leaf of the cavity-wall, will also warm up the layers of material on the inner side of the cold bridge, leading to an increased temperature factor. This reasoning is confirmed by 3D thermal computer-simulations (software: Trisco) as by temperature measurements in-situ. However, the increase in f-factor is very small. This is illustrated by the example below. Because of the dynamic boundary conditions, the temperatures were measured for several days. The temperature factor is calculated based on the running average of the measured temperatures over round amounts of 24 hours, similarly to the average method for the heat-flux measurements. The example below illustrates the analysis of the temperature factor of a lintel above an income door, through computer simultion (Fig. 6) and in-situ measurement (Fig. 7), showing an increase of the temperature factor from 0,71 before to 0,74 after insulating the wall.

There can be concluded that retrofit cavity-wall insulation won't lower the inside surface temperature at cold bridges. This means that the risk for inside surface condensation won't increase, on the condition that the indoor climate (air humidity) remains unchanged.

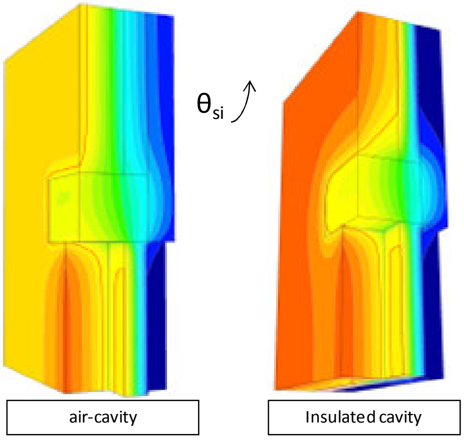

Fig. 6 3D heat transfer simulation of a lintel (software: Trisco)

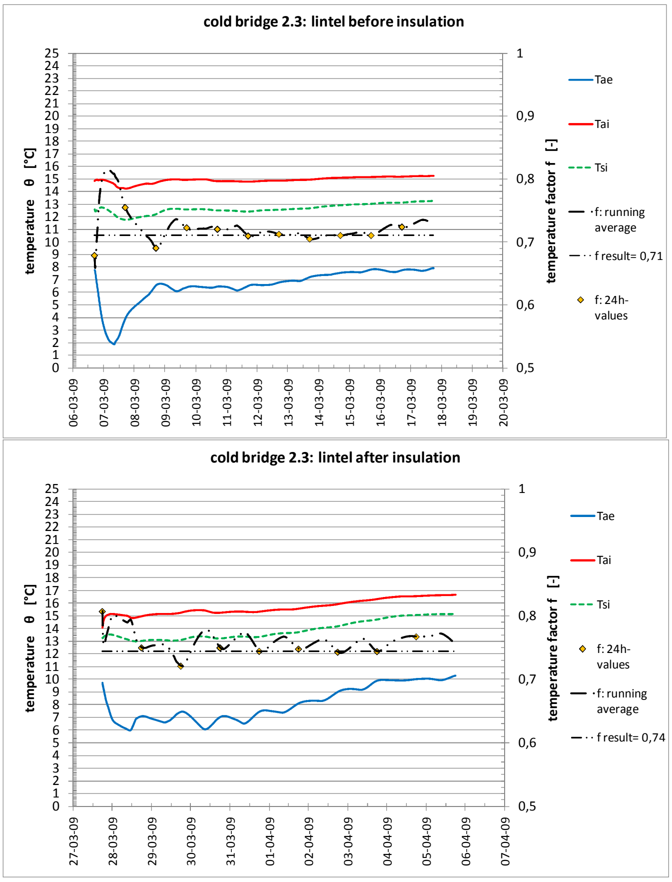

Fig. 7 temperature factor at lintel: in-situ measurement

## 5 AIR-TIGHTNESS

Very often, a side-effect of retrofit insulation, is an increase in air-tightness. That is often the case e.g. with retrofit roof insulation, especially when at the same time the missing underlayment is added. While a higher air-tightness might help to reduce heat losses through air infiltration and exfiltration, it might also influence the indoor air quality and especially the indoor air humidity if the ventilation of the building isn't well-conceived (of well-used). Therefore, the air-tightness has been tested for the houses from the case-study sample.

### 5.1 *Measurement: blowerdoor-test*

The air-tightness was measured by means of a blowerdoor-test using method A described in NBN_EN 13829;2000(E), to be representative of the air leakage of the building in use. Huge variations of air-tightness were measured between the different case-studies. Most of these were easily explained by the quality of the window frames, presences of heating chimneys, absences of underlayment in roofs. However, within the scope of this research, the main point of interest was the relative change of air-tightness for the same houses, before and after insulation. Improvements of air-tightness were measured for all cases, with reductions of air leakage mainly within a range of  5 to 20% (Fig. 8). One case, 2.5, showed a decrease of the air leakage of almost 50%. Improvements can be supposedly located not only over the plain wall, but mainly at the junctions between walls and windows. The large differences in existing air-tightness at those crucial places, when comparing the cases largely explains the differences in improvement of the air tightness.

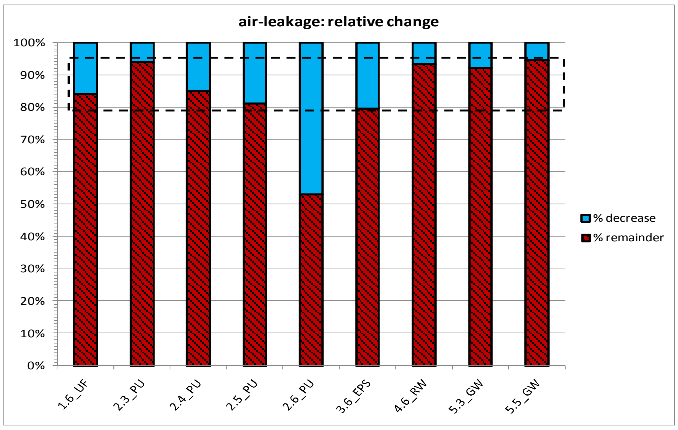

Fig. 8. Measured air-leakage: relative change

No significant difference could be derived between the different types of material. Not only the foam materials, but also the loose-fill materials did improve the air-tightness. To identify possible differences between materials on the level of air-tightness, laboratory tests should be performed. To compare products from measurements on the scale of whole houses, the differences in air-tightness between the houses remain too big, not only on absolute measured values, but also on the differentiation and location of the specific air leaks in relationship to the place of the cavity insulation.

The decrease of the air leakage isn't of enough importance to considerably reduce the heat losses by convection. The main improvement on heat losses by retrofit cavity wall insulation remains the improved thermal resistance of the wall. However, if the ventilation of the house isn't well conceived or well used, this increase in air-tightness might have a negative influence on the indoor air quality. If the change in air-tightness is big enough, relative humidity indoor might rise, also increasing the risk of condensation problems. This phenomenon remains common to many retrofitting interventions. Therefore, the importance of the ventilation of the house cannot be stressed enough as a part of retrofitting concepts.

## 6 CONCLUSION

Within the scope of this research, in-situ measurements on houses with retrofit cavity-wall insulation confirmed the theoretical analysis on levels of thermal resistance, cold bridges and air-tightness. Considerable improvement of the thermal resistance of the wall is achieved. The inside surface temperature at cold bridges isn't lowered, but has minimally risen. Even though of negligible amount to have a real effect on the heat losses, the air-tightness of the houses is improved.

Cavity-wall insulation is confirmed as having great potential for improving the insulation level of the Belgian houses on a large scale, especially when compared with the low cost, the limited intervention in comparison to inside and outside wall insulation. The main drawbacks remain the limited thermal insulation that can be achieved, due to the limited cavity width and the fact that heat losses through cold bridges remain unsolved.

## REFERENCES

ISO 10456:2007(E). *Building materials and products – Hygrothermal properties – Tabulated design values and procedures for determining declared and design thermal values.*

NBN B 62-002 *Thermal performances of buildings. Calculation of thermal transmittances of building components and building elements. Calculation of transmission and ventilation heat transfer coefficients*

ISO 9869:1994(E) *Thermal insulation – Building elements – In-situ measurement of thermal resistance and thermal transmittance*

NBN_EN 13829;2000(E) *Thermal performance of buildings - Determination of air permeability of buildings - Fan pressurization method(ISO 9972:1996, modified)*

Doran S. & Bernard C. (BRE) 2008,  *BRE Report 222077, Thermal resistance of walls of dwellings before and after application of cavity wall insulation.*

IWT-Tetra 2007. *Tetra-project 70127 'Injected insulation of existing cavity walls: analysis of quality and suitability of materials and installation methods' UGent, WenK St-Lucas Architectuur, WTCB, CIR*

Flemish Energy Agency (VEA) 2009. *Action plan of the Energy Renovation Program 2020 (in Dutch: Actieplan van het Energierenovatieprogramma 2020 voor het Vlaamse woningbestand)*

Physibel. *TRISCO v11.0W, software for 3D simulation of steady state heat transfer*

Ciga. *Cavity Insulation Guarantee Agency*

Venin. *Association of retrofit cavity-wall installers in the Netherlands ( Vereniging van Erkende Na-isolatiebedrijven in Nederland)*