A quantitative methodology to evaluate thermal bridges in buildings

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Abstract

The use of multi-layer walls with high thermal resistance values is widely used to reduce heat losses in buildings during wintertime. Nevertheless, it is extremely important to treat also weaker components of the envelope such as doors, windows and all the various thermal bridges, otherwise the efforts in increasing walls thermal resistance can be vanished.

If the improvement of the thermal performance of windows and doors has reached a significant development and a high level of standardization, the same is not true for the corrections related to thermal bridges, which therefore require a specific analysis in the design phase.

Thermal bridges, of whatever nature, are therefore a crucial point in the energy analysis of the building envelope. The analysis on existing constructions can be performed on site with thermographic techniques that describe in first approximation the qualitative energy performance of the building and put in evidence the main heat losses.

The paper proposes a methodology to perform a quantitative analysis of some types of thermal bridges, through simple thermographic surveys and subsequent analytical processing. From the simple measurement of the air temperature and the analysis of the thermogram, the thermal bridge effect can be estimated as a percentage increase of the homogenous wall thermal transmittance. This term is obtained without further information on the structure of both the thermal bridge and the stratigraphy of the wall.

The analytical methodology - which was validated with experimental and numerical analyses - is described and the results of surveys on different types of thermal bridges are reported. This method represents a quick and effective tool to define the actual heat loss of high-insulation buildings and to evaluate the benefits in treating thermal bridges.

Keywords
buildings, insulation, thermal bridges, infrared thermography, numerical analysis

Introduction

The study and reduction of buildings heat losses plays an important role on an integrated energy-saving policy. The infrared (IR) thermography imaging technique results useful to conduct \textit{in-situ} analyses, since it allows a qualitative survey to evaluate the surface temperatures of the envelope surfaces.

Following the Standard procedure, a comparative analysis has to be conducted with reference thermograms that describe the main defects. The qualitative approach of this investigation leads to the assessment of easily recognizable imperfections such as air infiltration, bad insulation, mould, etc.

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On the other hand, a comparative analysis among different kinds of thermal bridges becomes difficult when it is performed through purely qualitative evaluations. The present work tries to define a quantitative approach based on the analysis of the thermogram that describes the temperature field on the internal or external surface of a part of the envelope. The aim consists of evaluating the thermal bridge effect, providing a percentage increase of the homogenous wall thermal transmittance.

The IR thermographic analysis is influenced by many factors affecting the accuracy of the absolute temperature reading. After a quick analysis on the determination of the parameters involved in the IR scanner temperature output, the analytical description of the quantitative incidence factor of the thermal bridge is introduced.

The validation of the methodology has been executed with the realization of a thermal bridge in a controlled environment, so giving the possibility of comparing the proposed technique to other experimental data and to a finite volumes analysis. After the process validation, the investigation has been extended to other types of envelope singularities.

1. Literature review

The application of IR thermography in buildings may be characterized by different levels of deepening: a first step qualitative analysis is described by Balaras e Argirious [1], with diagnosis oriented not only to buildings energy losses, but also to non-destructive tests of ventilation, heating, air conditioning and electric plants.

Quantitative IR thermography has to take into account a number of variables linked to the heat transfer phenomena. Barreira and de Freitas [2] conducted a sensitivity analysis of the process to the emissivity, reflection, environmental conditions and surface colour, by means of laboratory measurements and “in situ” campaigns. Avdelidis and Moropoulou [3] proposed a detailed investigation on the influence of emissivity, while Datcu et al. [4] used experimental methodologies for the determination of the reflected temperature. Li et al. [5] suggested that a preparatory study in a laboratory gives important indications for the elimination of reflection bias.

Active thermography is suitable for the detection of internal defects, as explained by Grinzato et al. [6]. Albatici e Tonelli [7] defined a methodology for the evaluation of the thermal transmittance of an opaque component, through the IR thermography and the contemporary measurements of the external and internal air temperatures, comparing the results of three cases with data obtained from heat flow meters.

As far as the specific application of IR thermography to thermal bridges, Zalewski et al. [8] studied the effect of a steel junction inside a prefabricated panel with a preliminary thermographic analysis, making a further refinement by heat flow meters and three-dimensional numerical models. Finite element codes in conjunction with IR detectors were also used by Heinrich e Dahlem [9] (for the investigation of low consumption buildings) and Wröbel e Kisilewicz [10] (for testing structural thermal bridges).

Finally, Benko [11] indicated a quantitative analysis factor associated to the thermal bridges heat dispersion, obtained by means of the sole study of the thermogram of the external surface of a building.

2. Infrared thermography outlines

In figure 1 the heat transfer processes of a thermographic analysis are sketched [12]. The energy balance is synthesized by Eq. 1:

\[ W_{\text{tot}} = \varepsilon \tau W_{\text{obj}} + (1 - \varepsilon) \tau W_{\text{ref}} + (1 - \tau) W_{\text{atm}} \]  

(1)

where \( W_{\text{tot}} \) represents the total energy that hits the detector when the object to be analyzed is focused; the only term of interest for a quantitative analysis is \( W_{\text{obj}} \), the energy radiated from the object, that is a function of its temperature.
The other two addenda are related to contributions from different sources standing around the measurement field \((W_{\text{refl}})\) and the atmosphere absorption \((W_{\text{atm}})\). Once the last two terms are identified, the remaining uncertainty arises from the definition of the emissivity properties of the object under investigation.

Therefore, IR thermography detectors need a series of parameters to take into account of the physics of heat transfer: object emissivity, reflected temperature, atmosphere temperature, relative humidity, distance from the object.

The emissivity could be determined by the parallel measurement of the surface temperature with other instruments or using tapes with known emissivity, applied on the examined surface. The reflected temperature is obtained, for instance, laying a rubbed aluminum foil on the object surface, setting at the same time the detector emissivity to the unitary value. Because of the aluminum high reflectivity, the rub and the IR detector setting, the thermogram generated gives the reflected temperature \(T_{\text{refl}}\) linked to the radiative heat sources present in the measurement environment.

Finally, the imaging has to be executed with the detector lens not perpendicular to the object analyzed, at the aim of avoiding the so-called “narcissus effect”: the detector sees its lens reflected on the object.

All the previous actions are necessary to improve the quantitative thermography, minimizing the sources of errors and uncertainty [13].

3. Description of the methodology adopted for the quantitative analysis of thermal bridges

Each image obtained by an IR detector gives the temperature of each pixel hit by the radiation emitted form the object examined, so defining the entire thermal field of the area covered by the detector optic.

IR thermography applications for the evaluation of heat dispersions in buildings perform at their best if a minimum temperature difference of 10÷15 °C between the external and internal environment is guaranteed [14].

Analyzing, for example, the inner side of envelope components during the heating season, a decrease of surface temperature is easily registered (figure 2).

The aim of the present work is to introduce a parameter able to express the thermal bridge effect on the building dispersions, using only the information captured from the thermogram.

Generally speaking, a thermal bridge is individuated by the linear thermal transmittance, obtained by a two-dimensional calculation [15] and defined by the following equation:

\[
\psi = L_{2D} - \sum_{k=1}^{n} U_k l_k
\]

where \(L_{2D}\) is the linear thermal coupling term derived by the two-dimensional calculation, \(U_k\) is the thermal transmittance of the \(k^{th}\) one-dimensional component (length \(l_k\)) that separates the internal side from the external environment.
Thus, the quantitative classification of thermal bridges is identified by the value of $\psi$, that gives the thermal flux transferred per length and temperature unit in steady-state conditions. Besides, the linear thermal transmittance determines the thermal field visualized by the IR detector: in winter season, with the same indoor-outdoor temperature difference, thermal bridges with higher dispersions generate thermograms with lower temperature values in the internal side.

Figure 2: Example of a structural thermal bridge and window thermal bridge at the coupling of glass and frame.

The definition itself of thermal bridge [16] puts in evidence that it represents a zone with thermal properties significantly different from the rest of the envelope; as a consequence, the temperature of the inner side will be interested by considerable variations in the area influenced by the thermal bridge, assuming on the contrary an almost constant value in the part of the structure where the heat flux can be considered one-dimensional. In this “undisturbed” zone, the temperature is a function of the thickness and thermal conductivity of the layers that constitute the wall; in stationary conditions, the heat flowing through the one-dimensional wall can be written with as follows:

$$Q_{1D} = h_{1D,i} A_{1D} (T_i - T_{1D,is})$$

where $h_{1D,i}$ is the internal laminar coefficient, $A_{1D}$ is the area considered and the temperatures $T_i$ and $T_{1D,is}$ represent respectively the inner air and the inner surface temperatures.

In the case of the introduction of a thermal bridge in the area $A_{1D}$, the eq. 3 is not applicable since the temperature is far from being constant throughout the entire surface. Analyzing the area with an IR detector, the thermal field of the wall under investigation is available, therefore, a temperature value $T_{pixel,is}$ could be associated to each pixel that is representative of a part $A_{pixel}$ of the wall surface; the extension of $A_{pixel}$ depends from the resolution of the chosen detector. Hence, the evaluation of the heat flux is possible in each pixel, obtaining a formulation of the whole area dispersion:

$$Q_{tb} = h_{tb,i} A_{pixel} \sum_{pixel}^N (T_i - T_{pixel,is})$$

with the hypothesis of constant laminar coefficient and being $N$ the number of pixels that compose the entire area, according to the relation:

$$A_{1D} = NA_{pixel}$$

Then, the incidence factor of the thermal bridge $I_{tb}$ is defined as the ratio between the heat flowing in real conditions and the heat flowing in absence of the thermal bridge:
\[ I_{tb} = \frac{Q_{tb}}{Q_{1D}} = \frac{h_{tb,i}A_{\text{pixel}} \sum_{j=1}^{N} (T_i - T_{\text{pixel}\_is})}{h_{1D,i}A_{1D}(T_i - T_{1D\_is})} \]  

(6)

On the basis of eq. 6, a methodology of imaging is proposed, aimed to obtain the data necessary for the evaluation of the two heat fluxes with the only help of the acquisition of the internal environment temperature, minimizing at the same time the sources of errors.

For example, considering a structural thermal bridge constituted by a wall angle infinitely high, the thermogram will show a minimum in correspondence of the angle, moving then towards an asymptote that represents the wall behaviour in the one-dimensional zone, where the effect of the thermal bridge is negligible (figure 3).

![Figure 3: Example of an angular thermal bridge and relative thermogram output](image)

The choice of the area covered by the imaging plays a fundamental role, since the distance \( D \) (figure 3) has to be sufficient to include the undisturbed zone, whose temperature value is the term \( T_{1D\_is} \) of eq. 6. The advantage of acquiring in the same thermogram both the temperature of the thermal bridge area and the thermal field of the one-dimensional wall consists of avoiding the introduction of further errors linked to different instants of reading or different angles of view.

Besides, since the domain is limited and the image is captured in the same instant for all the surface, the laminar coefficient could be considered constant throughout the entire area:

\[ h_{1D\_i} = h_{tb\_i} \]

Therefore, also recalling eq. 5, the incidence factor of the thermal bridge becomes:

\[ I_{tb} = \frac{h_{tb\_i}A_{\text{pixel}} \sum_{j=1}^{N} (T_i - T_{\text{pixel}\_is})}{h_{1D\_i}A_{1D}(T_i - T_{1D\_is})} = \frac{A_{\text{pixel}} \sum_{j=1}^{N} (T_i - T_{\text{pixel}\_is})}{NA_{1D}(T_i - T_{1D\_is})} = \frac{\sum_{j=1}^{N} (T_i - T_{\text{pixel}\_is})}{N(T_i - T_{1D\_is})} \]

(7)

This quantitative factor could be also expressed in terms of an increase of the thermal transmittance \( U_{1D} \) of the undisturbed zone; considering the influence of the thermal bridge, and using the hypothesis of steady-state conditions, the actual value of the wall thermal transmittance \( U_{tb} \) can be written as follows:

\[ U_{tb} = U_{1D} \times I_{tb} \]

(8)

4. Model validation

In this section the validation process of the methodology described in the previous paragraph is reported. The thermal bridge selected for the purpose is the one generated in a window, by the
coupling between the glass and frame (figure 2). The choice was dictated by the possibility of installing the window inside an available climatic chamber, whose characteristic and dimensions do not permit the testing of a structural thermal bridge. The sample is mounted between two rooms with a temperature difference of about 20 °C, in steady-state, monitored and controlled conditions.

The validation of the proposed methodology has been assessed with two different approaches:

- an instrumental heat flow analysis, where the heat transfer is measured point by point through the window area;
- a numerical analysis, implementing a two-dimensional model of the node of the window considered

4.1 Thermographic analysis

Infrared thermographic measurements were carried out in the lab to verify the various parameters influencing the phenomenon, including steady-state conditions. The window was positioned between a conditioned space, kept at -1 °C, and the laboratory, kept at constant temperature too. The attention was focused on the window’s lower thermal bridge, whose section is characterized by aluminium with polyamide washers to assure the thermal cut. The glazing is a low emissivity one, mm 6/7 + mm 15 + mm 8/9 with an aluminum spacer.

The IR detector is manufactured by FLIR, model B360 with a FPA microbolometer without cooling, a spectral range from 7.5 and 13.0 µm, and a 320×240 pixel resolution.

To quantitatively evaluate the thermal field, it was necessary to perform calibration measurements and to acquire the various parameters to be inserted into the instrument to correct the thermogram. The surface emissivity was calculated thanks to surface temperature probes, varying the emissivity in the IR detector, so to obtain the measured temperatures. The reflected temperature was then evaluated with the methodology described in paragraph 2, using an aluminium foil (figure 4).

Figure 4: Measurement of the reflected temperature.

Thanks to thermohygrometric probes, environmental conditions were evaluated during the measurements. Also the distance between the sample and the IR detector was registered.

A particular attention was paid to the framing, to respect the value of the distance D from the thermal bridge defined in the previous paragraph. From the standard UNI EN ISO 10077-2 [17], which deals with the numerical calculations for the frames, a distance D of at least 200 mm was evaluated, to include in the thermographic image the undisturbed area. Figure 5 shows the thermogram which will be studied, also calculating the incidence factor of the thermal bridge; the thermal bridge is actually composed by the junction between the frame and the glass but, since the length of the opaque part is reduced to few centimeters, the analysis is limited to the transparent portion of the window. The domain considered for the validation process is constituted by an imaginary line (figure 5) on the central area of the glass (far away from the lateral thermal bridges). The trend of temperature along the line is shown in the figure.
5, where the asymptotic behaviour is clearly visible towards the temperature of the undisturbed area (17.7 °C).

![Image](image1.jpg)

Figure 5: Thermogram of the lower part of the window and trend of temperature along the imaginary line.

Calculating the number of pixels that compose the line and applying the above procedure for the evaluation of the *incidence factor of the thermal bridge*, the value of 1.174 is obtained, with an uncertainty of 6.4%, considering a confidence level equal to 95%. The error rate was estimated referring to the Standard UNI CEI ENV 13005 [18], taking into account of the uncertainty associated with the temperature read by the camera, provided its technical data.

4.2 Heat flow analysis

Before the execution of the thermographic analysis, a group of temperature and heat flow probes have been placed in the area subjected to investigation. Figure 6 shows the arrangement, with the sensors following the imaginary line described above. The heat flow probes allow the measurement of the heat flux density (W/m$^2$) in the undisturbed zone and throughout the whole area of the thermal bridge; the table 1 reports the values of the heat flow, with the relative areas of interest. In the undisturbed zone only one heat flow meter was placed, while the part closest to the frame and affected by the thermal bridge has been inspected with three heat flow meters, placed one above the other.

![Image](image2.jpg)

Figure 6: Heat flow meters to evaluate the thermal bridge in the transparent part of the window.
Table 1: Heat flow meters results, with the relative areas of interest.

<table>
<thead>
<tr>
<th>Φ_D</th>
<th>Heat flux density (W/m²)</th>
<th>A_D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Φ_1D</td>
<td>32.8</td>
<td>0.11</td>
</tr>
<tr>
<td>Φ_2D</td>
<td>38.5</td>
<td>0.03</td>
</tr>
<tr>
<td>Φ_3D</td>
<td>46.1</td>
<td>0.03</td>
</tr>
<tr>
<td>Φ_4D</td>
<td>63.4</td>
<td>0.03</td>
</tr>
</tbody>
</table>

The incidence factor of the thermal bridge is estimated using following equation:

\[ I_{th,IFM} = \frac{Q_{th}}{Q_1} = \frac{\varphi_D A_D + \varphi_{th} A_{th} + \varphi_{th} A_{th} + \varphi_{th} A_{th}}{\varphi_D (A_D + A_{th} + A_{th} + A_{th})} \]

The incidence factor of the thermal bridge results equal to 1.228 with an uncertainty of 7.4% (confidence level equal to 95%), associated to the presence of the heat flow probes [18].

4.3 Numerical analysis

The commercial code FLUENT [19] was used for the Computational Fluid Dynamic analysis. The section of the window was modelled taking into account the standard UNI EN ISO 10077-2 [17], to evaluate the thermal properties of the air space and of the materials. Boundary conditions are convective and the cool and hot side temperatures are defined by the laboratory measurements (hot side temperature: 22.2 °C, cold side temperature -0.7 °C), while the coefficients of convection are derived from the Standard.

As a matter of fact, the window is placed between two spaces whose environmental conditions are similar to the real ones; the cold side is characterized by forced convection while the hot one by natural convection. As far as convection, simulations were therefore carried out with standard conditions, so that the results could be easily extended to the real buildings conditions. The mesh is a triangular one, with a step of about 0.5 mm. Figure 7 shows the temperature field in the section of the two-dimensional model, together with the temperature trend along the imaginary line of figure 6.

To evaluate the incidence factor of the thermal bridge, the imaginary line was divided into small segments of the same length of the mesh. The hypothesis allowed to compare the simulation output data with the data taken from the thermogram, assimilating the behaviour of a pixel to the one of a single mesh. The value of the incidence factor of the thermal bridge obtained from the simulation is equal to 1.169, with an uncertainty of 4.6% (confidence level equal to 95%), derived from the indications of the Standard UNI EN ISO 10077-2.

Figure 7: Numerical analysis: thermal field in a generic section of the window and temperature trend along the imaginary line.
4.4 Comparison between the methodologies

Figure 8 shows the temperature trends of the three different methods along the imaginary line. In the case of the heat flow analysis, the sole points where the temperature probes were placed are reported; from a qualitative point of view, the temperature trend in the thermogram can be compared to the results of some studies found in literature [20].

The three methods show a good agreement, with a light difference in the central area of the thermal bridge. In figure 9 the results in terms of the incidence factor of the thermal bridge are sketched, together with the relative uncertainties; it is evident that, considering the confidence interval, results overlap, therefore, the method could be considered as validated.

5. Application of the methodology to in situ thermal bridges

Two different configurations of a floor with a low beam were chosen in situ to evaluate the incidence factor of the thermal bridge. The first configuration presents a correction of the thermal bridge with insulating panels (both inside and outside) while the second one is not insulated at all.

In both cases a thermographic image was acquired, including the undisturbed area and measuring at the same time the air temperature. The wall was not exposed to solar radiation; steady-state conditions were assumed, having evaluated the environmental conditions during the periods before the measurement. Also in this case, an imaginary line was considered starting from the internal edge between the floor and the wall (figures 10 and 11).
Figure 10: Thermogram of the insulated beam and temperature trend along the imaginary line.

Figure 11: Thermogram of the non-insulated beam and temperature trend along the imaginary line.

Analyzing the trends, two completely different thermal fields can be observed; it is also possible to see the asymptotic part and evaluate the temperature of the undisturbed area.

The difference between the two configurations is evident if we compare the two values of the incidence factor of the thermal bridge, which is equal to 1.606 for the configuration with the insulated beam and to 2.000 for the configuration with the non-insulated beam.

A further analysis was carried out for the investigated walls, evaluating thanks to a heat flux meter the thermal transmittance ($U_{ID}$) without the influence of the thermal bridge [21]. Thanks to the results, it was possible to evaluate the increase in the thermal transmittance of the wall, in the area of the thermal bridge, according to eq. 8 (table 2).

Table 2: Thermal transmittances of both configurations (undisturbed area and area of the thermal bridge).

<table>
<thead>
<tr>
<th></th>
<th>$U_{ID}$ (W/m$^2$K)</th>
<th>$I_{th}$</th>
<th>$U_{th}$ (W/m$^2$K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulated beam</td>
<td>0.42</td>
<td>1.606</td>
<td>0.67</td>
</tr>
<tr>
<td>Non insulated beam</td>
<td>0.39</td>
<td>2.000</td>
<td>0.78</td>
</tr>
</tbody>
</table>

It is therefore possible to obtain, thanks to the incidence factor of the thermal bridge, quantitative data concerning the thermal bridge even without a detailed knowledge of the stratigraphy of the wall.

In the case of the non insulated beam, a further analysis was carried out, since the stratigraphy was known. A computational analysis of the thermal bridge was therefore performed, obtaining a trend of temperatures similar to the real ones and a value of the incidence factor of the thermal bridge equal to 2.111.
A model in FLUENT was created to simulate also the correction of the thermal bridge (insulation of the beam). The calculated value of the incidence factor of the thermal bridge is equal to 1.262, so there is a reduction in the thermal bridge heat loss of about 40%.

In global terms, it is also possible to evaluate the benefits of such a correction in the heat losses of the whole flat. Simulations of the energy behaviour of the flat were carried out according to UNI TS 11300 [22]; an overall heat loss in wintertime of 4.684 W was evaluated, 13.4% of which due to the thermal bridge. The correction of the thermal bridge reduces the heat loss to a value of 4.307 W and the incidence of the thermal bridge to 8.8%.

The analysis allows to evaluate the global effects of the presence of thermal bridges in the envelope’s heat losses and to therefore in the energy primary demand of a building during wintertime.

Conclusions

The analysis of thermal bridges conducted with the IR thermography can be developed through various approaches, from qualitative investigations to the quantitative techniques of the active thermography.

In this work a quantitative factor was introduced, at the aim of evaluating in a simple and effective manner the effect of thermal bridges on the global dispersions of buildings. It was analytically defined the incidence factor of the thermal bridge that depends from the internal air temperature and the internal wall surface temperature, read by the IR detector. Afterwards, results acquired with the thermographic investigation were compared with data obtained by heat flow meters, and the findings of a finite volume analysis; this test was realized in a laboratory setup, where it was possible to monitor the boundary conditions, keeping the stationary conditions for the thermal bridge generated in a window from the coupling of glass and frame. It emerged that the thermal field obtained with the three methods is very similar, producing close values of the incidence factor of the thermal bridge.

Two in situ thermal bridges were then investigated, verifying the effect of the insulation on a floor beam; it came out that the incidence factor of the thermal bridge describes correctly the dispersion grade of the singularity, quantifying the result of the thermal bridge correction.

The factor could be also used to define an increase percentage of the undisturbed wall thermal transmittance, so proposing a simple and useful tool to calculate the actual heat dispersions of buildings by quick and easy in situ thermographic measurements, suggesting at the same time possible interventions for the improvement of insulation.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>A:</td>
<td>Area [m²]</td>
</tr>
<tr>
<td>CFD:</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>D:</td>
<td>Distance [m]</td>
</tr>
<tr>
<td>h:</td>
<td>Laminar coefficient [W/m² K]</td>
</tr>
<tr>
<td>I:</td>
<td>Incidence factor [-]</td>
</tr>
<tr>
<td>L:</td>
<td>Thermal coupling coefficient [W/K]</td>
</tr>
<tr>
<td>l:</td>
<td>Length [m]</td>
</tr>
<tr>
<td>N:</td>
<td>Number [-]</td>
</tr>
<tr>
<td>Q:</td>
<td>Thermal flux [W]</td>
</tr>
<tr>
<td>T:</td>
<td>Temperature [K, °C]</td>
</tr>
<tr>
<td>U:</td>
<td>Thermal transmittance [W/m² K]</td>
</tr>
<tr>
<td>W:</td>
<td>Energy [J]</td>
</tr>
<tr>
<td>ε:</td>
<td>Emissivity [-]</td>
</tr>
<tr>
<td>φ:</td>
<td>Heat flux density [W/m²]</td>
</tr>
<tr>
<td>τ:</td>
<td>Transmissivity [-]</td>
</tr>
<tr>
<td>ψ:</td>
<td>Linear thermal transmittance [W/m K]</td>
</tr>
</tbody>
</table>

Subscripts

1D: one-dimensional  
2D: two-dimensional  
atm: atmospheric  
HFM: evaluated with heat flow meter  
i: internal  
obj: object  
pixel: relative to each pixel  
refl: reflected  
s: surface  
tb: thermal bridge  
tot: total  
1: part of thermal bridge  
2: part of thermal bridge  
3: part of thermal bridge
References