Numerical and Experimental Study on the Impact of Humidity on the Thermal Behavior of Insulated Timber Walls

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Abstract

The push towards a lower environmental impact of the building sector has led to the widespread adoption of renewable organic materials such as wood and other bio-based insulation materials. These materials are characterised by a solid matrix with voids that can be filled with moist air and water and in which complex heat and mass transfer occurs, influencing the global thermal properties. Indeed, due to different heat transfer mechanisms involved, the apparent thermal conductivity varies both with temperature and moisture content because of water thermal conductivity is higher than air. However, many Building Simulation programs (e.g., EnergyPlus and TRNSYS) still adopt constant thermal properties for simulating the heat transfer in buildings, causing inaccuracies in calculations of heat flux and thus, in the prediction of the energy consumption of a building. The aim of this work is therefore to analyse experimentally and numerically the impact of both moisture and temperature on the thermal behaviour of an insulated timber wall. An experimental activity was conducted at the Building Physics Laboratory at the Free University of Bozen-Bolzano on Cross-lam (XLAM) and wooden insulation specimens to measure thermal conductivity at different temperatures and moisture contents by means of a heat flux meter (i.e., HFM) and a climatic chamber. A 1D model for coupled heat and mass transfer across the studied wall was then developed and calibrated against the experimental data. Finally, by simulating with both nominal (10 °C and 23 °C reference temperature) and actual thermal conductivity, hourly heat fluxes and energies were compared, taking into consideration climatic files relating to the Italian peninsula.

1. Introduction

The need to reduce the environmental impact of the building sector has led to the adoption of bio-materials such as wood. Wood, alone or as a component in different insulation products, guarantees a low environmental impact while ensuring reasonably good insulating properties because of the porosity in its structure, in which solid, gaseous and liquid phases coexist, and complex and interacting heat and mass transfer mechanisms operate (Bomberg and Shirtliffe, 1978; Künzel, 1995; Luikov, 1975; Rudtsch, 2000; Scheffler, 2008; Time, 1998).

Coupled heat and mass transfer influences the apparent thermal conductivity of materials, which is not a constant value measured at the reference conditions set by EN ISO 10456:2007 (CEN, 2007), and varies as a function of temperature and moisture content. Studies have shown how the thermal conductivity of wood and wood-based products increases with temperature and values can be 35 % higher than the reference value if the temperature is higher (Suleiman et al., 1999; Vololonorina et al., 2014). Similarly, thermal conductivity of a moist wood-based fibreboard can be from 12 % to 61 % higher than in dry conditions, depending on the temperature of the mean specimen (Troppová, 2015). This phenomenon is observed by Vololonorina et al. (2014) for other wood-based products. Furthermore, the specific heat of wood increases with both temperature and moisture content, as reported in the work of Radmanović et al. (2014).

Part of
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This dynamic change in the properties of the material can cause inaccuracies in the output of many Building Simulation programs in which thermal conductivity is kept constant. For this reason, this work aims to evaluate to what extent the moisture-temperature dependent thermal conductivity influences heat transfer across real insulated timber walls with different thicknesses. The work includes an experimental and a numerical part, in Section 2.1 and 2.2, respectively. The former consists of measurements of thermal conductivity at different temperatures and moisture contents for XLAM specimens and wooden insulation panels, carried out in order to correlate thermal conductivity to thermo-hygrometric conditions. Consequently, a 1D heat and mass transfer model was developed for three insulated walls with different thicknesses and the mass transfer was calibrated against experimental data. In particular, the vapor resistance factor was tuned by comparing simulated results with data from the conditioning process, from 80 % RH/ 23 °C to 10 % RH/ 23 °C. Finally, annual simulations were performed using the thermal conductivity measured in nominal conditions (10 °C and 23 °C reference temperature) and using the thermal conductivity in the actual conditions (i.e. thermal conductivity obtained from the thermal conductivity function). The results of these simulations were compared in terms of hourly specific heat fluxes and for seasonal energy exchanges in 110 cities.

2. Methodology

2.1 Experimental Activity

The experimental activity was focused on finding a correlation between thermal conductivity and mean temperature and water vapour partial pressure. Thermal conductivity measurements were conducted on 4 XLAM specimens (0.2 x 0.2 x 0.05 m) and 2 wooden insulation panels made of wood shavings, with dimensions of 0.3 x 0.3 x 0.05 m. Thermal conductivity measurements were repeated at different temperatures from 10 to 50 °C with 5 °C steps and different moisture contents (Table 1) obtained in a climatic chamber. The thermal conductivity was measured in the Building Physics Laboratory at the Free University of Bozen-Bolzano by means of a Netzsch HFM 436/3 Lambda™ (in compliance with ISO 8301:1991, EN 12664:2001 and EN 12667:2001). Samples had been previously pre-conditioned in an ATT Angelantoni DM340 climatic chamber, in accordance with EN ISO 12571:2013 (CEN, 2013). A drying process was carried out at 105 °C as suggested by EN ISO 12570:2000 (CEN, 2000). Conditioning processes are intermediate processes where the moisture content of the material is either increased or reduced in the climatic chamber; in particular, the term "drying" refers to the process of removal of water at a higher temperature.

2.2 Mathematical Model for Heat and Mass Transfer

A numerical 1D model of heat and mass transfer was developed to evaluate the impact of both moisture and temperature on the heat flux across insulated walls consisting of an XLAM and an insulation panel. The model was developed from scratch to allow for better control of its implementation. Thermal conduction (Fourier's law) and surface convection (Newton's law) were accounted for in the heat transfer, while Fickian vapor diffusion was assumed for the mass transfer process. The storage moisture capacity C_m adopted in the mass transfer model was calculated starting from the sorption isotherms determined experimentally for the insulation panel and from data found in the literature for the spruce (Fitzpatrick et al., 2013). The following heat (Equation 1) and mass (Equation 2) transfer equations were solved numerically by implementing a finite differences scheme.

$$\varrho\, c\, (\partial T / \partial t) - \nabla \cdot (\lambda\, \nabla T) = 0 \qquad (1)$$

$$C_m\, \varrho\, (\partial p_v / \partial t) - \nabla \cdot (\delta_p\, \nabla\, p_v) = 0 \qquad (2)$$

The main parameters of the materials (thermal conductivity and density) were measured or calculated, while others, like specific heat capacity c (1380 J kg^{-1} K^{-1} and 1281 J kg^{-1} K^{-1} for spruce and insulation, respectively) were taken from the literature. The vapor permeability δ_p for the XLAM was obtained after the calibration of the mass transfer model against experimental data (Section 3.2), while for the insulation panel, water vapor permeability was taken from the literature (Labat et al., 2016).

2.3 Simulation Procedure

Three insulated walls with different thicknesses were modelled (20 cm XLAM and 5, 10, 15 cm external insulation, respectively) for a period of one year. Space and time discretisation were 0.01 m and 1 h in the period. Surface convective heat transfer coefficients for horizontal heat flux, i.e. 20 W m^{-2} K^{-1} for the external side and 2.5 W m^{-2} K^{-1} for the internal side, were adopted. Effects of incident solar irradiance and precipitations were neglected. For the sake of simplicity, internal boundary conditions were assumed to be constant and equal to 20 °C, with 50 % relative humidity. On the external side, hourly data from the CTI database (https://try.cti2000.it/) for 110 Italian cities were considered. For all locations, simulations were run twice, and considered:

- nominal thermal conductivity, measured at both 10 °C and 23 °C in the low moisture content state, as suggested by the EN ISO 10456:2007 (CEN, 2007).
- actual thermal conductivity, in which linear correlations (Equations 3 and 4) in temperature and water vapor partial pressure were obtained from the experimental activity.

The analysed output variables were:

- linear percentage trend deviation between the specific heat fluxes, calculated in nominal and actual conditions obtained as the slope of the scatter plot of the two quantities.
- annual area-specific energy differences (expressed in watt-hour per square meter) for thermal losses, i.e. when the internal specific heat flux is directed towards the external, and positive thermal contributions, when it is directed towards the inside.

3. Results and Discussions

3.1 Experimental Investigation

Thermal conductivity for one representative specimen for both materials was measured at three different moisture contents *MC* (Table 1). The behaviour of the other tested samples, both for XLAM and for the insulation, was analogous. The low *MC* state and the high *MC* states shown in Table 1 were obtained in the climatic chamber by conditioning samples at the reported values of temperature and relative humidity, while the "as-is" condition is that of the sample in equilibrium with the laboratory humidity.

Table 1 – Moisture content values for the three different conditions for XLAM and the wooden insulation specimen (INS)

		XLAM	**INS**
State	**Condition**	***MC* (%)**	***MC* (%)**
Low *MC*	23 °C/10 % RH	3.5	3.6
"As-is"	20-26 °C/30-40 % RH	6.3	8.0
High *MC*	23 °C/80 % RH	13.2	13.6

As regards the XLAM, the measured dry weight was 651.0 g. The high *MC* state was obtained after 43 days of conditioning in the climatic chamber, starting from the "as-is" state with a mass increase of 6 %., while the low *MC* state was obtained after 9 days in climatic chamber at 23 °C/ 10 %, starting from the high *MC* state. The mass loss registered was of approximately 5 %. The drying process from the "as-is" state lasted 3 days and the registered mass loss was of 6 % with respect to the "as-is" condition.

As regards the insulation panel, the measured dry weight was 490.9 g. The duration of the conditioning processes and the drying was shorter because of the lower inertia of the material due to its structure. Indeed, the high *MC* state was obtained after 16 days in climatic chamber, while the low *MC* state was obtained after 12 days. The drying process lasted 3 days, as for the XLAM.

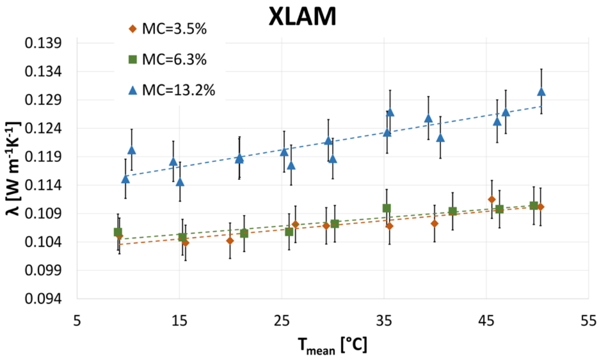

Fig. 1 – *λ* vs. *T* for the XLAM specimen at three different moisture conditions. Vertical bars represent the measurement uncertainty (3 %)

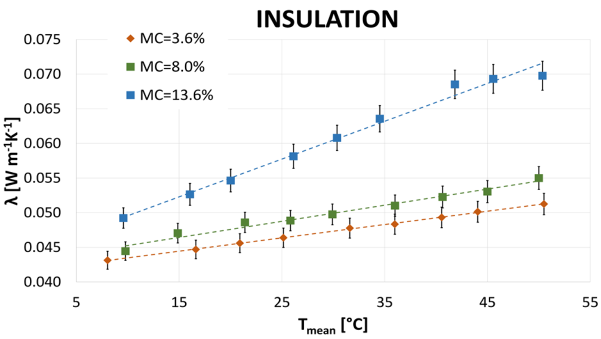

Fig. 2 – *λ* vs. *T* for the wooden insulation panel in three different moisture conditions. Vertical bars represent the measurement uncertainty (3 %).

Thermal conductivity λ of XLAM increased with temperature T in all the three cases, as expected (Fig. 1). The maximum difference obtained in the "as-is" state was equal to 11.3 %, by varying the temperature from 10 to 50 °C. By passing from the "as-is" to the high *MC* state, the obtained increase of thermal conductivity was 13.2 % at 23 °C. Thermal conductivity at the low *MC* state of 3.5 % had similar values to those in the "as-is" condition with 6.3 % *MC* (differences < 3 %), meaning that thermal conductivity had a strong non-linear behaviour.

As regards the wooden insulation, the trends were analogous (Fig. 2), but the percentage increases were higher. At a reference temperature of 23 °C, the percentage increase from the lowest *MC* to the highest was 22.6 %. By considering only temperature variation, the maximum increase was 41.7 % with the highest *MC*, while at the lowest *MC* the increase was 18.8 %. These larger differences were due to the lower value of thermal conductivity for the insulation than the wood. Nevertheless, the absolute increase was slightly higher for the insulation. Table 2 shows the calculated density and measured thermal conductivities used as input for the heat and mass transfer model. In particular, two values of nominal thermal conductivity were adopted: 10 °C and 23 °C, both in the low *MC* state.

Table 2 – Some input from the heat and mass transfer model obtained from the experimental activity

	XLAM		**INS**	
Density ρ	363		106.7	
Condition	Low *MC*/ 10 °C	Low *MC*/ 23 °C	Low *MC*/ 10 °C	Low *MC*/ 23 °C
λ	0.104	0.107	0.043	0.045

Equations 3 and 4 represent the obtained linear correlations between thermal conductivity (W m^{-1} K^{-1}) and temperature (°C) and water vapor partial pressure (Pa) for XLAM and insulation, respectively. The "as-is" data were neglected in the determination of the correlations because this state was not obtained in a controlled environment. The two following functions were adopted for simulations with actual conditions.

$$\lambda(T,p_v)=0.099 + 2.125 \cdot 10^{-4} \cdot T + 7.380 \cdot 10^{-6} \cdot p_v \quad (3)$$

$$\lambda(T,p_v)=0.034 + 3.694 \cdot 10^{-4} \cdot T + 6.760 \cdot 10^{-6} \cdot p_v \quad (4)$$

3.2 Mass Transfer Model Calibration

By using the conditioning data, the mass transfer model was calibrated for the XLAM in order to obtain the vapor resistance factor used in the mathematical model. In particular, the vapor resistance factor was tuned, by comparing simulated results with the process in the climatic chamber in which moisture content was reduced, i.e. from 23 °C/80 % to 23 °C/10 %, and by verifying that:

1. the simulated mass loss after 9 days is the same as the experimental mass loss (i.e., 34 g);
2. simulated and calculated mean fluxes correspond.

A value of 32 for the water vapor resistance factor μ was first obtained in the calibration stage by means of conditioning data from 23 °C/80 % to 23 °C/10 % and then checked against the experimental process which started from the "as-is" state to the high *MC* state (i.e., a mass increase of 46.5 g in 43 days). For the insulating material, no calibration process was performed because, firstly, the weighing time step suggested by the Standard EN ISO 12571:2013 (CEN, 2013) was too long for this material and furthermore, a higher precision balance would have been necessary and because the range of the μ-value in the literature for this kind of materials is narrow. For this reason, a value of 2 was chosen (Labat et al., 2016; Xing et al., 2018).

3.3 Average Percentage Impact

The overall effect of the actual thermal conductivity is to increase the heat flux and on average the deviation ranges from 3.8 to 4.8 %, considering the three different wall thicknesses (Fig. 3). Mean deviations were higher in the South than in the North because of the smaller magnitude of the flux (i.e. the smaller temperature difference between internal and external on average) in all the three configurations. With the lowest insulation thickness, the maximum mean deviation was 7.7 %, obtained in the southern climate of Reggio Calabria. By increasing the insulation thickness, mean deviations increased up to values of approximately 11 % in the South for Crotone. All the statistics related to the mean deviations are shown in Table 3.

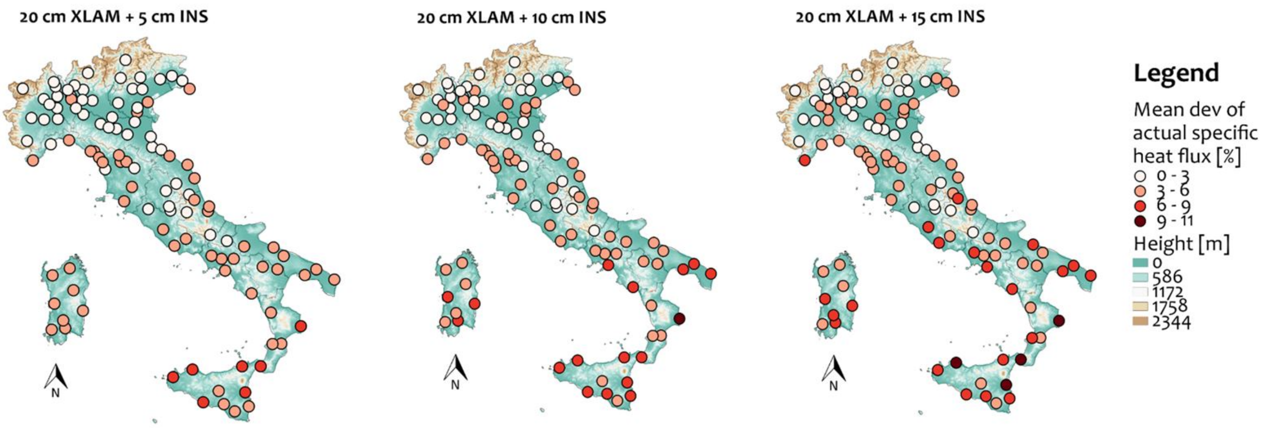

Fig. 3 – Percentage deviation (%) of the actual specific heat flux with respect to the nominal specific heat flux (at 10 °C) for each location in Italy and for the three configurations of the insulated wall

Table 3 – Statistics related to the mean deviation (%), the increase of positive and negative thermal losses (Wh m^{-2}) for the three wall configurations. Nominal thermal conductivity at 10 °C

	20 cm XLAM + 5 cm INS			20 cm XLAM + 10 cm INS			20 cm XLAM + 15 cm INS		
	Mean deviation (%)	Increase in thermal loss (Wh m^{-2})	Increasein thermal gain (Wh m^{-2})	Mean deviation (%)	Increase in thermal loss (Wh m^{-2})	Increase in thermal gain (Wh m^{-2})	Mean deviation (%)	Increase in thermal loss (Wh m^{-2})	Increase in thermal gain (Wh m^{-2})
Average	3.8	558	340	4.4	475	315	4.8	417	276
Minimum	0.9	288	88	0.5	171	77	0.4	129	65
1st quartile	2.6	501	247	2.8	414	229	3.0	359	201
Median	3.7	551	325	4.1	478	300	4.5	421	262
3rd quartile	4.9	614	413	5.7	539	381	6.3	481	330
Maximum	7.7	872	707	9.5	764	661	10.6	665	593

Table 4 – Statistics related to the mean deviation (%), the increase of positive and negative thermal losses (Wh m-2) for the three wall configurations. Nominal thermal conductivity at 23 °C

	20 cm XLAM + 5 cm INS			20 cm XLAM + 10 cm INS			20 cm XLAM + 15 cm INS		
	Mean deviation (%)	Increase of thermal loss (Wh m^{-2})	Increase of thermal gain (Wh m^{-2})	Mean deviation (%)	Increase of thermal loss (Wh m^{-2})	Increase of thermal gain (Wh m^{-2})	Mean deviation (%)	Increase of thermal loss (Wh m^{-2})	Increase of thermal gain (Wh m^{-2})
Average	0.8	61	262	0.8	28	246	1.0	31	217
Minimum	-2.2	-424	65	-3.2	-474	57	-3.6	-427	49
1st quartile	-0.4	-51	187	-0.8	-85	175	-0.9	-67	152
Median	0.7	81	248	0.5	46	231	0.7	46	203
3rd quartile	1.9	187	315	2.2	159	295	2.5	149	257
Maximum	4.8	326	557	6.1	289	529	7.0	269	483

When considering a reference temperature of 23 °C for the nominal thermal conductivity, the values change considerably (Table 4) even if their distribution all over the peninsula is the same. In these conditions, locations where previously small positive mean deviations were registered are characterised by negative values, meaning that with the actual thermal conductivity the fluxes are smaller, so the wall performs better than in the nominal case. This unexpected behaviour was explained by the fact that in some locations the reference temperature of 23 °C was too high since the average external temperature was lower. This happens especially in colder locations (cities in the north and/or in mountainous areas).

3.4 Absolute Impact

By adopting a variable thermal conductivity, there is a general increase in thermal losses, on average from 417 to 558 Wh m^{-2} for all the three configurations (Fig. 4). The maximum increase (872 Wh m^{-2} higher than with the nominal conductivity) was registered for the less insulated wall in Oppido Lucano, a southern city at an altitude of approximately 700 m, with a low mean external temperature (i.e. 13 °C). By increasing the insulation layer, the heat fluxes towards the outside decrease, in addition to the thermal losses. This is why with higher insulation thickness, the increase in thermal loss is lower. Moreover, thermal gains (towards the inside) increase all over the peninsula by considering a variable thermal conductivity (Fig. 5). On average, the increase is of approximately 340, 315 and 276 Wh m^{-2} respectively for the three configurations with increasing insulation thickness. The maximum increase is for the less insulated wall, for the same reason, i.e. thermal losses. The maximum value is obtained for Taranto, a southern city, where the average external temperature and thus the inward heat flux are higher. With higher insulation thickness, the increase is clearly reduced since the magnitudes of thermal fluxes are lower. When the nominal thermal conductivity is evaluated at 23 °C, locations in which the thermal losses were already low, in this case, are characterised by negative values of variation in thermal losses as for the case of the mean deviations. This occurs because the reference wall temperature overestimates the actual conditions for those locations. For the thermal gains, no negative values are registered. This is because thermal gains usually occur when the external temperature is higher than 20 °C, thus, usually higher than the reference wall temperature.

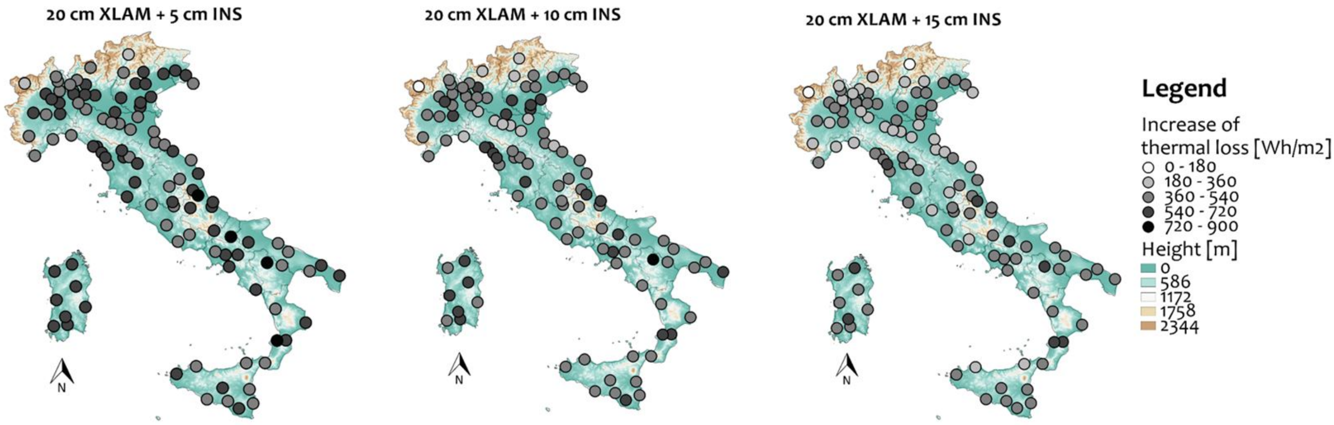

Fig. 4 – Increase in annual specific thermal losses (positive) calculated with variable thermal conductivity with respect to nominal thermal conductivity (at 10 °C) for the three configurations of the insulated wall (Wh m^{-2})

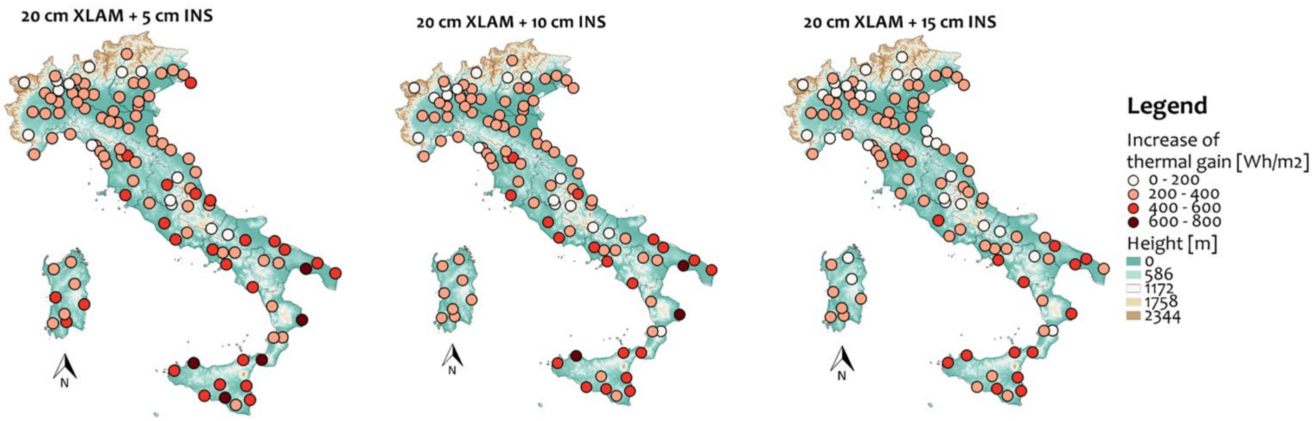

Fig. 5 – Increase in annual specific thermal gains (negative) calculated with variable thermal conductivity with respect to nominal thermal conductivity (at 10 °C) for the three configurations of the insulated wall (Wh m^{-2})

4. Conclusions

A numerical and experimental study on insulated timber walls was conducted in order to assess the impact of external temperature and water vapor partial pressure on thermal conductivity of wood and wood-based materials and subsequently on the specific heat flux across them. The focus was on both wood and wooden insulation, because of the higher sensitivity of wood to moisture variations than other building materials.

Thermal conductivity measurements were conducted at different temperatures and moisture contents for XLAM specimens and wooden insulation panels. From the experimental activity, thermal conductivity functions of the temperature and water vapor partial pressure were found for both materials. This allowed the implementation of a 1D heat and mass transfer finite difference model. Unknown parameters were obtained either after calibration of the model against experimental data or from the literature. With this model, the thermal behaviour of three insulated wooden walls with a 20 cm XLAM layer and 5, 10 and 15 cm of insulation in 110 Italian locations was studied. Results of the experimental activity and of annual simulations with both nominal (10 °C and 23 °C reference temperature) and actual thermal conductivity for each location show that:

- Experimental thermal conductivity of XLAM and the wooden insulation panel increase both with temperature (+11 % for XLAM and +41 % for the insulation by varying the temperature from 10 to 50 °C) and moisture content (+13 % for XLAM and +22 % for the insulation by passing from “as-is” to the high *MC* state). The higher percentage for the insulation is due to the smaller value of its thermal conductivity.

- When the heat flux is simulated by considering only the nominal thermal conductivity (at 10 °C) of the insulated walls, there is an underestimation of the heat flux throughout the Italian peninsula for each wall configuration (i.e. -11 % for the less insulated wall).
- The analysed locations show different trends, with northern climates characterized by a higher increase in thermal losses (up to 900 Wh m^{-2}) and southern climates by a larger increase (of 800 Wh m^{-2}) for all wall configurations.
- By increasing the external insulation thickness, differences among locations for both thermal losses and gains are less evident. This is because the specific heat flux decreases.
- It is fundamental to choose the proper reference temperature at which the nominal thermal conductivity is measured according to the climate. For example, in cold climates a reference temperature of 23 °C would be too high.
- Simulations with and without an insulation layer and the same boundary conditions show different results: without an insulation layer (i.e. with only 20 cm of XLAM), smaller percentage deviations and smaller increases in thermal losses and gains were obtained because the thermal performance (in terms of insulation power) of the wall is strongly influenced by the external insulation layer.

Further research in this area is planned and will include (i) the effects of temperature on mass diffusion; (ii) the effects of moisture content on specific heat; (iii) the phase change in the mass transfer model; and (iv) a better experimental characterisation in terms of both conditioning points in the climatic chamber and respective thermal conductivity measurements, in order to improve the fit for thermal conductivity data.

Acknowledgement

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Nomenclature

Symbols

c	specific heat capacity (J kg^{-1} K^{-1})
C_m	linear storage moisture capacity (kg kg^{-1} Pa^{-1})
∂	partial derivative
INS	insulation panel
λ	thermal conductivity (W m^{-1} K^{-1})
μ	vapor resistance factor (-)
MC	moisture content (% dry basis)
∇	gradient
p_v	water vapour partial pressure (Pa)
ρ	density (kg m^{-3})
RH	relative humidity (%)
T	temperature (°C)
t	time (s)

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