Thermal insulation of existing buildings and interstitial condensation: Comparative assessment in different European climate contexts

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***Abstract*—This study focuses on the introduction of different types of insulation materials into existing building systems in Europe, where the chosen scenarios differ by climate zone and according to the Köppen climate classification. The insulation materials used are specifically: natural fibre materials, mineral fibre materials and artificial materials. The analysis in question was based on the assessment of the risk of interstitial condensation between the existing masonry and the insulation and the WCI [Kg/m^2] (Water Content in the Insulation), through various simulations in dynamic mode, over a reference period of 10 years prior to the energy upgrading intervention. The case study buildings were taken from TABULA and divided by climatic zone, for the years of construction from 1945 to 1969 related to the building typology of single-family houses, wherein each building system the insulation was placed towards the warm side with a fixed thickness of 5 cm. The simulations concerned: a) the application scenario, b) the type of stratigraphy chosen, (c) exposure of the existing building system. The outputs generated by the simulations provided the data to determine in which type of building, depending on the insulating materials, interstitial condensation is formed or not. It was shown that only for the climate zones of the cities of Oslo and Brussels, associated with their own building typologies, for the insulating materials: mineral and natural, there is the formation of interstitial condensation.**

Keywords—thermohygrometric evaluation; interstitial condensation; thermal insulation; WUFI; TABULA; Köppen classifications

I. INTRODUCTION

The installation of insulating materials in existing buildings improves the energy performance of buildings. The scientific literature and several case studies report examples of how increasing energy efficiency through such interventions leads to a reduction in energy needs for both heating and cooling [1][2][3][4]. The insulating layer can be positioned on the external, intermediate or internal side of the masonry, the latter case is the subject of study in this article and previous research [5][6][7]. The insulating materials in the building sector are of various kinds, they are distinguished by their nature and their technical characteristics. The possibility of introducing natural/organic materials as an alternative to synthetic ones, as the studies carried out in this direction, show that in certain cases the use of materials of an organic nature, such as hemp fibre or linen fibre panels, can effectively reduce the risk of condensation [8][9], with particular attention to collection, production, manufacturing and maintenance procedures. These precautions, for the types of natural/organic materials, serve to avoid the risk of negative effects caused by humidity and free water, since the latter materials are putrescible [10]. In fact, it is precisely these phenomena that cause the greatest damage to buildings, as it has been shown that humidity can be a risk to building structures and is the first cause of damage in construction (48.3%) [11]. The building typologies concerning the European real estate , have similar characteristics in the historical and economic technological field [12], also from the point of view of the construction of the building elements. In order to help identify the type of building, it is necessary to consult TABULA [13] (Typology approach for building stock energy assessment), which introduced a common methodology in order to define building types and to create references to building types within Europe [14]. This methodology makes it possible to quantify the possible energy savings generated by renovations, in fact, it has been demonstrated that more than 40% in terms of energy savings could be achieved through basic renovations [14]. Interventions aimed at ensuring the greatest result in terms of energy efficiency on the building envelope see the possibility to intervene in various aspects of the building. However, not all building envelopes are suitable for energy

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requalification, in this regard, was provided by Ferreira et al. (2013) [15] a review of decision support tools for the renovation of buildings.
Concerning the improvement of energy performance, it is necessary to determine the reference building typology, TABULA proposes a series of typologies associated with the period of construction, where for each reference period there are different construction systems associated, with typical stratigraphies of the place of belonging, sorted by type of building element [16][13]. The year of construction of the individual building types plays a fundamental role in the choice of the type of stratigraphy to be chosen for energy restoration, as over the years the building stratigraphy have changed both from the technological point of view of materials and energy. The choice of the reference period to be associated with an energy refurbishment intervention must include several combined factors [15]. Another important factor for an increase in the energy efficiency of the envelope is to identify the types of buildings to which such interventions can be more efficient, also in this direction it has been demonstrated that only some buildings are more functional than others, in fact, the thermal insulation of the opaque envelope in single-family houses is more effective from the energy point of view than other buildings in Europe [1][12]. The renovation work on the buildings, in any case, provides the study of the climate in which the shell is inserted, in this regard, being in Europe the latter predominantly continental, there are significant variations between the south and north and between the mountainous and flat areas. For this purpose, the subdivision of climate zones according to the classification of Köppen climates (where each climate is defined with respect to predetermined values of temperature and precipitation) [17] is useful to determine the reference climate zones . The regulatory framework at international level proposes, in addition to the traditional method of the Glaser diagram [18] based on stationary analysis, the possibility to use dynamic hygrometric simulations. In this regard, with reference to standard UNI EN 15026 [19], the analysis provided for the assessment of crevice condensation was obtained through a variable steam migration calculation using WUFI PRO (Wärme und Feuchte Instationär)software [20]. The choice to carry out the simulations through a software able to elaborate a calculation in dynamic regime, has allowed evaluating climatic conditions closer to reality, also considering all the processes of moisture transport in materials that the stationary method is not able to consider [21]. Hygrometric simulations allow, if used correctly, to evaluate almost all phenomena relevant to building practice, such as water absorption, precipitation, solar radiation, steam diffusion, moisture accumulation, capillary liquid transport and much more.

II. Goals

The objective of this article is to compare different types of insulation materials, introduced in existing building types in Europe, derived from TABULA to obtain information about the risk of interstitial condensation and the amount of water in the insulation.
The information obtained will concern the presence or absence of crevice condensation and MWCI [kg/m^2] (Maximum Water Content in Insulation), depending on the guidelines. Also, the exact time frame (dd/mm/yyyy) at which these phenomena may develop over the 10 years of simulations. It is thus possible to determine the type of insulation, whether or not installed in a given type of building, which favours interstitial condensation and high WCI, depending on the orientation and climate zone.

III. Research Methodology

The methodology adopted for the research involves the definition of certain parameters:

A. *Definition of the building typologies studied by TABULA;*
B. *Definition of the cities in the climatic zones of Köppen;*
C. *Choice of insulation materials;*
D. *Selection of software and orientation;*
E. *Application scenarios.*

A. Definition of building types

For the determination of the different types of buildings, reference has been made to TABULA WebTool [16], the following WebTool, provides for the introduction of some data concerning the type of building and the year of its construction. Only through the identification of these parameters, it is possible to recognize the type of construction to develop the simulations in the variable regime. Once the type of construction system to be analysed has been identified, it has been chosen to introduce the insulation in the internal part of the wall profile, with a thickness of 5 centimetres. For the choice of the type of building to refer to, a search was carried out from EUROSTAT data [22], from which it emerged that, as in Europe, 33.6% of the population live in independent single-family houses. Furthermore, as demonstrated [1][12], single-family houses, in the European context, lend themselves to be more effective in energy requalification interventions, which involve the insulation of the opaque shell, compared to the other building types proposed by TABULA. For these considerations, this typology has been chosen for the development of the simulations. TABULA WebTool takes into consideration the building typologies and the reference period in which the buildings have been realized.
The reference period, associated with the chosen typology, has also been obtained from a search from EUROSTAT data [23] related to the period of single-family house construction in Europe. Where through the research database it was found that 26.85% of the European building stock was built between 1945 and 1969. By reporting this historical moment deriving from the EUROSTAT source, with the data related to the less effective redevelopment interventions both from the energy and economic point of view, i.e. those interventions applied to the most recent building types with construction period 1976 - 2005 [1].

B. Cities and climate zones

The choice of geographical areas in which to identify the type of building is associated with a variable data, in fact, for each location, of the six choices, there will be a different type of building resulting from TABULA. The choice of the reference city was determined through the geographical division of Europe into areas: northern, central European and southern. The chosen cities are:

- Milan and Malaga for the Southern Europe area;
- Vienna and Brussels for the Central Europe area;

- Oslo and Hamburg for Northern Europe.

Each of these cities has been assigned a climate classification of Köppen [17][24], in order to further subdivide them by climate zone.

C. *Insulating materials*

This article compares different types of insulating material, which can be distinguished from each other by their nature of origin. The materials chosen for the generated simulations are mineral, natural/organic and synthetic nature. The choice in using these types of insulators falls on the fact that every single material has different behaviour in hygrothermal terms in response to the surface where it is installed [25]. The chosen insulators are:

- Hemp fibre and flax fibre panels (natural fibre materials);
- Rock wool and glass wool (mineral materials);
- EPS and XPS (synthetic materials).

Every single insulating insulator differs in several aspects from each other, such as: ε material porosity (m3/m3), ρ material density (Kg/m^3), λ thermal conductivity of the material (W/mK) and μ vapour permeability coefficient (-) and *s* insulation thickness (cm) (Table 1. “Insulating Data”). The introduction of the insulating panel in the determined building systems, foresees its arrangement in the internal part of the masonry profile, therefore on the hot side of the masonry under analysis. The choice of the arrangement in this specific configuration is due to the desire to determine the univocal case. In addition, simulations will be proposed using a fixed thickness of 5 cm on all the chosen building systems and for any type of insulation adopted.

D. *Simulation and orientation software*

The software chosen for data processing is WUFI PRO 6.3 which requires you to set the duration period of the simulations, where, for each of them has been generated a variable calculation of 10 years, starting from 1/10/2019 to 1/10/2029 (87600 hours), in order not to interrupt the cold season, which would happen if you start the simulations on January 1, remains, in any case, an arbitrary choice.

The last variable input data necessary for the analysis turns out to be the orientation: the simulations were carried out in variable regime considering the three main orientations (south, north, east/west), thus being able to obtain information related to the cardinal exposure of the wall profiles.

E. *Definition of scenarios*

The data processing procedure described above was carried out using the WUFI PRO software. In each stratigraphy determined by TABULA (Fig. 1), each type of insulation was introduced towards the hot side of the building package with a fixed thickness of 5 cm (Fig. 2). For all types of insulation material and building system associated with the location, 3 simulations were performed, each one associated with a different orientation. The total number of simulations for each chosen city and for each insulation applied is 18, for a total of 108 numerical simulations generated, including each building system, city and orientation (Table 1).

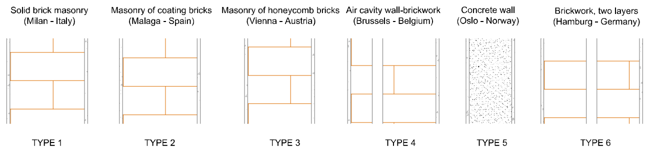

Fig. 1. Types of wall stratigraphy determined by TABULA by reference location

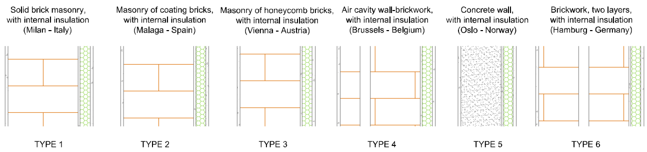

Fig. 2. Introduction of the insulating panel in the various types of wall stratigraphy determined by TABULA by reference

TABLE I. INPUT DATA CONCERNING THE CITY OF MILAN, TOTAL NUMERICAL SIMULATIONS 18 FOR EACH LOCATION, FOR A TOTAL OF 108 SIMULATIONS IN VARIABLE REGIME CONSIDERING ALL THE CHOSEN AREAS

Scenarios						**Insulation data**				
City	***Classification according to the Köppen system***	***Type of insulation***	***Orientation***	***Simulation departure date [dd/mm/yyyy]***	***End date of simulation [dd/mm/yyyy]***	***μ***	***ρ***	***λ***	***ε***	***s***
MI	Cfa	Hemp fibre	North	01/10/19	01/10/29	1,5	50	0,038	0,95	5
MI	Cfa	Hemp fibre	South	01/10/19	01/10/29	1,5	50	0,038	0,95	5
MI	Cfa	Hemp fibre	East/West	01/10/19	01/10/29	1,5	50	0,038	0,95	5
MI	Cfa	Linen fibre panel	North	01/10/19	01/10/29	1,5	39	0,0376	0,95	5
MI	Cfa	Linen fibre panel	South	01/10/19	01/10/29	1,5	39	0,0376	0,95	5
MI	Cfa	Linen fibre panel	East/West	01/10/19	01/10/29	1,5	39	0,0376	0,95	5
MI	Cfa	Glass wool	North	01/10/19	01/10/29	1,3	30	0,035	0,99	5
MI	Cfa	Glass wool	South	01/10/19	01/10/29	1,3	30	0,035	0,99	5
MI	Cfa	Glass wool	East/West	01/10/19	01/10/29	1,3	30	0,035	0,99	5
MI	Cfa	Rock wool	North	01/10/19	01/10/29	1,3	119	0,034	0,956	5
MI	Cfa	Rock wool	South	01/10/19	01/10/29	1,3	119	0,034	0,956	5
MI	Cfa	Rock wool	East/West	01/10/19	01/10/29	1,3	119	0,034	0,956	5
MI	Cfa	EPS	North	01/10/19	01/10/29	50	30	0,04	0,95	5
MI	Cfa	EPS	South	01/10/19	01/10/29	50	30	0,04	0,95	5
MI	Cfa	EPS	East/West	01/10/19	01/10/29	50	30	0,04	0,95	5
MI	Cfa	XPS	North	01/10/19	01/10/29	100	40	0,03	0,95	5
MI	Cfa	XPS	South	01/10/19	01/10/29	100	40	0,03	0,95	5
MI	Cfa	XPS	East/West	01/10/19	01/10/29	100	40	0,03	0,95	5

IV. RESULTS

The results obtained from the numerical simulations in dynamic mode in WUFI PRO have returned the following results:

A. *climate data;*
B. *data on insulation materials.*

A. *Climate data*

The histogram graphs (Fig. 3) shows the average and maximum IRH [%] (Interstitial Relative Humidity) values, expressed as a percentage, by subdivision according to the Köppen system and according to the chosen cities. Fig. 3 allows comparing the percentage of humidity between insulation and masonry existing on the y-axis, with the climatic subdivision according to the Köppen system on the abscissae axis, representative of the cities considered. Fig. 4 shows the WCI values, mean and maximum, by subdivision according to the Köppen system and according to the selected cities. The graph allows to compare the amount of water present in the insulation on the y-axis with the climatic subdivision according to the Köppen system on the abscissae axis, representative of the cities considered.

Fig. 3. Results of IRH values (%), maxima and averages, by subdivision according to the Köppen system

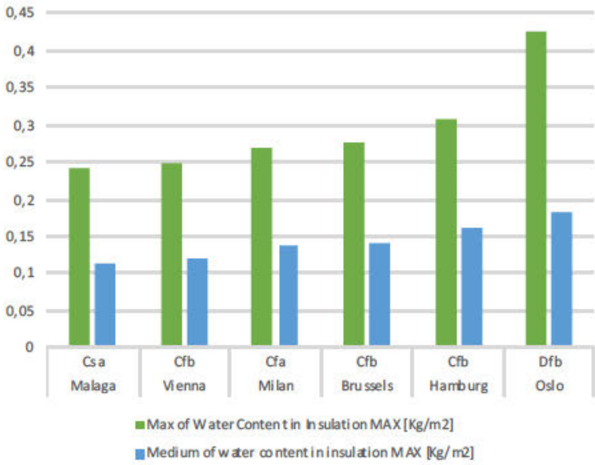

Fig. 4. Results of WCI values (Kg/m2), maxima and averages, by subdivision according to the Köppen system

B. *Data on insulation materials*

The histogram graph (Fig. 5) shows along the y-axis the values in percentage of the presence of IRH and in abscissa the types of insulation used divided by location. Table 2 shows results in terms of orientation, location and type of insulation.

The dispersion graphs (Fig. 6) represent a) the trend of the average density of the insulation (Kg/m^3) as a function of the quantity of IRH (%); b) the trend of the average density (Kg/m^3) with respect to the WCI (Kg/m^2). The average density has been calculated with respect to the reference period in which the maximum IRH value occurs in the 10 years of simulation.

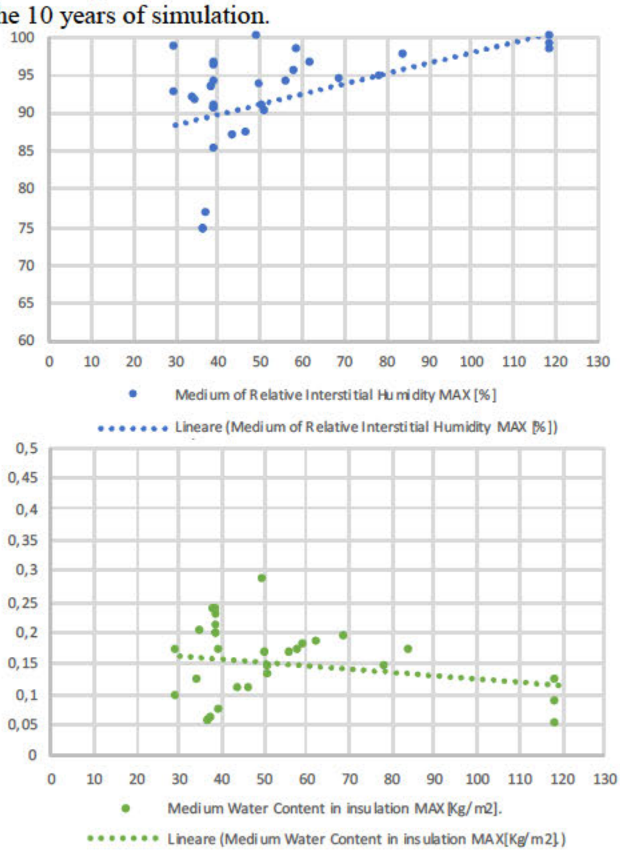

Fig. 6. a) Results of the insulation density mean values as a function of the amount of IRH; b) Results of the insulation density mean values as a function of the amount of WCI.

V. DISCUSSION

The results show that the MIRH [%] (Maximum Interstitial Relative Humidity) depends on the climatic context (Köppen) of the city (Fig. 3). The maximum condensation values occur for the Köppen Cfb (Vienna, Hamburg, Brussels) and Dfb (Oslo) areas, in contrast, for the Cs group (temperate climates with dry summer, Malaga) the IRH value is lower. Likewise, MWCI also depends on the climate zone (Fig. 4), showing that the context and climate zone play a relevant role in the WCI, since as the index of the main group of its classification increases there is an increase in the value associated with the amount of water. This makes it difficult to standardise applications and for different European contexts.

The types of insulating material adopted, in the individual climate zones, determines the formation of interstitial condensation between the existing masonry and the thermal insulation (Fig. 5). In places such as Oslo and Brussels, the formation of interstitial condensation occurs with the use of hemp fibre insulation, glass wool and rock wool. For the other configurations, the percentage of humidity never reaches saturation. In fact, since the latter has a lower average density (30 Kg/m^3) compared to competing materials, the graph (Fig. 6.b) shows that when the density of the material decreases there is an increase in terms of total water content in the material. Therefore the climate has an influential role on the risk of interstitial condensation, in fact, all cities located in adverse climate zones as Cfb (Temperate oceanic climate), Cfa (Humid subtropical climate) and Dfb (Warm-summer humid continental climate) have high IRH contents, on the contrary, cities in the driest and driest zones as Csa (Hot-summer Mediterranean climate) have lower values. The formation of condensation, when it occurs, does not depend on the orientation: in all four cardinal configurations are the climatic areas associated with the Dfb zone (Oslo), colder climates, on the contrary, in the other zones (Brussels), the formation of condensation is verified for the north, east and west orientation but not always for the south (Table 2). The locations subject to the presence of interstitial condensation are Brussels and Oslo, associated with hemp fibre, glass wool and rock wool insulation. As far as the city of Brussels is concerned, it can be seen that only stone wool shows the formation of interstitial condensation in all three exposures, while for the other two types of insulation, the southern exposure is free of interstitial condensation.

Materials with high density (Kg/m^3) tend to have a higher risk of crevice condensation, while materials with lower density tend to have lower IRH values. In contrast, WCI tends to increase if the density is lower and decrease if the density is higher (Fig. 6). As the density increases, there is an increase in the percentage of moisture between wall and insulation. The maximum values found are relative to stone wool (with a density of 119 Kg/m^3), in fact, this material as shown in Fig. 5 has the highest value in each IRH configuration. On the contrary, the tendency of the values relative to the density of the insulation decreases according to the water content of the insulation (Fig. 6.b). Stone wool insulation has a low WCI, although it guarantees the presence of crevice condensation between the existing masonry and the insulation. Therefore materials with a high value of the vapour permeability coefficient tend to have a lower risk of relative interstitial condensation, while if this coefficient tends towards to zero, the risk of this phenomenon increases. The same consideration is valid for the amount of water in the insulation, in fact, the latter has the same tendency.

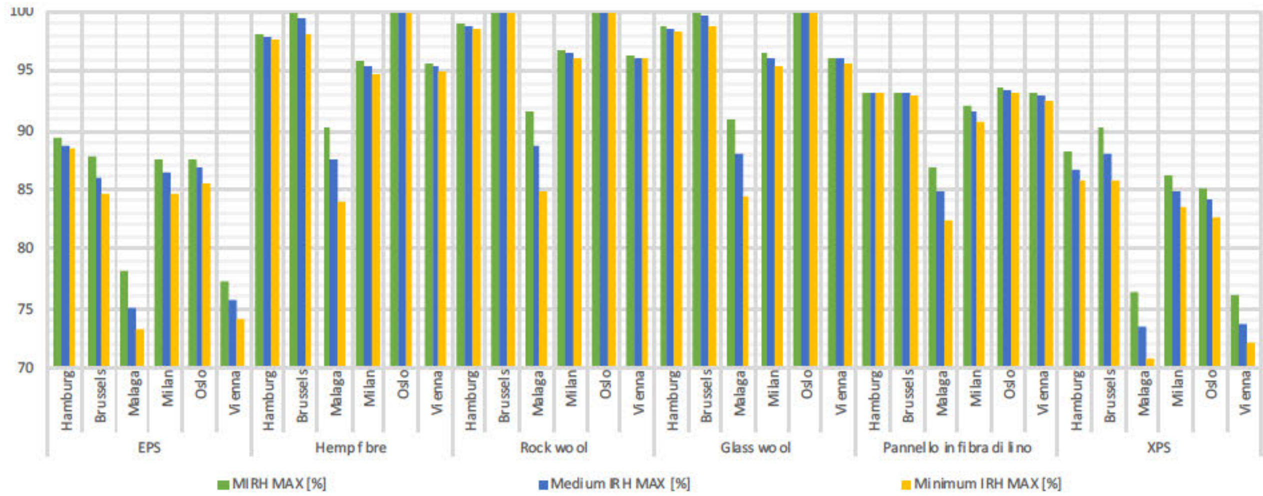

Fig. 5. Results of maximum, average and minimum IRH values (%), broken down by insulation type and application scenario.

TABLE II. RESULTS IN TERMS OF ORIENTATION, LOCATION AND TYPE OF INSULATION OF THE PRESENCE OR ABSENCE OF INTERSTITIAL CONDENSATION BETWEEN INSULATION AND EXISTING MASONRY

City	Orientation	Type of insulation					
		EPS	*Hemp fibre*	*Rock wool*	*Glass wool*	*Linen fibre*	*XPS*
Hamburg	East/West	NO	NO	NO	NO	NO	NO
	North	NO	NO	NO	NO	NO	NO
	South	NO	NO	NO	NO	NO	NO
Brussels	East/West	NO	YES	YES	YES	NO	NO
	North	NO	YES	YES	YES	NO	NO
	South	NO	NO	YES	NO	NO	NO
Malaga	East/West	NO	NO	NO	NO	NO	NO
	North	NO	NO	NO	NO	NO	NO
	South	NO	NO	NO	NO	NO	NO
Milan	East/West	NO	NO	NO	NO	NO	NO
	North	NO	NO	NO	NO	NO	NO
	South	NO	NO	NO	NO	NO	NO
Oslo	East/West	NO	YES	YES	YES	NO	NO
	North	NO	YES	YES	YES	NO	NO
	South	NO	YES	YES	YES	NO	NO
Vienna	East/West	NO	NO	NO	NO	NO	NO
	North	NO	NO	NO	NO	NO	NO
	South	NO	NO	NO	NO	NO	NO

VI. CONCLUSION

The research shows that it is possible to relate the results obtained about the presence of interstitial condensation and the WCI, with the climatic zones according to the Köppen classification, with the nature of the insulating materials, as well as with the building types chosen. The results show that there is a close correlation between the risk of interstitial condensation and the climate zones according to the classification, in fact, the categories attributable to this phenomenon concern only groups C and D with subgroups Cf and Df, related to temperate climates with humid summer and cold climates with humid winter. Specifically, the formation of interstitial condensation has been recorded only for areas Cfb (Brussels) and Dfb (Oslo). The results obtained may be useful in identifying the ideal type of insulation material that avoids the formation of interstitial condensation, when it is necessary to ensure an increase in the energy efficiency of the opaque envelope in certain geographical contexts associated with specific building types. Possible future research could include the possibility of extending this analysis to the case where insulation is applied on the external part of the wall stratigraphy, to determine which type of configuration could be more advantageous to reduce the risk of interstitial condensation formation.

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REFERENCES

[1] I. Ballarini, V. Corrado, F. Madonna, S. Paduos,F. Ravasio,"Energy refurbishment of the Italian residential building stock: energy and cost analysis through the application of the building typology" Energy Policy, vol. 105, pp. 148–60, 2017. https://doi.org/10.1016/j.enpol.2017.02.026

[2] N. Aste, A. Angelotti, M. Buzzetti, "The influence of the external walls thermal inertia on the energy performance of well insulated buildings" Energy Build, vol. 41, pp. 1181–1187, 2009. https://doi.org/10.1016/j.enbuild.2009.06.005

[3] M. Lawrence, "Reducing the environmental impact of construction by using renewable materials", Journal of Renewable Materials, vol. 3, no. 3, pp. 163-174, 2015. https://doi.org/10.7569/JRM.2015.634105

[4] D.I. Kolaitis, E. Malliotakis , D.A. Kontogeorgos , I. Mandilaras , D.I. Katsourinis, M.A. Founti, "Comparative assessment of internal and external thermal insulation systems for energy efficient retrofitting of residential buildings", Energy and Buildings, vol. 64, pp. 123–31, 2013. https://doi.org/10.1016/j.enbuild.2013.04.004

[5] C. Xu, S. Li, K. Zou, "Study of heat and moisture transfer in internal and external wall insulation configurations", J. Build. Eng., vol.24, pp. 100724, 2019. https://doi.org/10.1016/j.jobe.2019.02.016

[6] A. Dell'Orto, "Isolamento dall'interno - Sintesi del Quaderno Tecnico n.1 "Soluzioni per isolare dall'interno" ad uso della committenza privata (Insulation from the interior - Summary of Technical Book n.1 "Solutions for insulating from the interior" use for private clients)", pp. 1–13, 2019.

[7] G. Galbusera, A. Riva, "Isolamento termico dall'interno senza barriera al vapore (Thermal insulation from the interior without vapor barrier)", Anit, pp.1–24, 2013.

[8] E. Latif, S. Tucker, M.A. Ciupala, D.C. Wijeyesekera, D.J. Newport, M. Pruteanu, "Quasi steady state and dynamic hygrothermal performance of fibrous Hemp and Stone Wool insulations: Two innovative laboratory based investigations", Build. and Environ, vol. 95, pp. 391–404, 2016. https://doi.org/10.1016/j.buildenv.2015.10.006

[9] A. Hussain, J. Calabria-Holley, M. Lawrence, Y. Jiang, "Hygrothermal and mechanical characterisation of novel hemp shiv based thermal insulation composites" Constr. Build. Mater, vol. 212, pp. 561–8, 2019. https://doi.org/10.1016/j.conbuildmat.2019.04.029

[10] H.R. Kymäläinen, A.M. Sjöberg, "Flax and hemp fibres as raw materials for thermal insulations", Build. Environ., vol. 43, pp. 1261–9, 2008. https://doi.org/10.1016/j.buildenv.2007.03.006

[11] B. Cristina, "Le guide pratiche del Master CasaClima 7 - Umidità e tenuta all'aria (The practical guides of the ClimateHouse Master 7 - Humidity and air tightness)", 2014.

[12] T. Csoknyai, S. Hrabovszky-Horváth, Z. Georgiev, M. Jovanovic-Popovic, B. Stankovic, O. Villatoro, G. Szendrőa, "Building stock characteristics and energy performance of residential buildings in Eastern-European countries", Energy Build., vol. 132, pp. 39–52, 2016. https://doi.org/10.1016/j.enbuild.2016.06.062

[13] V. Corrado, S.P. Corgnati, I. Ballarini, N. Tala', "Building Typology Brochure – Italy", Politecnico di Torino, pp. 1-117,2014.

[14] I. Ballarini, S.P. Corgnati, V. Corrado, "Use of reference buildings to assess the energy saving potentials of the residential building stock: The experience of TABULA project", Energy Policy, vol. 68, pp. 273–84, 2014. https://doi.org/10.1016/j.enpol.2014.01.027

[15] J. Ferreira, M. Duarte Pinheiro, J. de Brito, "Refurbishment decision support tools review – Energy and life cycle as key aspects to sustainable refurbishment projects", Energy Policy, vol. 62, pp. 1453–1460, 2013.

[16] TABULA n.d. http://webtool.building-typology.eu/#bm.

[17] W. Köppen, Graz und R. Geiger, "Das geographische System der Klimate - Handbuch der Klimatologie", Bull Am Geogr Soc 1911; vol. 43, pp. 935, 1936. https://doi.org/10.2307/200498

[18] UNI EN ISO 13788:2013, Prestazione igrotermica dei componenti e degli elementi per l'edilizia – Temperatura superficiale interna per evitare l'umidità superficiale critica e condensazione interstiziale – Metodi di calcolo

[19] UNI EN ISO 15026:2008 - Valutazione del trasferimento di umidità mediante una simulazione numerica. Anit, 2016.

[20] V. Cascione, "Valutazione igrotermica di soluzioni tecniche d'isolamento dell'involucro edilizio per il recupero energetico in Italia per mezzo di simulazioni dinamiche (Hygrothermal evaluation of technical insulation solutions of the building envelope for energy recovery in Italy by means of dynamic simulations)", Politec Di Bari, 2016.

[21] Construction WF, Construction LRD. ASHRAE, Handbook of Fundamentals, Criteria for Moisture-Control Design Analysis in Buildings. Chapter 23, 2009. 1999.

[22] EUROSTAT n.d. https://ec.europa.eu/eurostat/statistics-explained/index.php/Housing_statistics#Type_of_dwelling.

[23] EUROSTAT n.d. https://ec.europa.eu/energy/en/eu-buildings-database.

[24] M. Kottek, J. Grieser, C. Beck, B. Rudolf, F. Rubel, "World map of the Köppen-Geiger climate classification updated", Meteorol Zeitschrift, vol. 15, pp. 259–63, 2006. https://doi.org/10.1127/0941-2948/2006/0130

[25] S.P. Bjarløv, G.R. Finken, T. Odgaard, "Retrofit with interior insulation on solid masonry walls in cool temperate climates - An evaluation of the influence of interior insulation materials on moisture condition in the building envelope", Energy Procedia, vol. 78, pp. 1461–6, 2015. https://doi.org/10.1016/j.egypro.2015.11.171