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Building thermal bridge heat losses quantification by infrared thermography. Steady-state evaluation and uncertainty calculation

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Abstract. This study deals with the measurement of thermal bridges properties in building walls. The methodology is tested on an experimental wall built in laboratory. The setup thermal bridges transmission coefficients ψ and χ are measured in steady-state by infrared thermography. To do so, the thermal bridges impact factor I_{tb} is calculated. In the proposed method, the value of the surface emissivity is not required: only apparent temperatures are used. Experiments proved good reproducibility. Calculations of the uncertainties enabled to identify infrared measurements as the main sources of error.

1. Introduction

A building's thermal insulation cannot be homogeneous. Elements such as windows, floor/wall junctions, or mechanical systems used to hold insulating materials generate local additional heat losses. These elements are called "Thermal bridges" and may be responsible for 30% of the building energy demand [1]. This study focuses on thermal bridges originating from insulation material fixing on walls: they are called "Integrated Thermal bridges". The present work was made in the context of a PhD thesis on the measurement of thermal-bridge-induced heat losses using active infrared thermography (that is to say by artificially heating the wall). Results presented here are from a preliminary study focused on the steady-state characterization of several thermal bridges included inside an experimental setup. Measured values will be used as reference for validation of the transient methodology currently under development. The originality of the present paper mainly lays in the calculation of the impact factor I_{tb} (ratio of the heat flux on the thermal bridge over the heat flux on a sound area) only based on infrared thermography measurements. The wall emissivity is not required, which reduces the measurement uncertainties.

2. Experimental setup

2.1. Presentation

In order to test the thermal bridge characterization methodology, a full scale experimental wall was built in laboratory. As shown in Fig 1a, it has three layers. From the inside to the outside, they are made out of gypsum, glass wool and extruded polystyrene. The wall global thermal resistance is about 2.9 $m^2.K.W^{-1}$. Within the glass wool layer, more conducting materials are

inserted to create thermal bridges. These materials are commonly used in internal insulation systems: a metal rail, a wood stud and two metal pins. Several thermocouples and heat flux meters are positioned inside the setup. In addition, a flat heating resistance is placed on the rear side. It is used to generate a temperature gradient that allows thermal bridges visualization. Finally, the assembly is inserted inside a polystyrene frame: only the front face is visible and observed with an infrared camera. The latter is from FLIR (reference SC7000). It has a 320×256 pixels matrix cooled sensor, sensitive to the 7.7-9.2 μm band and of sensitivity 20 mK.

2.2. Thermal images

Figure 1b shows the front face of the setup, in the infrared spectrum. The presented thermal image is a time-average over several hours of steady-state (reached after feeding the heating resistance with 25W for at least 24h). Thermal bridges are visible. From the recorded thermogram, the apparent temperature profiles T^{app} in the vicinity of the thermal bridges are extracted, as shown in Fig 2.

(a) *Presentation of the experimental setup (dimensions in mm)*   (b) *Thermogram of the setup and regions of interest*
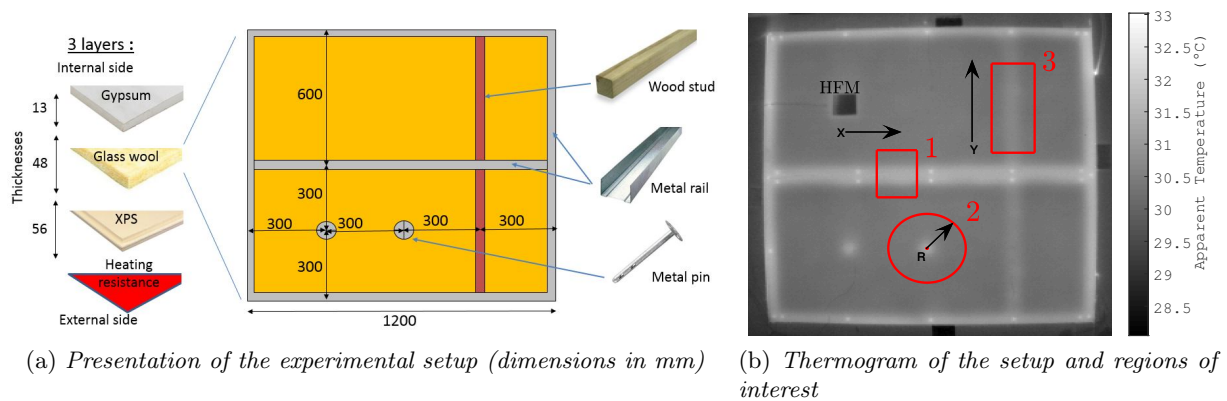
Figure 1: *Overview of the setup and thermogram obtained in steady state (25W heating power). Thermal bridges as well as a surface heat flux meter are visible.*
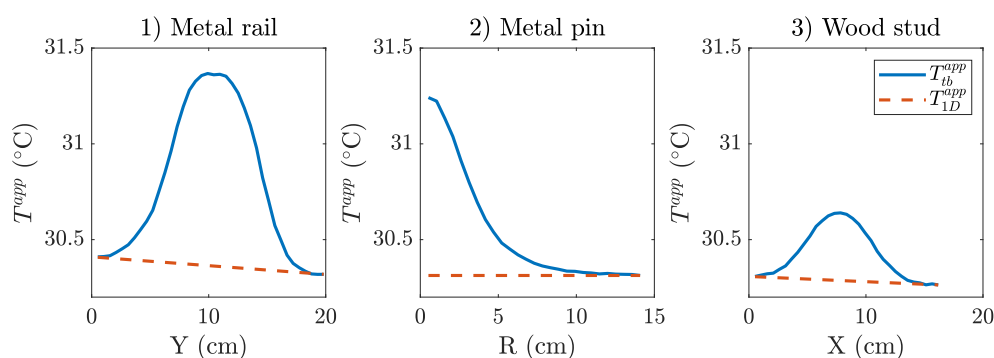
Figure 2: *Apparent temperature profile near thermal bridges (space average of regions of interest shown in Fig 1b). The metal pin profile is circular.*

3. Methodology

3.1. Transmission coefficients calculation

First, the overall insulation level of the wall without thermal bridge is needed. It is characterized by a transmission coefficient U in $W.m^{-2}.K^{-1}$. This allows to work out the linear and punctual

thermal bridge transmission coefficients ψ and χ.

3.2. Wall U-value calculation
The wall U-value is given by:

$$U = \frac{1}{R_{si} + R_{wall} + R_{se}} \tag{1}$$

with $R_{si} = 0.13$ m^2.K.W^{-1} and $R_{se} = 0.04$ m^2.K.W^{-1} the internal and external superficial resistances (values from [2]) and R_{wall} the wall thermal resistance. In steady-state:

$$R_{wall} = \frac{\Delta T_{stat}}{\varphi_{stat}} \tag{2}$$

with φ_{stat} the surface heat flux and ΔT_{stat} the temperature difference between the two sides.

3.3. Thermal bridges transmission coefficients calculation
Transmission coefficients ψ and χ respectively refer to linear and punctual thermal bridges [3]. In steady-state, the ψ coefficient is given by:

$$\psi = \frac{\phi_{tb}}{L_z \times \Delta T_{ie}} \tag{3}$$
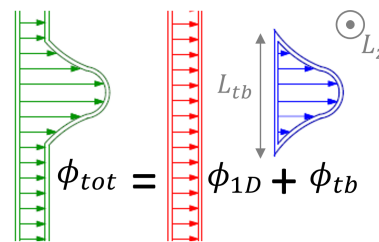
or

$$\psi = L_{tb}(U_{tb} - U_{1D}) \tag{4}$$

Figure 3: *Scheme of additional heat flux ϕ_{tb}*

with ϕ_{tb} the additional heat flux due to the thermal bridge (as illustrated in Fig 3), ΔT_{ie} the internal/external temperature difference and L_z the thermal bridge length. U_{tb} is the mean surface transmission coefficient including the thermal bridge while U_{1D} is its equivalent without thermal bridge. L_{tb} is the width of the thermal bridge impact zone (heat transfers are supposed 1D outside this zone). Asdrubali *et al* introduced the impact factor [4] :

$$I_{tb} = \frac{U_{tb}}{U_{1D}} \stackrel{steady-state}{=} \frac{\varphi_{tb}}{\varphi_{1D}} \tag{5}$$

Therefore, linear and punctual transmission coefficients may be expressed a functions of three parameters:

$$\psi = L_{tb}U_{1D}(I_{tb} - 1) \tag{6}$$
$$\chi = S_{tb}U_{1D}(I_{tb} - 1) \tag{7}$$

With S_{tb} (m^2) the impact zone of the punctual thermal bridge. The following assumption is then made:

$$I_{tb} = \frac{\varphi_{tb}^{rad}}{\varphi_{1D}^{rad}} \tag{8}$$

This equation is true if the air temperature is equal to the mean radiant temperature (which is realistic indoor) and if the radiative and convective heat exchange coefficients are uniform on the portion of the wall studied (also realistic given the small surface temperature difference between thermal bridges and sound areas). The surface emissivity must be uniform as well.

Hypothesis of Eq 8 is of interest because radiative heat flux measurements with an infrared camera are straightforward and more accurate than total heat flux measurements. Indeed, the radiative heat flux is easily derived from apparent temperatures and does not depend on the surface emissivity :

$$\varphi^{rad} = \sigma_{sb} \left[(T^{app})^4 - (T_{env}^{app})^4 \right] \tag{9}$$

With σ_{sb} the Stefan-Boltzmann constant. Apparent temperatures are those directly measured by the infrared camera (unit emissivity). It is the temperature of a black body that would have an emitted radiative heat flux equal to the heat flux received by the camera. T_{env}^{app} is the so called the "Mean Radiant Temperature". The environment is supposed black with a view factor equal to 1. Hence the impact factor :

$$I_{tb} = \Sigma_{i=1}^{P} \frac{T_{tb,i}^{app} - T_{env}^{app}}{T_{1D,i}^{app} - T_{env}^{app}} \tag{10}$$

with P the considered number of pixels. The heat flux ratio is calculated on each pixel of an apparent temperature profile, such as those given in Fig 2.

4. Uncertainty Calculation

To demonstrate the advantage of the proposed method that uses apparent temperatures, the measurement uncertainties are calculated and compared with those obtained if real temperature are used (standard method). The example of the metal rail is considered here.

4.1. Uncertainty of the proposed method (calculations from apparent temperatures)
Measurement uncertainties on ψ (similarly χ) were propagated according to [5]:

$$u(\psi) = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial \psi}{\partial \beta_i} u(\beta_i) \right)^2} \tag{11}$$

with u the uncertainty and $\beta_1, \beta_i, ...\beta_n$ the quantities from which ψ is derived. ψ is calculated from three quantities: L_{tb}, U_{1D}, and I_{tb} (see Eq 6). Each one is itself a function of several parameters that are detailed in Tab 1. Nominal values and uncertainties are also given. The measured thermal bridge width L_{tb} is given by:

$$L_{tb} = N_p \times \frac{L_{ref}}{N_{ref}} \tag{12}$$

with N_p the number of pixels in the thermal image. A ruler of known length L_{ref} is introduced in the view field of the camera and N_{ref} is its corresponding number of pixels on the image.

Table 1: Input data for coefficient ψ uncertainty calculation (metal rail example)

$\psi = L_{tb}U_{1D}(I_{tb} - 1)$		
L_{tb}: Eq 12	U_{1D}: Eq 1 et 2	I_{tb}: Eq 10
$L_{ref} = 1200 \pm 1$mm	ψ_{stat}=11.7W.m^{-1}.K$^{-1} \pm 3\%$	$\overline{\Delta T_{tb}^{app}} = 0.91 \pm 0.02°C$
$N_{ref} = 230 \pm 3$	$\Delta T_{stat} = 31.4 \pm 0.5°C$	$\Delta T_{1D}^{app} = 0.52 \pm 0.02°C$

4.2. Uncertainties of the "standard method" (Calculations from T)
Here, the calculation of I_{tb} is made by replacing apparent temperatures in Eq 10 by real temperatures. Basically, the measurement of the real temperature T with an infrared camera is given by:

$$T = \left[\frac{1}{\epsilon} (T^{app})^4 + \left(1 - \frac{1}{\epsilon} \right) (T_{env})^4 \right]^{\frac{1}{4}} \tag{13}$$

with ϵ the object emissivity, T^{app} its apparent temperature and T_{env} the mean radiant temperature. The later is similarly evaluated by disposing an infrared mirror (aluminum sheet) of known reflexivity on the wall. Its temperature is measured with a thermocouple. From Eq 13, the measurement uncertainty on I_{tb} for the "standard method" is evaluated. Similarly to paragraph 4.1, the uncertainty on ψ and χ coefficients is then derived.

5. Results
Several experiments were made on the setup to test the presented methodology. They were made in two different rooms, two setup orientations and several different heating powers. This allowed to evaluate the method reproducibility. The estimation results are gathered in Fig 4 and summarized in Tab 2.
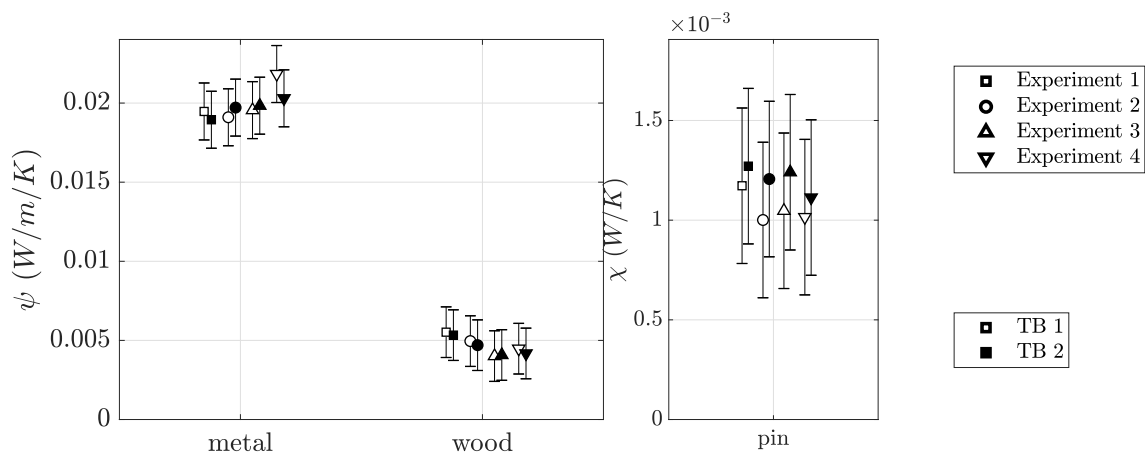

Figure 4: *Results of thermal bridge coefficients estimation. Each thermal bridge transmission coefficient is calculated at two locations.*

Table 2: *Detailed results on thermal bridge transmission coefficients estimation (averaged values of several measurements). Comparison of uncertainties between methods.*

TB	Unit	Measure	Spread (%)	u	u (standard method)
ψ_{rail}	W.m^{-1}.K^{-1}	0.0198	4.1	0.0018	0.0040
ψ_{wood}	W.m^{-1}.K^{-1}	0.0045	15.8	0.0016	0.0038
χ_{pin}	W.K^{-1}	0.0011	11.2	0.0004	0.0009

First, there is a rather good reproducibility: results spread is of 4% for the metal rail and between 10 and 15% for the other thermal bridges. Basically, measurements on the metal rail are

more accurate because it has a higher surface temperature contrast. Also, the spread between measurement is smaller than the calculated uncertainties u. The measurement uncertainties in the "standard method" are significantly higher, which shows the interest of the proposed approach. In addition, parameters relative contribution to the measurement uncertainty on ψ are given in Fig 5. It may be observed that most of the measurement uncertainty on ψ comes from the calculation of the impact factor I_{tb} that is to say from the measurement of the apparent temperatures T_{tb}^{app} and T_{1D}^{app}.
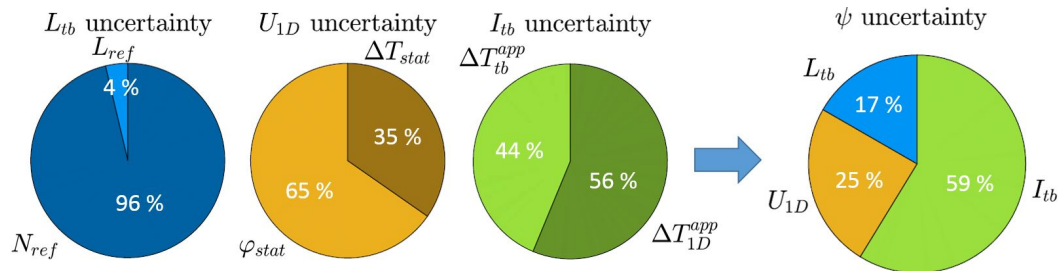

Figure 5: *Relative uncertainty of each parameter in ψ coefficient calculation. For a quantity Y function of parameters β_i, each parameter relative contribution to Y uncertainty is:* $\left| \frac{\partial Y}{\partial \beta_i} u(\beta_i) \right|$

6. Conclusion

Infrared thermography may be used for the quantification of heat losses due to integrated thermal bridges. In steady-state, thermal images allow to work out an impact factor I_{tb} which is a heat flux ratio. The proposed methodology requires no knowledge of the surface emissivity: the I_{tb} factor is directly calculated from apparent temperatures. This more than halves the measurement uncertainties when compared to the standard method. Linear and punctual transmission coefficients ψ and χ are then derived. Measurements performed on a lab-scale experimental wall proved the method reproducibility and accuracy. The measurement spread is between 5 and 15% depending on the thermal bridge. These values might seem high, but are due to the very small magnitude of ψ and χ coefficients for some of the studied thermal bridges: $\psi = 0.0045$ W.m^{-1}.K^{-1} and $\chi = 0.0011$ W.K^{-1} for the smallest ones. Finally, infrared measurements were identified as the highest source of uncertainty. The present study is not intended to be applied in-situ. The calculated thermal bridge coefficients will be used as reference values for heat losses estimations using transient methods that are currently being developed.

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